CrossMark

Risk assessment of abandoned wells affected by CO_2

Mingxing Bai · Jianpeng Sun · Kaoping Song ·
Kurt M. Reinicke · Catalin Teodoriu

Abstract Flawless operation during injection and a long-term seal of the storage reservoir after injection are the prerequisites for successful CO_2 storage in the geological subsurface. This requires the sealing of the porous permeable horizons by a tight caprock and long-term integrity of open and abandoned wells which have penetrated these horizons. As a basic requirement for the inception of a CO_2 injection scheme in any sequestration project, the integrity of the existing wells in the field must be proven. This paper reviews the relevant items including the geology, relevant wells and their standards, well integrity, and integrity evaluation methods. At the end, a novel concept is introduced to evaluate well integrity for abandoned wells. It is concluded that the verification of technical well integrity is significantly more difficult for abandoned wells, because measurements and tests to close information gaps are no longer possible. If information is lacking for a direct assessment, the quantification of the risk of leakage is only possible indirectly. For an indirect assessment, a realistic risk assessment should consider the composite system casing-cement-rock as a whole and also include self-healing caused by CO_2 interaction with the composite system and/or the indigenous rock. The proposed new method covers both qualitative and quantitative analysis, and it is more comprehensive, sophisticated and easier to implement.

Introduction

Flawless operation during injection and a long-term seal of the storage reservoir after injection are the prerequisites for successful CO_2 storage in the geological subsurface (Novak et al. 2014; Martens et al. 2012; Bai et al. 2014c). This requires the sealing of the porous and permeable horizons by a tight caprock and the long-term integrity of both open and abandoned wells, which have reached the horizons (Wiese et al. 2013; Ngoc et al. 2014; Sandig et al. 2014). In the North German Basin there are a number of horizons serving as tight barrier rocks, including shale and salt horizons with permeability values in the range of 10^{-21}–10^{-19} m^2 (Brasser et al. 2008; Reinicke et al. 2011; Kissinger et al. 2013). The caprocks of the North German Basin have been penetrated by many wells, which may provide potential migration pathways. As a basic requirement for setting up a CO_2 injection scheme in a sequestration project, the integrity of the existing wells must be proven. The objectives of this paper are to introduce and review methods for assessment of well integrity and the related risk assessment of abandoned wells. In this context, the geology, relevant wells, well standards, well integrity, and integrity evaluation methods are considered. Furthermore, a novel concept to evaluate integrity for abandoned wells, which are no longer accessible for their integrity to be surveyed, is introduced, covering both qualitative and quantitative aspects.

M. Bai (✉) · J. Sun · K. Song
Department of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, China
e-mail: baimingxing@hotmail.com

M. Bai · K. M. Reinicke · C. Teodoriu
Institute of Petroleum Engineering, TU Clausthal, 38678 Clausthal-Zellerfeld, Germany

Deep wells and geology in Germany

In Germany, most of the wells deeper than 3000 m have been drilled since the second half of the nineteenth century, typically in the context of developing gas reservoirs. The total depths of the wells drilled range from a few 100 m in the nineteenth century to 9101 m reached in 1994 by the continental deep drilling project KTB close to Windischeschenbach, Bavaria.

Plugged and abandoned wells in Germany

Today, about 50 % of the wells drilled in the North German Basin are plugged and abandoned according to LBEG (Landesamt für Bergbau, Energie und Geologie) database. The hydrocarbon well database at LBEG, in the Geozentrum Hannover, provides information about the header date and technical measured data for approximately 29,000 oil and gas wells and other mining wells in Germany (Fig. 1). The majority of hydrocarbon wells are located in the North German Basin. Besides hydrocarbon exploration and production wells, the database also lists deep wells drilled for other purposes, including geothermal and mining exploitation. Almost 80–90 % of the hydrocarbon wells drilled in Germany are plugged and abandoned while only approximately 3500 wells still remain accessible or open. The status of archived information for wells drilled after
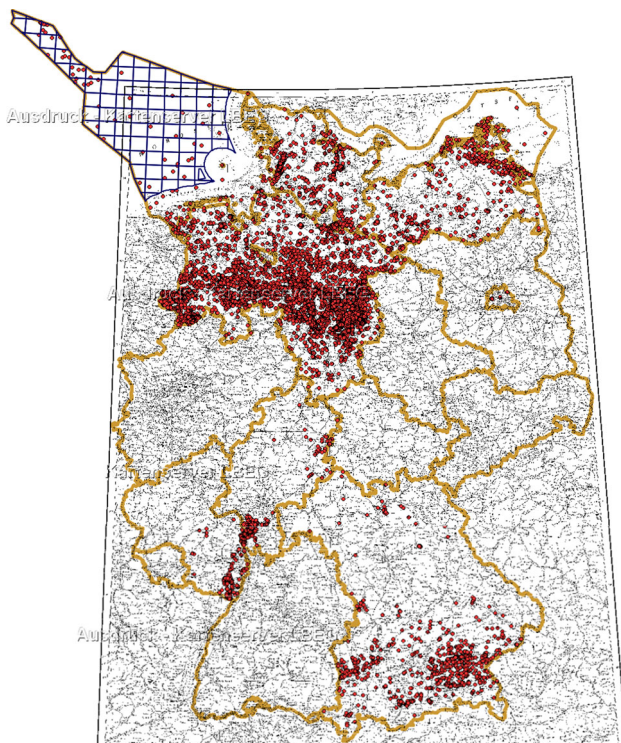

Fig. 1 Hydrocarbon wells in Germany (hydrocarbon well database of the Landesamt für Bergbau, Energie und Geologie (LBEG), 2011)

1950 (Tran-Viet 2013) is good and—as a rule—becomes better the later the well has been drilled. Typically, relatively little information on the way wells have been constructed and abandoned, is available on wells drilled prior to the World War II.

Potential storage and barrier horizons in the North German Basin

The geology of the North German Basin is quite well known due to the large number of wells drilled. The presence of oil and gas reservoirs provides evidence on formations suitable for storage and intact caprocks. Figure 2 shows the lithostratigraphy of the North German Basin in the Germany's province of the lower Saxony including the Northeast German part of the basin as confirmation.

Development of well drilling depth in Germany

Until the 1960s, oil fields were the focus of industrial exploration and development activities. In Germany, oil reservoirs are predominantly found in limestones and sandstones of younger geological formations of the Jurassic to Cretaceous ages at depths up to approximately 2000 m. It was with the onset of the search for natural gas in the 1960s of the previous century that wells were drilled deeper than 2000 m with targets in the Triassic, the Permian and the Carboniferous reservoir formations. Figure 3 shows the development of drilling depths over time in a large field 80 × 90 km in the North German Basin (Tran-Viet 2009).

