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Monitoring of well integrity by magnetic imaging defectoscopy (MID) at the Ketzin pilot site, Germany

Kornelia Zemke*, Axel Liebscher, Fabian Möller

Section 6.3 Geological Storage, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Abstract

At the Ketzin CO_2 storage site, Germany, an interdisciplinary, comprehensive monitoring concept focusses on the storage complex, the overburden, the surface and the wellbores. Well integrity as one key requirement for safe storage operation has been monitored by combined video inspection, pulsed neutron gamma logging PNG, magnetic imaging defectoscopy MID and continuous annuli pressure monitoring. The time-lapse MID derived casing thicknesses are within the production specifications, conform to the API standards, and provide no hints to time dependent changes or to any other signs of corrosion. The comprehensive monitoring data indicate well integrity throughout the entire Ketzin life-cycle.

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Keywords: Ketzin CO_2 storage test site; well integrity; magnetic imaging defectoscopy

1. Introduction

One of the key requirements for safe CO_2 storage operation is to ensure wellbore integrity. Because safety and the protection of humans and environment take highest priority, comprehensive monitoring of CO_2 storage sites is a key issue. At the Ketzin pilot site in Germany, CO_2 was injected into an Upper Triassic sandstone reservoir and the influence of carbon dioxide on the reservoir and cap rock formations was subject to multidisciplinary research over several years. For the first time, the research activities at the Ketzin pilot site will cover the complete life-cycle of a CO_2-storage at the pilot scale [1]. An interdisciplinary monitoring concept was developed and applied which focusses

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* Corresponding author. Tel.: +49-331-288-2816; fax: +49-331-288-1529.
E-mail address: zemke@gfz-potsdam.de

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on the storage complex, the overburden, the surface and the wellbores covering the entire life-cycle of the storage site (Fig.1). Central aspect of this concept is the combination of different monitoring methods, each with different temporal and spatial resolutions [2].

Wellbore integrity has been monitored at the Ketzin site by a combination of pulsed neutron gamma logging PNG, video inspection, magnetic imaging defectoscopy MID and continuous annuli pressure monitoring. PNG logging provides information on potential changes in pore fluid composition in the very near wellbore area and by this may be indicative for cement integrity. Video inspection provides visual images of corrosion effects of the inner casing surface while MID provides information on casing thickness and therefore also on potential outer casing surface corrosion. The different well inspection techniques have been applied since start of injection on a roughly annual basis and are continued during the post-injection phase until final abandonment.

2. Background

2.1. Ketzin CO_2 storage test site

The Ketzin pilot site is located 25 km west of the German capital Berlin, approximately 1.5 km south of the top of a double anticline structure. At the injection site four deep wells have been drilled to reservoir depths. Figure 1 shows a schematic sketch of the Ketzin anticline and infrastructure built at the pilot site for injection and monitoring purposes. The 10 to 20 m thick target reservoir represents the typical channel facies of fluvial deposits of the Stuttgart Formation and its top is at about 620 to 630 m depth at the injection site. The primary seal is > 165 m clay- and mudstones of the Weser and Arnstadt Formations, which are overlain by a thick sequence of alternating permeable and impermeable layers of Upper Triassic and Jurassic age. The geological setting and the monitoring concept of the storage site has been described in detail in various publications [2-4].

