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Review Article

Well Integrity Evaluation during CO_2 Storage and Enhanced Gas Recovery

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Abstract: With the industrialization in the 19th century the desire for energy rose continuously resulting in a high emission of CO2 which is one of the greenhouse gases. Storage of CO2 in the underground, e.g., depleted oil and gas reservoir, is proved to be one means of mitigating greenhouse effect and meanwhile enhancing oil and gas recovery. In order to ensure an effective long-term containment of CO2 in the underground, the well integrity has to be evaluated prior to the commencement of implementation. The evaluation of well integrity for plugged and abandoned well is a big challenge, because conventional methods to assess well integrity, e.g., logging, coring, cannot be applied on abandoned wells. Many researchers have proposed generic methods to assess well integrity. This paper is going to provide a review over these methods and put forward a structure of a new comprehensive methodology which can bring a step forward for well integrity evaluation.
Keywords: CO_2 storage; enhanced gas recovery; well integrity; risk assessment; leakage rate

INTRODUCTION

Storage of CO_2 in the underground, e.g., depleted oil and reservoirs, saline aquifers and coal seam, is one important means of mitigating greenhouse effect and enhancing oil and gas recovery. In case there are many wells in the field, the well integrity affects tremendously the storage efficiency. One of the prerequisites of CO_2 underground storage is to ensure a satisfying well integrity of the large amounts of wells in the field, especially old abandoned wells. These wells suffered from stress and temperature changes in the whole life, which result in down hole conditions change. After injection CO_2 has a potential to react with cement or casing leading to loss of well integrity. Therefore it is of paramount importance to evaluate well integrity prior to the commencement of CO_2 injection. It has been proved that it is the existing wells that will pose the greatest risk instead of the CO_2 injection wells.

Evaluation of well integrity is relatively simple for accessible wells (Fig. 1a), which can be surveyed to directly assess the conditions [1]. Evaluation of the technical integrity of plugged and abandoned wells (Fig. 1b) is a big challenge. Because the data available from these wells does not suffice for a direct integrity assessment, and moreover to re-open and survey an abandoned well is costly and economically not worthy, a lot of researchers have tried to use some alternative methods, for instance, risk assessment. The overall aim of risk assessment is to investigate the storage system's behavior over time. These methods are going to be reviewed in this paper. Based on this a structure of a new methodology is going to be introduced which takes all the main relevant THMC (thermal-hydraulic-mechanical-chemical) processes affecting well integrity into consideration and evaluates the well integrity over long time frames indirectly.

Challenges Of Well Integrity Evaluation During Co_2 Sequestration

If a well is no longer needed, it is plugged. The necessary plugging operations are governed by regulations of the mining authorities. The standard plugging procedures include a bottom cementation to shut off the formation and further plugs to provide additional barriers. The spaces in between the plugs are filled with heavy weight mud. Typical mud is suspensions of bentonite in fresh water with densities ranging from 1.1 to 1.4 g/cm^3. To minimize leakage risks, the plugs are usually placed across potential problem zones, for example, at the top of the liner (Fig. 1b). If un-cemented zones are detected, the casing is perforated and cement is squeezed into the annulus behind the casing. At the top of the well, the casing is cut approx. 3 m below the surface and covered by a concrete or a steel plate [2]. The near wellbore zone is defined as the well and the immediate area around it. Within the near wellbore zone, leakage can occur along a number of pathways through the wellbore system which consists of the cement plugs, mud inside the casing, the casing-cement-rock composite system. CO_2 leakage through or along wells during and after the injection phase can be attributed to:

- Casing or cementation defects due to improper design or construction;
- Corrosion of the casing and deterioration of cement plugs by CO_2 or brine;

- Well head failure, leaking pipe connections and defective materials;
- Well collapse, etc.

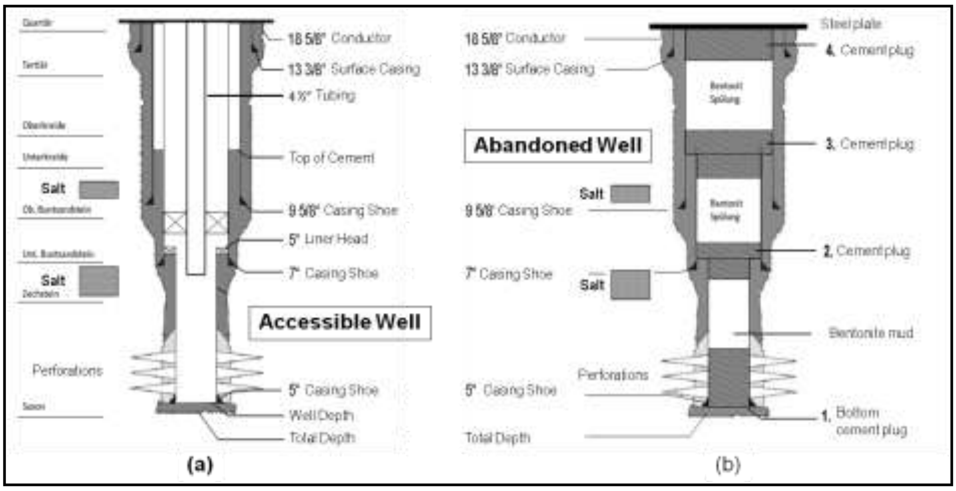

Fig. 1: (a) Accessible well structure (b) Abandonment standard (Reinicke and Fichter [1])