The analysis of a particular area investigated by Tran-Viet (2009), (2013) in the course of a case study shows that only 7 % of the 362 wells drilled had final depths of more than 2300 m, reaching potential Triassic storage horizons. Apart from some few exceptions, all these wells deeper than 2300 m were drilled after 1961. This implies that for all practical purposes all deeper wells are constructed according to today's standards, particularly in terms of casing and cementation and that a part of the recently drilled wells has also been logged with acoustic cement log (e.g., cement bond log).

Current standards to construct and abandon deep wells

Wells are constructed to provide a tight connection between the surface and the geological reservoirs in the deep subsurface. A tight connection is achieved by the introduction of steel pipes—called casings—into the borehole and by the introduction of cement into the annulus between pipe and rock, so as to fix the casing in place. For optimum cementation, the borehole wall is cleaned and the casings
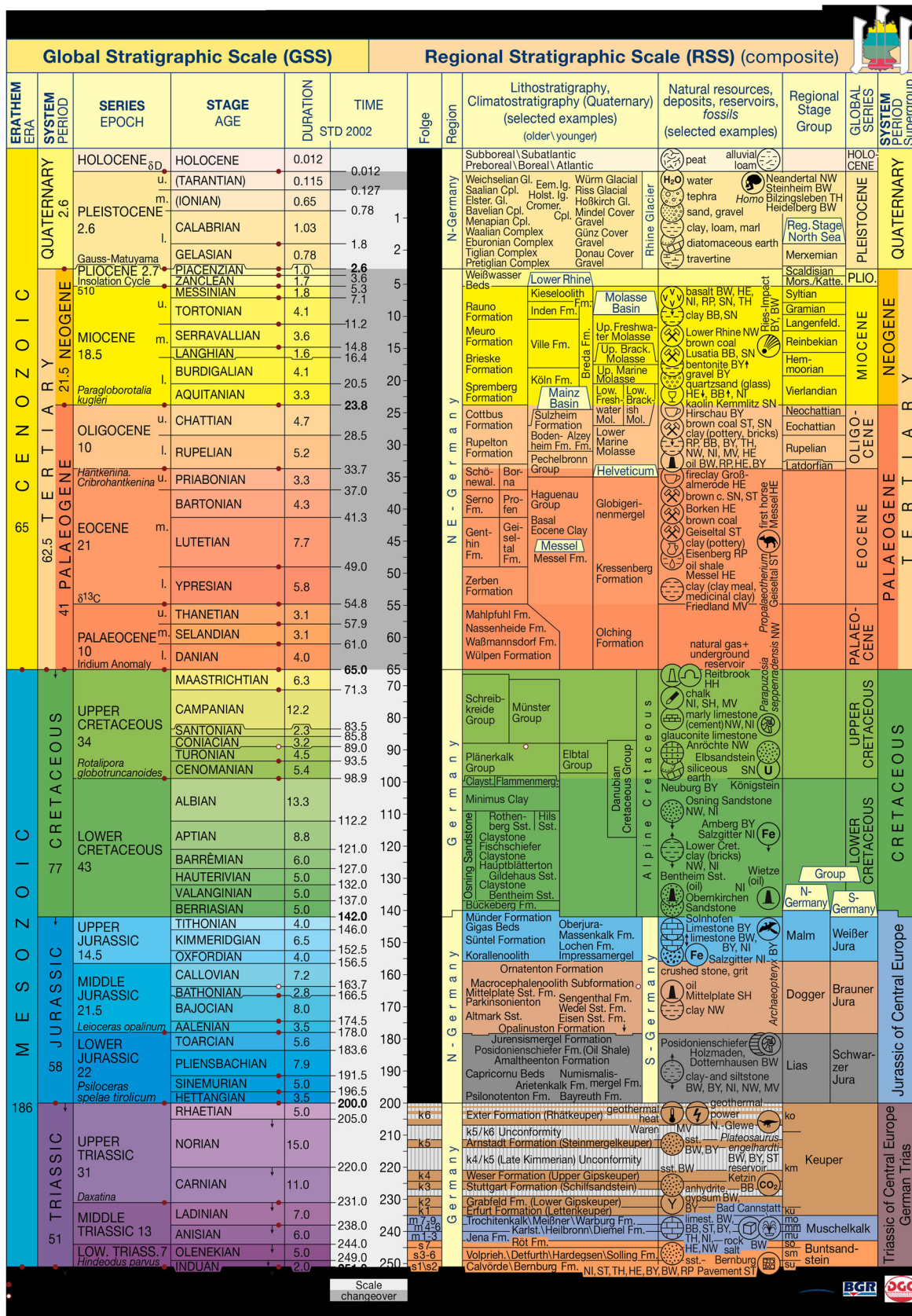
Fig. 2 Lithological and stratigraphic division of the North German Basin (http://gfzpublic.gfz-potsdam.de/pubman/item/escidoc:124241/component/escidoc:124243/STDKe%202013%2006%2019%20KZ%20MZ.pdf)
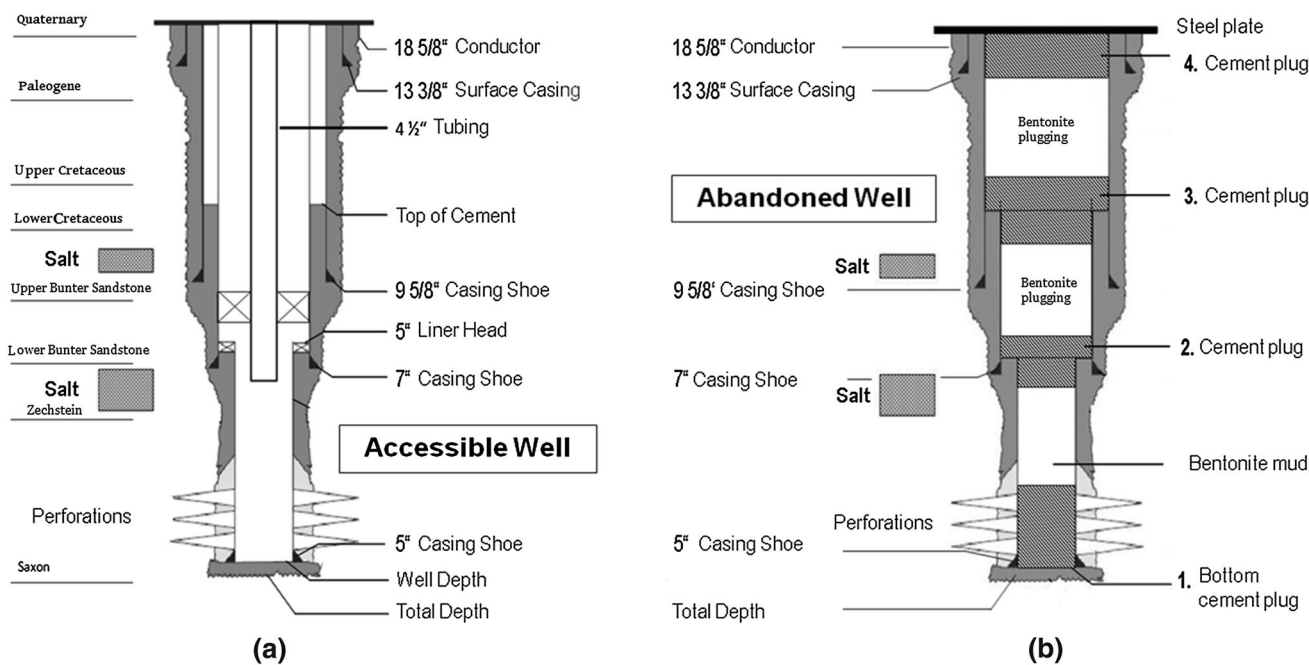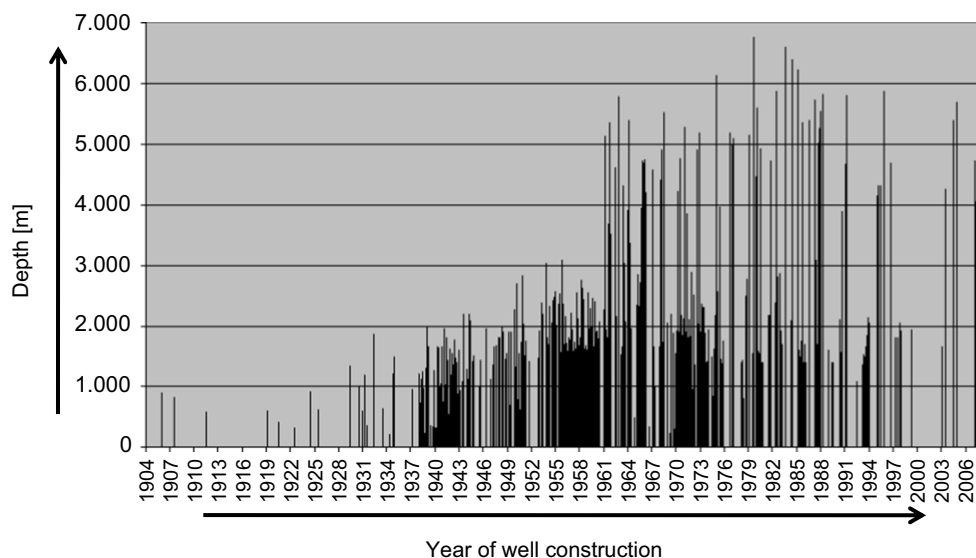
Fig. 4 Schematic representation of an accessible (**a**) and an abandoned well (**b**) (after Reinicke and Franz 2008)