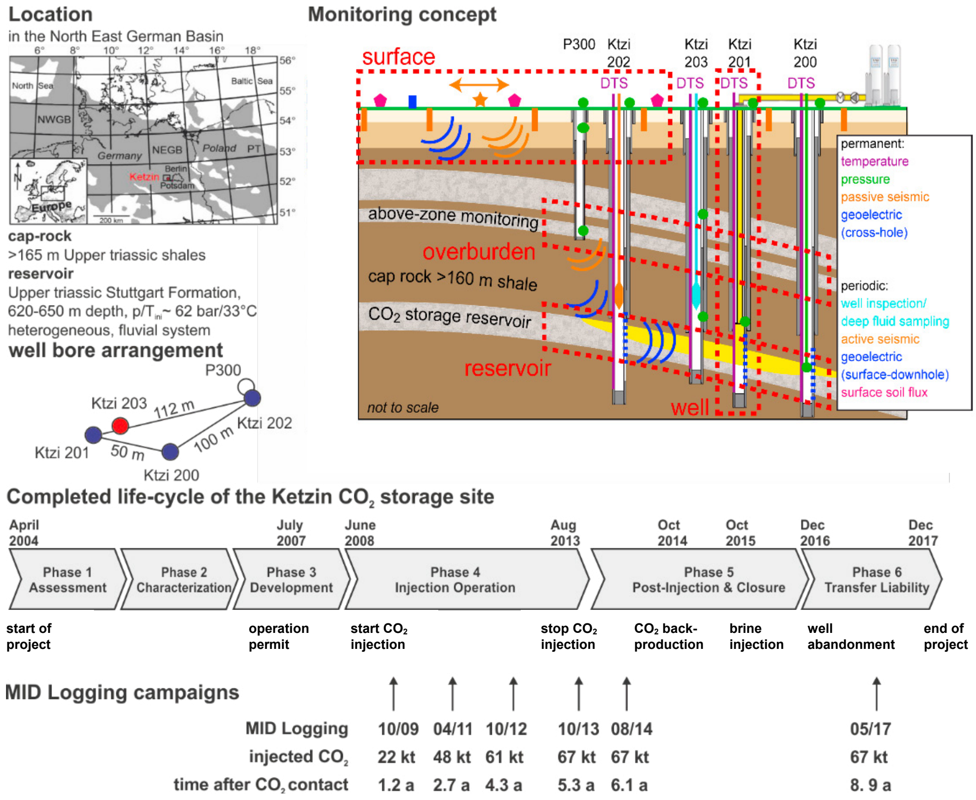

Fig. 1. Ketzin CO_2 storage test site – location, monitoring concept and Ketzin life-cycle with MID logging campaigns.

One combined injection-observation well Ktzi 201 and two observation wells Ktzi 200 and Ktzi 202 have been drilled prior to start of injection to depths of about 750 to 800 m with distances of 50 m (Ktzi 200) and 112 m (Ktzi 202) between injection and observation wells. The shallow well P300 reaches the first aquifer above the cap rock at a depth of about 450 m and allows for above-zone monitoring.

The whole injection phase of the Ketzin site lasted from June 2008 until August 2013 and a total of ~ 67 kt tons of CO_2 were injected. After four years of injection and ~ 61 kt of CO_2 a fourth observation well Ktzi 203 has been drilled through the CO_2 reservoir [4]. Well Ktzi 202 has already been abandoned in two stages in 2013 and 2015 and is not available anymore for post-injection monitoring. The wells are equipped with different types of smart casing that allow for downhole pressure and temperature monitoring, distributed temperature sensing along the wells, and downhole geoelectric measurements with permanently installed electrodes [2].

2.2. Corrosion monitoring as part of the monitoring concept

Due to the acidic in-well environment caused by formation of carbonic acid and the uncertainties about the actual down-hole conditions, detecting and monitoring any changes in the integrity of the wells are of pivotal importance. The CO_2 triggered acidic in-well environment may lead to pitting and/or surface corrosion, eventually to fatigue of well casings and cementation and by this may give rise to wellbore leakage. A main objective in well integrity analysis is the location of metal losses in tubing and/or casing caused by corrosion, erosion or other types of pipe damage.

Corrosion effects are conventionally monitored by measurement of inner casing surface, internal diameter and wall thickness. Caliper logging provides inner surface and internal diameter data, but provides no data for outside corrosion effects and is also affected by scale build up. Ultrasonic tools measure both the internal diameter and casing thickness as well as the bonding between casing and cement, but do not work in gas-filled wells and are affected by roughness and excessive corrosion. However, both tools can only monitor and characterize the innermost casing. The downhole cameras for video inspection can locate visible damages of the inner casing, but need a clear borehole fluid and provide no information on wall thickness.