are centered within the borehole using centralizers prior to circulating the cement slurry into the casing and around the casing shoe into the annulus behind the casing, (Fig. 4a). The quality of the cementation is evaluated by pressure testing the casing shoe and running acoustic measurements—for example, cement bond logs (CBL)—over the entire cemented length of the casing.

If a well is no longer needed, mining regulations require that the well has to be plugged and abandoned. In order to abandon the well, respective guidelines and regulatory

requirements of the mining authorities have to be observed as documented, for example, in the mining authority directive for the plugging and abandonment of wells. These guidelines provide the requirements that the connection to the reservoir has to be shut off by bottom cementation. Above this lowermost cement plug in Fig. 4b, additional cement plugs are placed from time to time, if necessary, in combination with mechanical plugs. To avoid the risks of leakage, the plugs are placed across potential problem zones, e.g., above the liners or where the casings are cut,

Table 1 Development of well construction technique over time according to a case study area (Tran-Viet 2009)

Well age	Cementation and logging information, classified according to the well age	Maximum depth (m)
Before 1920	No cemented casings/no cement fill ratio: ∼1 % of all investigated wells	<1,000
1920–1940	Seldom cemented casings/seldom cement fill ratio: ∼8 % of all investigated wells	<2,000
1940–1953	Mostly cemented (bottom cementation), no acoustic cement log ratio: ∼20 % of all investigated wells	Mostly <2,000 max. 3,000
1953–1961	All wells cemented, no acoustic cement log ratio: ∼16 % of all investigated wells	<3,000
After 1961	All wells cemented, increasingly measured with acoustic cement logs ratio: ∼53 % of all investigated wells	<6,500

etc. If a section of poor cementation behind the casing is identified or if such an interval of poor cementation is suspected, a squeeze cementation is normally carried out to inject cement slurry behind the casing to fill any voids which may exist, in case of required zonal isolation, for example, above the reservoir formation, fluid content horizons and so on. The space between the cement plugs within the abandoned casing is typically filled with drilling mud (drilling fluid or Bentonite plugs). In addition, a complete fill of the casing with cement is practiced. In the near surface, the casings are cut a length of minimum 1 m for onshore wells and 5 m for offshore wells and covered by a cement plate or a steel plate (Fig. 4b).

Development of well completion standard over time

The methods of constructing deep wells as well as the techniques to plug and abandon them have been continuously improved since the first wells in the nineteenth century (Table 1). While the construction and abandonment of the early wells were carried without an obligation to observe particular regulatory requirements, today a deep well in Germany is neither drilled nor abandoned without the permission of the regulatory agencies, i.e., the mining authorities. So substantial efforts are made to permanently plug and abandon the well and ensure its long-term sealing capacity. The approach taken was significantly influenced by the start of development of high-pressure natural gas reservoirs in the 1960s.

Well integrity

Wells, which have penetrated the barrier formation of CO_2 storage, may provide leakage pathways (Fig. 5) for the ascent of CO_2 from a storage horizon. These pathways can be due to deficient construction, excessive mechanical and thermal loading, as well as chemical corrosion and so on during the operation or after the abandonment of the wells. The implementation of a CO_2 underground storage project, therefore, requires evidence of the sustainable technical integrity of all wells, which are in the area affected by the
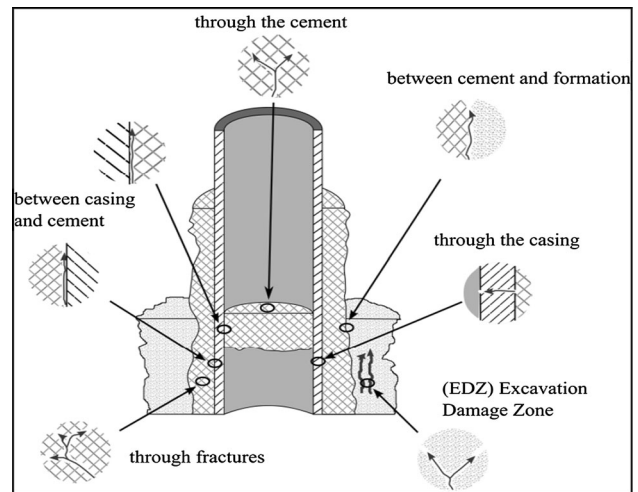

Fig. 5 Potential leakage pathways within the wellbore zone of an abandoned well (Reinicke and Fichter 2010)

injection of CO_2 and which have penetrated the barrier rock.

Technical integrity of a well is generally assumed (US Environmental Protection Agency EPA 1998), if: (1) there is no "significant" leak in the casing, tubing, or packer (the well is pressure-tight); and (2) there is no "significant" fluid movement into an underground source of drinking water (the well is loss-free). The concept of a significant event is used because tightness can only be established within the limits of a measurement-based assessment.

Mechanisms responsible for a loss of technical integrity

Damage in the wellbore zone may be incurred, during construction, operation, abandonment, and/or after abandonment, causing potential flow paths from the storage to the biosphere. The wellbore zone is defined as the well in its respective state together with the near wellbore zone, including potential excavation damage zone (Fig. 6). The mechanisms which may lead to damage of the wellbore zone are known and can be modeled in principle. They may be subdivided into chemical loading (e.g., metal and cement corrosion), mechanical-thermal
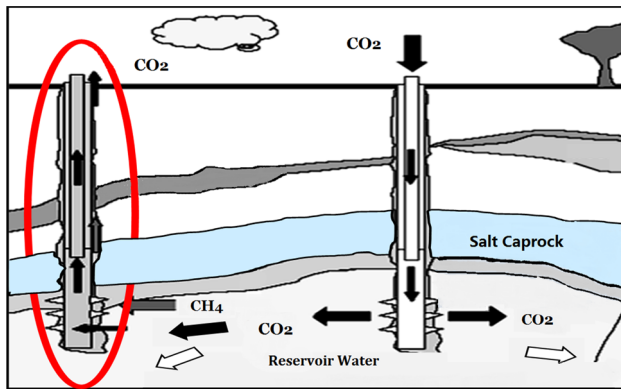
Fig. 6 Schematic diagram of the wellbore zone

loading (e.g., cyclic pressure and temperature) and construction defects (e.g., insufficient centralization, solids sedimentation and insufficient cleaning of the well). All the processes significantly weaken the wellbore zone's integrity (De Lucia et al. 2012). The relevant damages and damage mechanisms have been described by Reinicke and Fichter (2010).

A mechanical-thermal loading situation may occur, for instance, as a result of high external pressures, variable internal pressure caused by varying production, decreasing internal wellbore pressures due to reservoir depletion, and tensional loads caused by reservoir compaction and so on. Under chemical loading in particular, it is the electrochemical corrosion of the metallic components and the leaching and corrosion processes of wellbore cement in the wellbore zone, which needs consideration. The affront of galvanic corrosion, pitting, and trough corrosion as well as crevice corrosion are mostly causing local limited damages, which can lead to small leakages in the metal. All these corrosion types are causing material removal and consequently the metal becomes thinner. CO_2 also attacks the cement and causes severe corrosion, leading to a decreased compressive strength and changed permeability and porosity.

Key factors affecting the evaluation of technical integrity of a well

The evaluation of technical integrity of a well is influenced by its accessibility and the availability of information. This assessment will be relatively straightforward for accessible, i.e., unplugged, wells. If the available information is not sufficient to conclusively evaluate the technical integrity of the well and the well is accessible, the missing information can be obtained directly from downhole measurements. For this, numerous measurement and testing methods are available including those which can provide evidence of the state of the well (Table 2).

Table 2 Integrity measurement methods for accessible wells (Reinicke and Fichter 2010)

System area	Damage	Survey
Casing	Corrosion, internal	Caliper survey, isolation scanner
	Corrosion, external	Isolation scanner, electromagnetic wall thickness survey
	Material loss	Isolation scanner, electromagnetic wall thickness survey
	Deformation	Caliper survey, isolation scanner, electromagnetic wall thickness survey
	Leakage	Caliper survey, isolation scanner
Cement	Annulus filling	CBL, isolation scanner
	Micro annuli	CBL, isolation scanner
	Channel formation	Isolation scanner
	Crack	Isolation scanner

The evaluation of plugged and abandoned wells is significantly more difficult. The state of data is fixed, often insufficient, and cannot be improved by additional measurements and tests as described in Table 2. An indirect verification of technical integrity requires sufficient knowledge of the penetrated geological horizons, their properties, well construction, production history, abandonment as well as the thermo-hydraulic-mechanical processes in the vicinity of the wellbore. If any of the above-mentioned important information is missing, a thorough analysis and conclusive assessment of technical integrity may not be possible.

Direct or indirect assessment of technical integrity

Technical integrity can be directly or indirectly assessed for underground CO_2 storage. For example, in the cavern industry, proof of technical integrity is commonly provided directly by a pressure test on the casing shoe. In the 1990s, a cavern storage well was assumed tight, if the leakage rate recorded in such a test was smaller than 50 kg/d recommended by SMRI (1996). Because of advances in the measurement abilities, today's thresholds are quite smaller or even null emission, but exact information was not available to the authors.