The electromagnetic induction tool - magnetic imaging defectoscopy - allows calculation of casing thickness and detection of metal losses both inside and outside of the casing as well as losses from an outer casing string. This method works in multiple string settings, it operates in any fluid, runs on monocables and as a slim-hole tool (42 mm diameter) passes through narrow wellbores. At Ketzin, the four deep wells have been monitored by repeat MID logging on a roughly annual basis in cooperation with VNG Gasspeicher GmbH (VGS) and GAZPROMENERGODIAGNOSTIKA LCC (GED), applying their in-house MID-K tool.

3. Measurement principle

The Magnetic Imaging Defectoscope is an electromagnetic downhole logging tool that records magnetization decays induced by high-power electromagnetic pulses, that can penetrate through multiple tubulars, providing information about pipe condition that was not previously available. The measurements reflect the well sketch and the position of the downhole tools (collar, casing shoes, packers and valves, etc.). They can be used to determine the thickness of the tubing and casing in wells and detect various damages such as corrosion, deformation, crack, fracture, and/or holes in the pipe string.

The electronic module of the used MID-K tool by GED, contains four sensors: a vertical exciter coil, two horizontal receiver coils, and a temperature sensor. The vertical exciter coil generates square pulses equivalent to harmonic oscillations, which magnetize the metal casing [5]. After end of the pulse sequence magnetization starts to decay. The tool induces eddy currents in the cross section of the tubulars being evaluated and measures in time domain the decaying electromagnetic response generated from the induced signal with the receiver coils as a complex time profile. The amplitude and decay of the signal in the receiver coil depends on five parameters: magnetic permeability and electrical conductivity of the metal, the pipe diameter and pipe wall thickness of every barrier, and the temperature.

Multiple metal pipe barriers each contribute to the total magnetization decay with different response times, which makes it possible to differentiate each of them and determine their individual thicknesses (Fig. 2). By matching the time response from short to long times, one can capture individual barrier impacts. Thickness determination requires numerical finite-element modelling of each recorded magnetization decay. The calculation of the system response to magnetic disturbance is restricted to calculation of the magnetic field near the receiver coil, which is described by Maxwell's equations.

It is assumed that the response is determined by the metal completion and is independent of the surrounding medium, due to the great difference between the electromagnetic characteristics of metals, rocks and fluids. Therefore, magnetic permeability, electrical conductivity and wall thickness are the only variables. For the electromagnetic parameters one can reasonably well assume constant values for the identical media, leading to direct proportionality between pipe wall thickness and response decay time.

The simulated magnetization decays are used to calculate pipe parameters and estimate their thicknesses. This is an iterative fitting process of the properties and thicknesses of each individual metal barrier by minimizing the discrepancy between simulated and measured responses. Then, simulated decays compared with actual responses enables the quantitative calculation of wall thicknesses of the first and second barriers independently.

Defects in the pipes or metal losses disturb the magnetic field and attenuation and amplitude of the induced signal will therefore change in case a pipe is damaged or corroded. The effect of the first pipe closest to the exciter coil is higher than that of the second pipe and complicates the determination of thickness for the outer strings. The method can be used in liquid as well as gas-filled sections (above the water level) of the well. In refurbishments of existing wells, especially during perforation work, this measuring method is used to ensure that the wells can withstand the stresses of the work. The depths of the pipe connections as well as the filter sections can also be determined very well. Holes in the casings represent a disturbance in the measuring signal of the probe and can thus also be detected.