Pressure tests on the casing shoe, so-called leak-off tests, are carried out in the course of constructing oil and gas wells. Similar to the CCS (carbon capture and storage) wells, oil and gas wells provide a connection not to a horizon below the casing shoe but in general to horizons above the shoe. The production casing/liner has to be perforated above the shoe to open the hydrocarbon-bearing horizons. Therefore, the pressure test on the shoe is no evidence for the tightness of the composite system towards

the biosphere above the storage horizon. Evidence that the "well is loss-free" is therefore provided indirectly. A hydraulic isolation behind the casing is generally assumed, if a minimum interval of quality cementation, whose value depends on the specific formations and the companies involved, can be identified. Measurement methods have evolved to the point, where evaluation can be carried out with a high degree of confidence (Reinicke and Fichter 2010; Schutze et al. 2012). In the case of excessive loading, the integrity of oil wells is commonly assessed by a water test, as for instance in the case of thermal wells, to provide evidence that the "well is pressure-tight". In a test like this, the oil-bearing formation is plugged off and the casing subjected to pressure loading.

The application of the pressure test used in the CCS industry to establish the "well is loss-free" above the storage horizon is possible in principle. It would, however, require destroying a possibly intact composite system above the storage horizon (Crow et al. 2009; Reinicke and Fichter 2010).

Restoration of technical integrity by cement self-healing

The phenomenon of self-healing in wells, which has penetrated natural salt formations, is well known. According to the current state of scientific research, it is ascribed solely to the plastic behavior of the natural salt deposits. This property is commonly regarded as an essential criterion for the suitability and safety of subsurface storage, taking into account the storage of gases in the subsurface (Reinicke and Fichter 2010).

Soft clay layers are also known to have self-healing effects, which are ascribed to plastic behavior. Under suitable geological conditions, clay layers are used to establish a second natural barrier when plugging a well (Williams et al. 2009). The self-healing of voids and cracks is known for hydraulic binders used in the surface construction industry (Jacobsen et al. 1998; de Rooij et al 2013). The accompanying material rearrangement mechanisms, in particular those caused by CO_2 containing water, are described in numerous publications for the construction industry.

More recently, self-healing effects have been observed for wellbore cements depending on the lithology, although a systematic investigation of these processes is still outstanding for the Portland cement systems used as wellbore cements. This is particularly valid for the salt cement systems used to cement the saliniferous strata in the geologic subsurface, which has been investigated in the context of CO_2 exposure.

For Portland freshwater cement systems (freshwater as mixing water for cement slurry), Carey et al. (2007) report on the filling of cracks in the cement sheath of a 55-year-old well, in the SAGROC unit in West Texas, with calcite, aragonite and halite. The well, in which the observation was made, had been used for 30 years, in the context of an enhanced oil recovery (EOR) project, as a CO_2 injector. The authors ascribe the observed halite fill to brines, which have ascended from the reservoir area. Bachu and Bennion (2009) note the importance of secondary calcite, generated when CO_2 reacts with cement in the process known as carbonation.

For Portland saltwater cements (salt saturated water as mixing water for cement slurry), Reinicke et al. (2011) report the secondary healing of artificial defects after 60 days for tri-axial experiments on large-scale samples representing the composite system. The fill consisting of definitely determined secondary minerals (calcium carbonate, halite, potassium halite, larnite) is most likely the result of chemical reactions within the system's salt-cement casing. In particular, the presence of the clinker phase larnite in the secondary crystallization of the fill suggests that the cement system plays an important role in the context of the observed self-healing mechanisms. The results show that self-healing mechanisms, known for a long time, may not only be ascribed to the plastic properties of the saliniferous strata, but also to material transport and chemical reactions within the composite system itself.

Risk evaluation of plugged and abandoned wells

The task of evaluating the technical integrity of abandoned wells is a big challenge. The desired information necessary for a conclusive assessment may not be available, but the wells are no longer accessible to collect additional information. If information is available, the status it reflects may not be representative of the current status, in particular in the case of old wells or information, which has been obtained in the course of constructing the well, like, for example, the cement bond logs.

If sufficient information of good quality is available, and qualitatively valuable plugging is ascertained, the quantification of the leakage risk can be carried out, deterministically to a great extent. If considerable gaps in knowledge remain, the risk assessment has to be done on the basis of probabilistic methods, which are also indispensable for the long-term prognosis of well integrity development. In any case, to assess the risk of well leakage requires the structured processing of the available well information, in particular, geology, well geometry, well construction, and well abandonment with information on materials used, methods and results. For this purpose, well file information must be synthesized and integrated, giving particular consideration to corrosion of the primary cement sheath and the well casing (Mulders 2007).
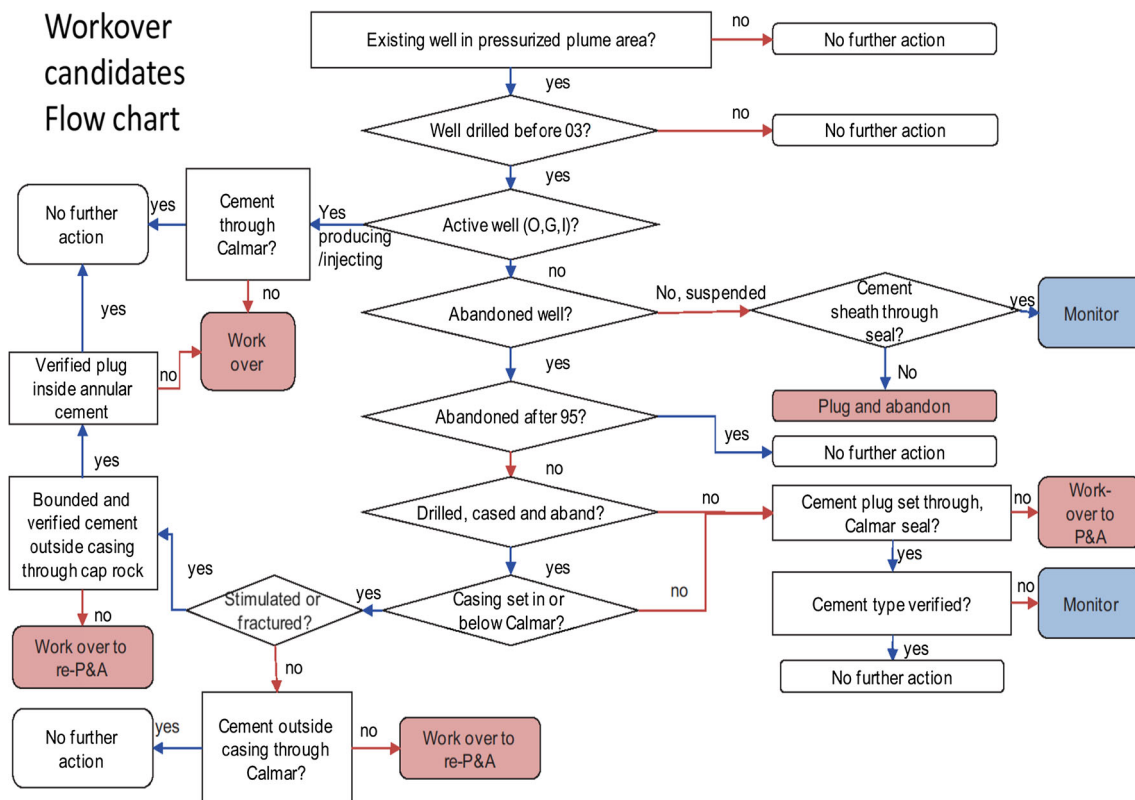
Fig. 7 Flow chart for identifying wells which are candidates for re-entering and conducting workover operations to improve leakage integrity (Nygaard 2010)

One way to process the available information is to use the method described by Nygaard (2010) as shown in Fig. 7. The method allows for the differentiation between three groups of wells, i.e., "no further action", "monitor" and "workover to re-P&A". This approach may also be applied, in a modified form, to the conditions in Germany.

Existing methods to evaluate CO$_2$ well leakage risks in a repository

Risk-based FEP method

The task of evaluating the technical integrity of a CO$_2$ well is very similar to the evaluation of the technical integrity of a repository for radioactive wastes. For the latter task structured methods have already been developed and applied (Mazurek et al. 2003). In principle, these methods consist of the two main steps: scenario development and consequence analysis. Scenarios describe the possible future developments of a system under consideration, defined by a combination of features, events, and processes (FEPS). Features describe static factors and parameters of the CO$_2$ storage system. Processes are developments of the current and future aspects

of the CO$_2$ storage system and they will last for some time. Events are future occurrences, future changes to features and future alterations of processes, e.g., blowout (Bai et al. 2014d). The developed scenarios are evaluated in the context of consequence analyses. For these analyses the events and processes are modeled and simulated to quantify the implications of a potential leakage. The process steps of a typical method used for the evaluation of leakage risks based on the FEP method (Metcalfe et al. 2009) are shown in Fig. 8.

For a risk-based analysis, the Quintessa FEP database, which is a generic database to describe the behavior of the storage system, is a good starting point to carry out analysis (http://www.quintessa.org/co2fepdb/). It has totally 178 FEPs which are categorized as assessment basis, external factors, CO$_2$ storage, CO$_2$ properties, interactions and transport, geosphere, boreholes, near-surface environment and impacts. People can modify the database according to the specific purposes. Obviously, FEPs database is only a qualitative way of describing the static characteristics and dynamic performances of a storage system, and it cannot provide a quantitative evaluation. It can be seen as a reference book or an initial help in the early phase of a storage project and provides the basis for modeling (Bai et al. 2014d).
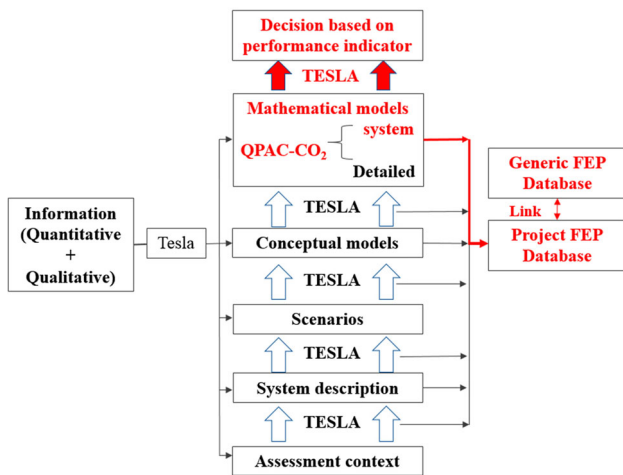
Fig. 8 Integrity evaluation using the FEP method (Metcalfe et al. 2009)

Performance and risk (PR^TM) method

A performance and risk (PR^TM) method was developed by the company Oxand S.A. and Schlumberger (Bai et al. 2014b; Le Guen et al. 2009). Different from FEPs analysis, the PR^TM method is a quantitative tool to evaluate well integrity. The workflow comprises mainly of data collection, static model development, dynamic model development, leakage simulation, risk mapping and so on, as shown in Fig. 9. The data includes all the information about well itself, formation, fluid, production, and so on. The most distinct feature of this method is a well completion and leakage simulator Simeo^TM-Stor, which can numerically predict the

quantitative impact of leakage paths along the wellbore over time. However, since the data available is normally uncertain, a risk assessment is always performed. This method is advantageous over FEP-based method in that it can take into consideration not only the uncertainties of the available data, but also the dynamic variation of the cement and tubular properties. For plugged and abandoned wells, however, the lack of data needs always some assumptions, which leads to a very uncertain evaluation (Bai et al. 2014d).

Reliability of the results (ROR): practical assessment method

Tran-Viet (2013) develops a new concept for how to arrive from limited data or information at well-founded results about the well integrity. As mentioned above, the documented data for plugged and abandoned wells are rather sparse, missing data required for the integrity assessment have to be derived by other sources (laboratory, analogy, simulation, etc.). The quality of the assessment results therefore depends on the uncertainties of the data sources. Tran-Viet (2013) provides a practical assessment concept in which the "reliability of the results" of an assessment is put in relation to the quality of the data source and to the weighting of a parameter. As a quick look the parameter "reliability of the results" can be calculated and it expresses in per cent (0–100 %) the reliability of the assessment result given by the input data from different sources. Stakeholders (Authorities, CCS operator, NGOs, etc.) can define a minimum value for "reliability of the results" as limit, below which the results will not be accepted due to the associated uncertainty arising from data sources used. This method