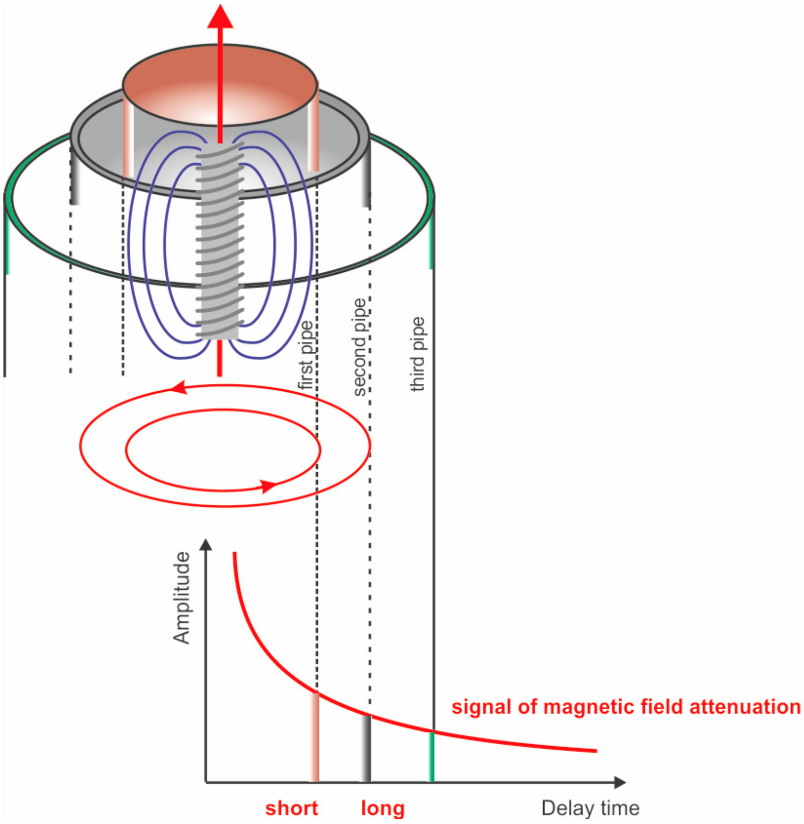

Fig. 2. Relationship between measured signal of magnetic field attenuation, pipe diameter, wall thickness and time.

4. MID measurements at Ketzin

The first MID measurements of the three deep wells Ktzi 200, 201, and 202 took place in October 2009 and then served as the baselines for the following repeat measurement campaigns. The timing of these first measurements corresponds to about 16 months of CO_2 contact for well Ktzi 201 (start of CO_2 injection June 2008), 13 months of CO_2 contact for well Ktzi 200 (CO_2 break-through September 2008), and six months of CO_2 contact for well Ktzi 202 (CO_2 break-through April 2009).

MID logging was then repeated on a roughly annual basis. The first MID measurement and therefore baseline for the later drilled well Ktzi 203 took place in 2013. Dates of MID logging campaigns within the life-cycle of Ketzin pilot site are also displayed in Figure 1. The last logging campaign before abandonment of the wells was performed by the end of May 2017.

4.1. Borehole design as input parameter for quantitative calculation of wall thickness

The three wells Ktzi 200, 201 and 202 have an identical casing layout, including a stainless casing, equipped with pre-perforated sand filter segments in the reservoir section and fiber-optical and multi-conductor monitoring sensors and cables [6]. The three to four lines of monitoring cables were installed and cemented in all three boreholes on the outside of the stainless steel 5 ½” production string. Special cable clamps were mounted on the casings in order to protect the cables while tripping. The 150 m long bottom section of the 5 ½” string at the reservoir is externally coated with a fiber-glass-resin wrap for electrical insulation and support for the geoelectric measurements. In total there are 15 electrodes installed in the reservoir section of every well. The well sketch in Figure 3 shows the downhole installation in the reservoir section for the injection well Ktzi 201. The whole well design, particularly pipe material, their electromagnetic properties, diameter, and nominal wall thickness (Table 1) are input parameters for the fitting process of the MID data. The MID-K tool allows calculate the wall thickness with 0.5 mm accuracy for a single string and 0.7 mm for a second string.

Table 1. Technical construction of the injection well Ktzi 201 in the reservoir section.