Fig. 9 Integrity assessment workflow of Schlumberger-Oxand method (Le Guen et al. 2009)
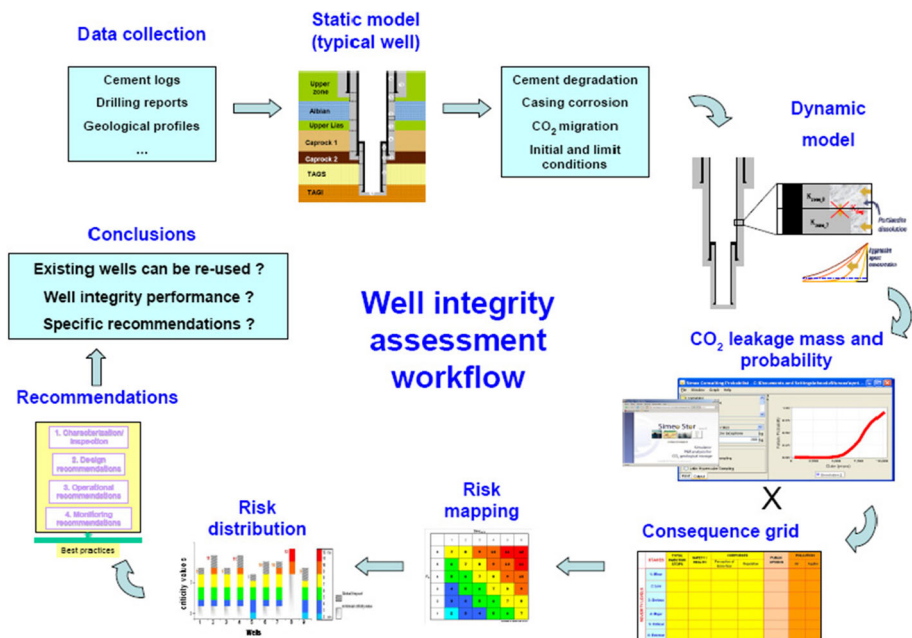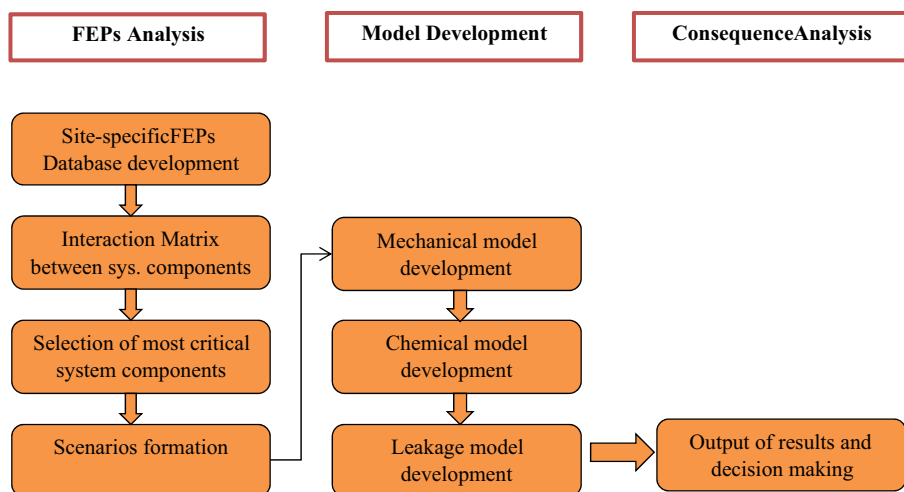
Fig. 10 Flow chart of well integrity evaluation concept (Bai et al. 2014b)

avoids a number of time-consuming works for simulation and the data collection could be reduced drastically.

A new concept for well integrity evaluation

Based on all the approaches described, a new comprehensive assessment method will be developed with the application in a pilot CCS area in Germany CLEAN (CO_2 large-scale enhanced gas recovery in the Altmark Natural Gas Field) (Bai 2014; Bai et al. 2014a, b). This assessment method is going to describe the whole near wellbore zone and quantitatively simulate the critical events and processes, which influence well integrity and estimate the long-term leakage rate within the storage period. The proposed method consists of three steps, which are FEPs (features, events and processes) and scenario analysis, model development including mechanical model, chemical model and CO_2 leakage model, and consequence analysis, as shown in Fig. 10. In comparison to the above-mentioned methods, the proposed method in this paper is comprehensive and takes account of all the static and dynamic factors influencing well integrity. It covers both qualitative and quantitative analysis. The goal is to reach a sound risk analysis for well integrity coupling both a thorough FEPs analysis and quantification of the leakage risk of CO_2 along a defected wellbore under a series of mechanical and geochemical processes.

Conclusions

The implementation of CO_2-storage projects requires evidence of the sustainable technical integrity of all wells within the distribution area of the injected CO_2. The verification of technical well integrity is significantly more difficult for abandoned wells, because measurements and

tests to close information gaps are no longer possible. If information is lacking for a direct assessment, the quantification of the risk of leakage is only possible indirectly. For an indirect assessment, a number of well-developed methods are available, usually based on the results of the risk research carried out in the context of the permanent disposal of radioactive wastes. The quantification of the leakage risk of a well requires reliable information on the wellbore zone as well as a comprehensive understanding of the processes taking place in this zone. A realistic risk assessment should consider the composite system wellbore-pipe-cement-rock as a whole and also include self-healing caused by CO_2 interacting with the pipe composite system and/or the indigenous rock.

An integrated approach is introduced which couples FEPs analysis, geo-mechanical model development and CO_2 leakage simulation. In comparison with the existing methods, this approach, covering both qualitative and quantitative analysis, is more comprehensive, sophisticated and easier to implement. If an application of this method results in a leakage risk which is low, no further action is required. Medium risks should result in monitoring activities, while high-risk wells require reopening and re-plugging.

References

Bachu S, Bennion DB (2009) Experimental assessment of brine and/or CO_2 leakage through well cements at reservoir conditions. Int J Greenh Gas Control 3:494–501

Bai M (2014) Risk Assessment for CO_2 leakage along abandoned wells using a Monte Carlo simulation in a CO_2 sequestration site. J Pet Sci Technol 32:1191–1200

Bai M, Reinicke KM, Song K, Li Y, Sun J (2014a) Relative permeability model and CO_2 leakage through abandoned wells during CO_2 underground storage. Oil Gas Eur Mag 40(3):161–165

Bai M, Song K, Li Y, Sun J, Reinicke KM (2014b) Development of a novel method to evaluate well integrity during CO_2 underground storage. SPE J, SPE 173000

Bai M, Song K, Sun Y, He M, Li Y, Sun J (2014c) An overview of hydrogen underground storage technology and prospects in China. J Petrol Sci Eng 124:132–136

Bai M, Song K, Gou J, Zhao Y, Zhao J (2014d) Well integrity evaluation during CO_2 storage and enhanced gas recovery. Sch J Eng Technol 2(1):1–8

Brasser T, Herbert H J, Miehe R, Schmidt G (2008) Endlagerung wärmeentwickelnder radioaktiver Abfälle in Deutschland Anhang Wirtsgesteine Potenzielle Wirtsgesteine und ihre Eigenschaften. BMWi FE-Vorhaben 02E9783. ISBN 978-3-939355-22-9, Braunschweig/Darmstadt, September 2008