Well Ktzi 201	Injection string	Production string	Intermediate string	Reserve string	Conductor string	Stand pipe
Diameter	3 1/2” 89 mm	5 1/2” 140 mm	9 5/8” 244 mm	13 3/8” 340 mm	18 5/8” 473 mm	24” 610 mm
Wall thickness	6.45 mm	9.17 mm	8.94 mm			
Material	C-95	13 Cr80	K55	K55	X56	4140
Depth	544.64 m	746.2 m	588.8 m	340 m	150 m	30 m

4.2. Results of MID baseline measurement in October 2009

As an example of the “baseline” measurements from October 2009, Figure 3 shows the MID-K results for the injection well Ktzi 201 after 16 months of CO_2 contact for the depth interval 500 and 670 m including the reservoir section. The first two columns show the raw data of the MID-K tool for the magnetic field attenuation. Z6 to Z25 are the magnetic attenuation in the horizontal receiver for the short delay times (delay time in ms) and relate to the innermost string (first column). Z32 to Z50 are the magnetic attenuations in the horizontal receiver for longer delay times and relate to the second string (second column). Downhole installations, collars and electrodes are displayed in these curves as an increase in signal amplitude relative to the nominal value due to an increased amount of casing material. Contrary, a decrease in signal amplitude relative to the nominal value would indicate decreased amount of casing material and potentially indicate corrosion.

The result of the quantitative interpretation in terms of wall thickness is given in the right column. The blue curve represents the calculated thickness of the 5 ½” production string and the red curve the thickness of the 3 ½” injection string. The tool also measured Natural Gamma Ray for depth correction and temperature (not displayed). There is a double pipe string down to 589 m and different kinds of material and wall thickness on the pipe string. The thickness curves of the production string appear to become noisier with the additional barrier of the intermediate string down to 589 m.

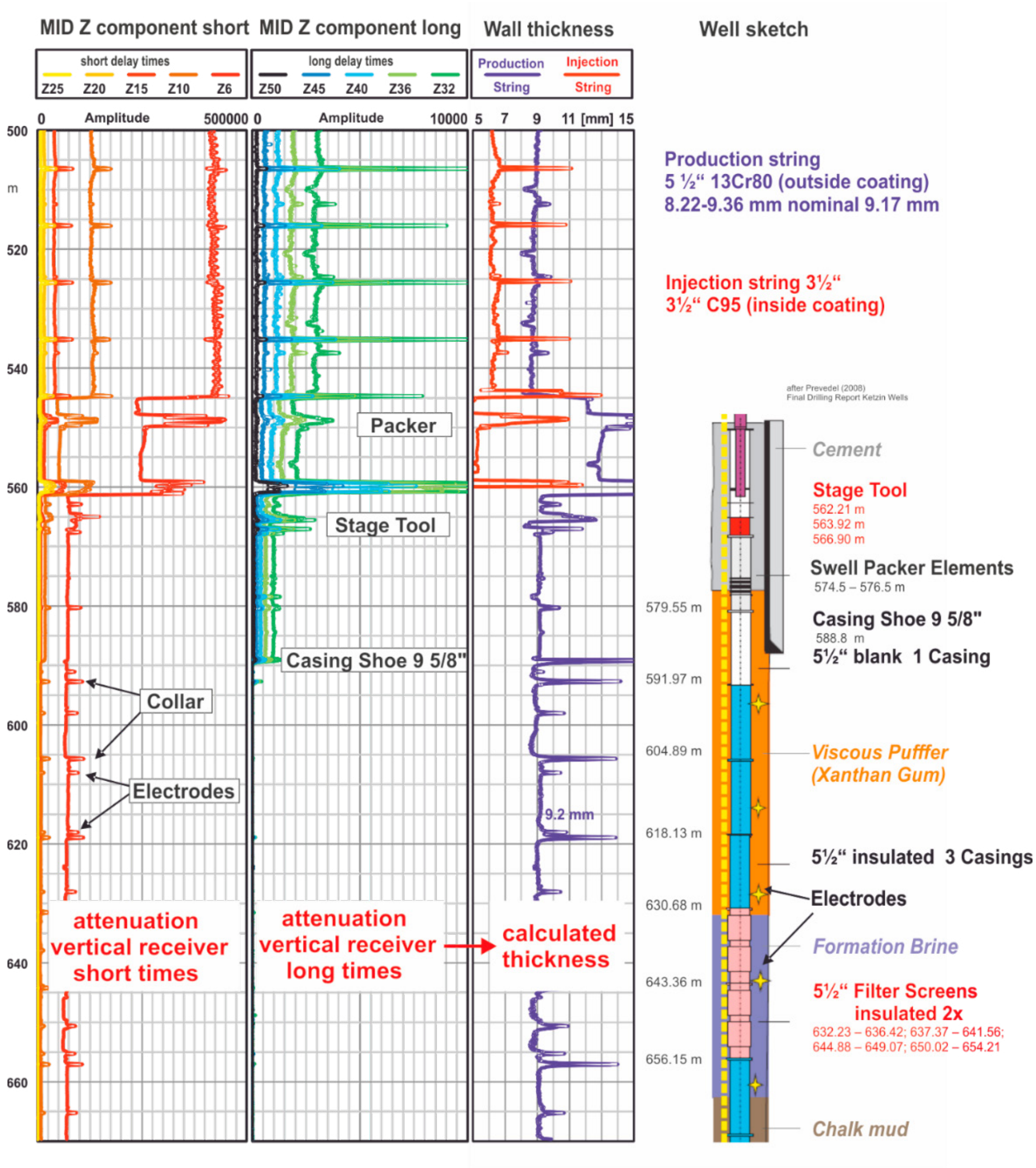

Fig. 3. Results of the first MID-K of the injection well Ktzi 201 in relation to the well construction between 500 and 670 m depth.

The measured MID response agrees well with the pipe model. The right side of Figure 3 shows the sketch of the borehole construction with the technical installations. The MID based depth-resolved casing thickness data clearly image the depth positions of the pipe-connectors of the tubings, the position of electrodes and filter screens in the production string and of all downhole installations in perfect agreement with depth data from the drilling reports.

Due to the magnetic imaging defectoscopy the thickness of at least the two innermost casings is determined in agreement with the production specifications. Also the transition from steel casing to glass fiber reinforced casing in well Ktzi 203 is well resolved (not displayed). Within the limits of the investigation interval, no cracks, breaks or other defects in the injection string and production string are detected.

4.3. Time-lapse MID measurements

The MID tool generally provides a high signal-to-noise ratio, which makes MID logs highly repeatable. Figure 4 shows the time-lapse analysis of logs for one short (10 ms) and one long decay time (40 ms) recorded by four MID surveys in the injection well Ktzi 201 in 10/2009, 04/2011, 10/2013, and 08/2014. The baseline from 10/09 was measured 16 months after start of injection and 22 kt CO_2, in 04/11 the first repeat was performed after 2.7 years and 48 kt CO_2. The second repeat is from 10/13 after 5.3 years and 67 kt CO_2 and roughly two month after cessation of the injection and the third repeat 08/14 was measured one year after cessation of the injection. Identical MID surveys exist also for the other wells. After automatic depth data matching, the logs appear to be virtually identical.