Carey JW, Wigand M, Chipera SJ, Wolde-Gabriel G, Pawar R, Lichtner PC, Wehner SC, Raines MA, Guthrie GD Jr (2007) Analysis and performance of oil well cement with 30 years of CO_2 exposure from the SACROC unit. SACROC unit, West Texas

Crow W, Carey WJ, Gasda S, Williams DB, Celia M (2009) Wellbore integrity analysis of a natural CO_2 producer. Int J Greenh Gas Control 4:184–194

De Lucia M, Bauer S, Beyer C, Kuhn M, Nowak T, Pudlo D, Reitenbach V, Stadler S (2012) Modelling CO_2-induced fluid-rock interactions in the Altensalzwedel gas reservoir. Part I: from experimental data to a reference geochemical model. Environ Earth Sci 67(2):563–572

de Rooij M, Van Tittelboom K, De Belie N, Schlangen E (eds) (2013) Self-healing phenomena in cement-based materials. State-of-the-Art Report of RILEM Technical Committee 221-SHC, vol 11. Springer, p 266

Environmental Protection Agency EPA (1998) Determination of the mechanical integrity of injection wells. United States Environmental Protection Agency Region 5—Underground Injection Control (UIC) Branch—June 11, 1998

Jacobsen S, Marchant J, Gerard B (1998) Concrete cracks. In: durability and self healing—a review. concrete under severe conditions 2: Gjorv O E, Sakai K, Banthia N E, FN Spon New York 1998, ISBN 0 419 23860 3

Kissinger A, Helmig R, Ebigbo A, Class H, Lange T, Sauter M, Heitfeld M, Klunker J, Jahnke W (2013) Hydraulic fracturing in unconventional gas reservoirs: risks in the geological system, Part 2. Environ Earth Sci 70(8):3855–3873

Le Guen Y, Meyer V, Poupard O, Houdu E et al. (2009) A risk-based approach for well integrity management over long term in a CO_2 geological storage project. Presented at the 2009 SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, 4–6 August

Martens S, Kempka T, Liebscher A, Luth S, Moller F, Myrttinen A, Norden B, Schmidt-Hattenberger C, Zimmer M, Kuhn M (2012) Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany: a progress report after 3 years of injection. Environ Earth Sci 67(2):323–334

Mazurek M, Pearson F J, Volckaert G, Bock H (2003) Features, events and processes evaluation catalogue for Argillaceous media. NEA4437, radioactive waste management, ISBN 92-64-02148-5, OECD 2003

Metcalfe R, Maul PR, Benbow SJ, Watson CE, Hodgkinson DP, Paulley A, Limer L, Walke RC, Savage D (2009) A unified approach to performance assessment (PA) of geological CO_2 storage. GHGT-9. Energy Procedia 1(2009):2503–2510

Mulders F (2007) Analysis of abandoned well integrity at a potential CO_2 storage site, July 2007, IEA 3rd Well Bore Integrity Workshop

Ngoc TDT, Lefebvre R, Konstantinovskaya E, Malo M (2014) Characterization of deep saline aquifers in the Bcancour area, St. Lawrence Lowlands, Qubec, Canada: implications for CO_2 geological storage. Environ Earth Sci 72(1):119–146

Novak K, Malvic T, Velic J, Simon K (2014) Increased hydrocarbon recovery and CO_2 storage in neogene sandstones, a Croatian example: part II. Environ Earth Sci 71(8):3641–3653

Nygaard, R. (2010): Well Design and Well Integrity Wabamun Area CO_2 Sequestration Project (WASP). Energy and Environmental Systems Group, Institute for Sustainable Energy, Environment and Economy (ISEEE) January 4, 2010

Reinicke KM, Fichter C (2010) Measurement strategies to evaluate the integrity of deep wells for CO_2 applications. In: Procceding of the Sino-German conference on underground storage of CO_2 and energy, Beijing, China, 6–13 July 2010. doi:10.1016/j.egypro.2013.06.611

Reinicke KM, Franz O (2008) CO_2 Lagerung im Geogrund: Bohrungsintegrität akzeptabel für CSEGR (Carbon Sequestration with Enhanced Gas Recovery). Presented at german society for petroleum and coal science and technology-spring conference (DGMK/ÖGEW-Frühjahrstagung), Celle, Germany, April 10–11

Reinicke KM, Teodoriu C, Fichter C, Weichmann M J, Weinlich F H, Krebs R, Zhang Z L (2011) Untersuchung von Selbstheilungsmechanismen im Verbundsystem Rohr-Zement-Gebirge von CO_2-Bohrungen. German society for petroleum and coal science and technology-spring conference (DGMK/ÖGEW-Frühjahrstagung), Celle, Germany, 11–12 April 2011

Sandig C, Sauer U, Brauer K, Serfling U, Schutze C (2014) Comparative study of geophysical and soil-gas investigations at the Hartousov (Czech Republic) natural CO_2 degassing site. Environ Earth Sci 72(5):1421–1434

Schutze C, Sauer U, Beyer K, Lamert H, Brauer K, Strauch G, Flechsig C, Kampf H, Dietrich P (2012) Natural analogues: a potential approach for developing reliable monitoring methods to understand subsurface CO_2 migration processes. Environ Earth Sci 67(2):411–423

SMRI (1996) SMRI reference for external well mechanical integrity testing/performance, data evaluation and assessment. SMRI Spring Meeting, Crotogino F, Short Class, Houston 1996

Tran-Viet, T. (2009): Bewertung Technische Integrität: Bewertung bestehender Verfahren, In: CLEAN Zwischenbericht Dezember 2009 und CLEAN Jahrestreffen Januar 2010

Tran-Viet T (2013) Methodological development of a practicable concept for assessing the integrity of abandoned wells. PhD Dissertation, TU Clausthal, Germany

Wiese B, Zimmer M, Nowak M, Pellizzari L, Pilz P (2013) Well-based hydraulic and geochemical monitoring of the above zone of the CO_2 reservoir at Ketzin Germany. Environ Earth Sci 70(8):3709–3726

Williams S, Carlsen T, Constable K, Guldahl G (2009) Identification and qualification of shale annular barriers using wireline logs during plug and abandonment operations. SPE/IADC 119321, SPE Well Abandonment, Aberdeen, Scotland, UK, 30 June 2009