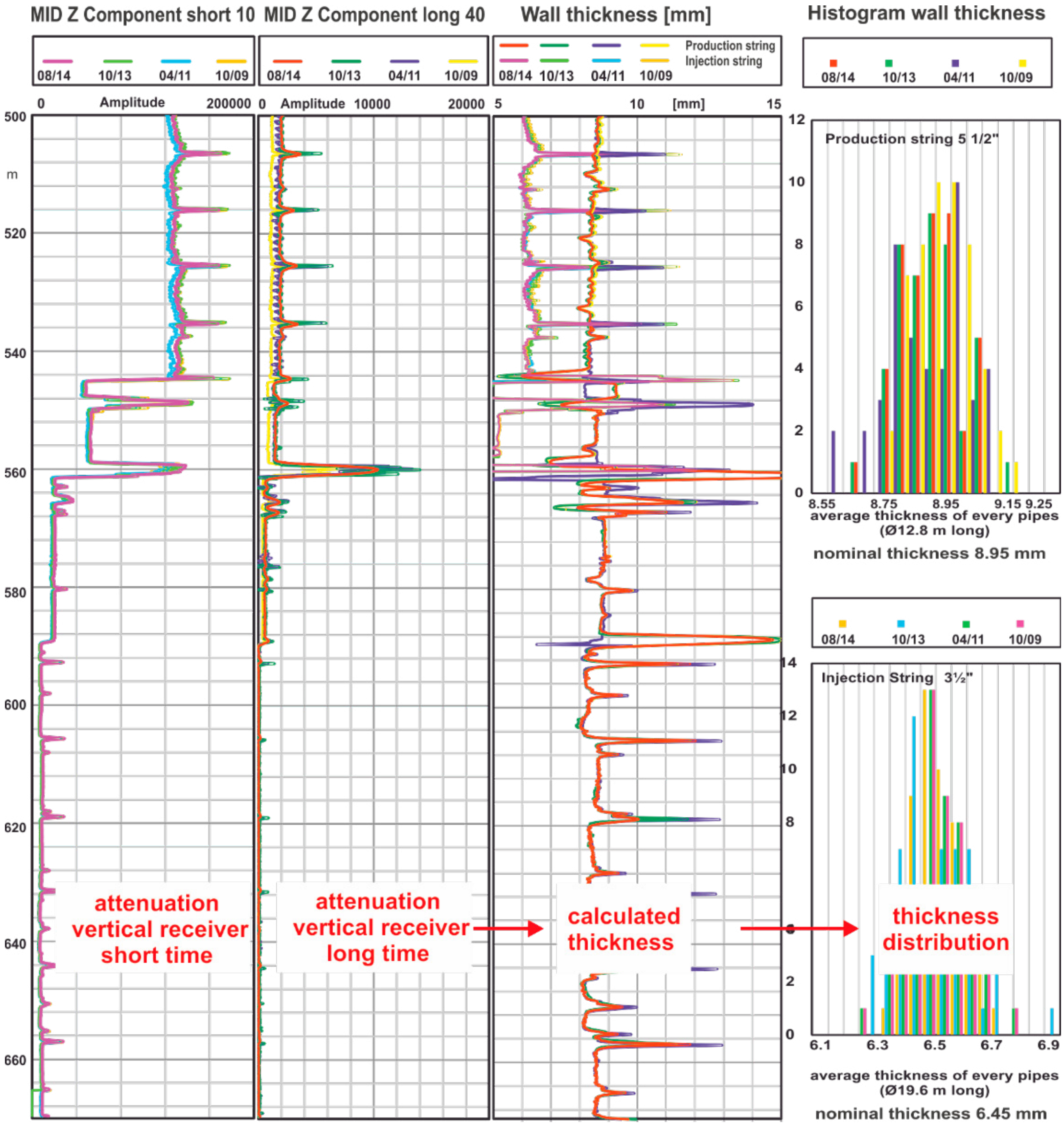

Fig. 4. Time-lapse MID-K measurements of the injection well Ktzi 201 between 500 and 670 m depth. The two left columns represent exemplary recordings of a short delay time Z10 (= injection string) and a long delay time Z40 (= production string), the third column presents the calculated thicknesses of the two casings. Right column shows histograms of calculated thicknesses of all pipe sections of injection string and production string of well Ktzi 201.

As the comparison shows, identical decay-time curves of the MID repeat measurements match and the sleeve connections and elements of the injection string and the production string can be clearly identified and fixed. In Figure 4 the right histograms show exemplary the calculated average wall thickness for each individual pipe segment from the injection string and the production string of well Ktzi 201. The calculated wall thickness of the pipes from the 2009, 2011, 2012 and 2013 repeats are very close to each other and are all within the permissible production tolerance. The wall thickness of the 3 ½” injection string should be between 6.24 mm – 6.99 mm with a nominal thickness of 6.45 mm, the 5 ½” production string should be between 8.22 mm – 9.36 mm with a nominal thickness 9.17 mm. The data therefore provide no evidence of any reduction of the metal mass by corrosion

5. Conclusions

MID is an advanced logging method for non-destructive testing and has the great advantages that it can be operated in gas-filled boreholes and provides information also for outer casings. At Ketzin, the four deep wells have been monitored by repeated MID logging on a roughly annual basis. The MID based depth-resolved casing thickness data clearly image the thickness of at least the two innermost casings and the depth positions of the pipe-connectors and of all downhole installations in perfect agreement with depth data from the drilling reports. In addition, the transition from steel casing to glass fiber reinforced casing in well Ktzi 203 is well resolved. The MID derived casing thicknesses are within the production specifications and conform to the API standards. Comparison between the different time-lapse data sets provides no hints to time dependent changes in casing thickness or to any other signs of corrosion. These results agree with the video inspection of the wells and the investigation of in-situ samples of pulled casing material recovered during abandonment of well Ktzi 202. The Ketzin time-lapse MID data set provides unique field evidence on applicability of MID monitoring and longevity of wellbore steel casing in a real CO_2 storage environment. It thereby substantially improves our knowledge on CCS safety assessment due to the key role of well integrity during the entire storage life-cycle.

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References

[1] Martens, S., Moeller, F., Streibel, M. (2014) "Completion of Five Years of Safe CO_2 Injection and Transition to the Post-closure Phase at the Ketzin Pilot Site." *Energy Procedia*, 59, 190-197.

[2] Bergmann, P., Diersch, M., Götz, J., Ivandic, M., Ivanova, A., Juhlin, C., Kummerow, J., Liebscher, A., Lueth, S., Meekes, S., Norden, B., Schmidt-Hattenberger, C., Wagner, F., Zhang, F. (2016) "Review on geophysical monitoring of CO2 injection at Ketzin, Germany." *Journal of Petroleum Science and Engineering*, 139: 112-136.

[3] Norden, B., Förster, A., Vu-Hoang, D., Marcelis, F., Springer, N., Le Nir, I. (2010) "Lithological and petrophysical core-log interpretation in the CO_2SINK, the European CO_2 onshore research storage and verification project." *SPE Reservoir Evaluation & Engineering*, 179-192, doi: 10.2118/115247- PA.

[4] Liebscher, A., Möller, F., Bannach, A., Köhler, S., Wiebach, J., Schmidt-Hattenberger, C., Weiner, M., Pretschner, C., Ebert, K., Zemke, J. (2013) "Injection operation and operational pressure-temperature monitoring at the CO_2 storage pilot site Ketzin, Germany-Design, results, recommendations." *Int J of Greenhouse Gas Control* 15: 163–173.

[5] Ansari, A., Arsalan, Ziad Libdi, Khan Naeem, Arthur Aslanyan, Irina Aslanyan, Maxim Volkov, Andrey Arbuzov Andrey Achkeev Fathi Shnaib Ruslan Makhiyanov. (2015) "Triple-Barrier Thickness Scanning Using Through-Tubing Pulse-Magnetic Logging Tool." *SPE-176655-MS, SPE Russian Petroleum Technology Conference*, 26-28 October 2015, Moscow, Russia.

[6] Prevedel, B., Wohlgemuth, L., Legarth, B., Henninges, J., Schütt, H., Schmidt-Hattenberger, C., Norden, B., Förster, A., Hurter, S. (2009) "The CO_2SINK boreholes for geological CO_2 storage testing." *Energy Procedia*, 1: 2087–2094.