Loss of well integrity due to CO_2 corrosion

The biggest challenge of CO_2 injection wells is the corrosion fatigue of metals. 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. Steel products in wellheads, casing and completion strings are subjected to corrosion in an acidic environment. The solid iron dissolves into iron ions in solution and creates a corroded surface on the steel, see following equation. The basic requirement for this reaction to occur is water.

$$Fe(s) + 2H^{+} = Fe^{2+}(aq) + H_2(g)$$

CO_2 also attacks the cement of the well and causes severe corrosion. Therefore the compressive strength decreases and the permeability and porosity of the cement change. The process can be described with the following reactions:

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$
$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$$
$$\text{C-S-H} + H_2CO_3 \rightarrow CaCO_3 + \text{amorphous silica}$$
$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$$
$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3 + 2H_2O$$

The calcium carbonate continues to react with the carbonic acid and builds water-soluble calcium bicarbonate. The last reaction is very critical, because the formation of water allows dissolution of more CO_2 [3, 4].

Loss of well integrity due to mechanical processes

The field and experimental data have shown that the chemical degradation can affect well integrity severely only when there are already existing pathways [5, 6]. Thus, to study mechanical integrity of cement plug and cement sheath is of more significance for a safe long-term containment of CO_2. Typical reasons for the composite system failure include mainly:

- Improper operation during well completion
- Mud cake buildup and mud channeling
- Due to pressure variation
- Due to temperature variation

Unlike accessible wells, the abandoned wells are much more complicated. For some old abandoned wells, which have been drilled, cased and abandoned with very old standards (or no standards and no cement), there only exists minimal or even no information about the quality of the well components.

METHODOLOGIES FOR WELL INTEGRITY EVALUATION

FEP-based analysis

In long-term storage of CO_2 a lot of activities can lead to unwanted impacts on the storage system. In order to have a comprehensive view about these possible activities, Features, Events and Processes (FEPs) databases were developed by some researchers and applied [7-11]. 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. To get an imagination about these possible activities, analyses and models were executed to build FEPs. After that, all potential FEPs which impact the storage system have to be identified. A brainstorming of experts will support this execution. This is the first step in developing a FEP database, which can be used as an assessment basis.

The Quintessa FEP database includes 178 FEPs which are describing the behavior of a CO_2 storage system. The hierarchical structure is divided into eight groups including assessment basis, external factors, CO_2 storage, CO_2 properties, interactions and transport, geosphere, boreholes, near-surface environment and impacts. Quintessa database can be accessed at http://www.quintessa.org/co2fepdb/. It is a generic database and can be modified by researchers or companies according to the case-specific purposes. SAMCARDS (Safety Assessment Methodology for Carbon Dioxide Sequestration) is developed by the TNO–NITG in the Netherland. The whole process is divided into two main steps, viz., qualitative analysis and quantitative analysis (Figure 2). The qualitative analysis involves mainly the FEP and scenario analyses. These FEPs have to be identified, classified and analyzed first. A combination of FEPs generates a scenario which describes one possible future state of the storage system. The next step is the model development. The results of these models can be tested immediately by means of some other ways.

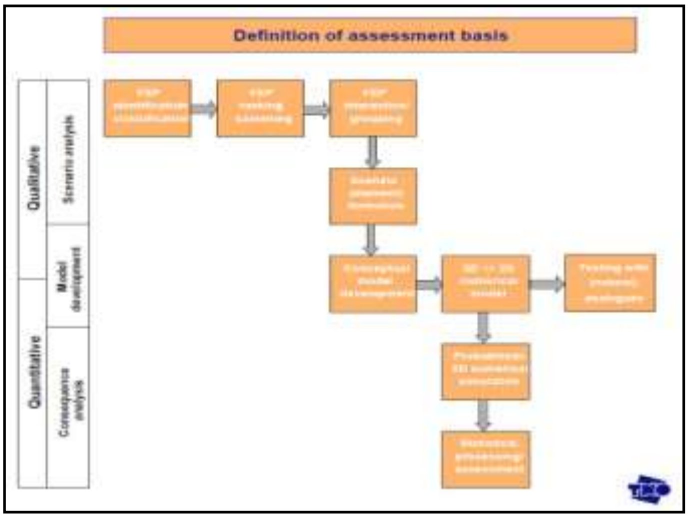

Fig. 2: SAMCARDS (Wildenborg *et al.* [11])

Data mining

One strategy for evaluating and ranking abandoned wells relevant to the integrity of an envisaged storage option is data mining of all the well information collected by regulatory agencies, particularly with focus on surface casing vent flow and gas migration data. The Alberta Energy Resources Conservation Board collects and maintains data regarding cement types used in primary cementing of casing strings, stimulation information and abandonment data. These data were used to determine the potential for deep wellbore leakage in the presence of CO_2 [12, 13]. Major focus of data mining is to find factors contributing to wellbore leakage in the context of CO_2 storage. This approach relates a number of well features to the magnitude of impact on the leakage risk. Based on these features, a decision tree or matrix can be used to rank all these wells involved according to the risk severity (Fig. 3). Table 1 shows various factors investigated which influence well integrity.

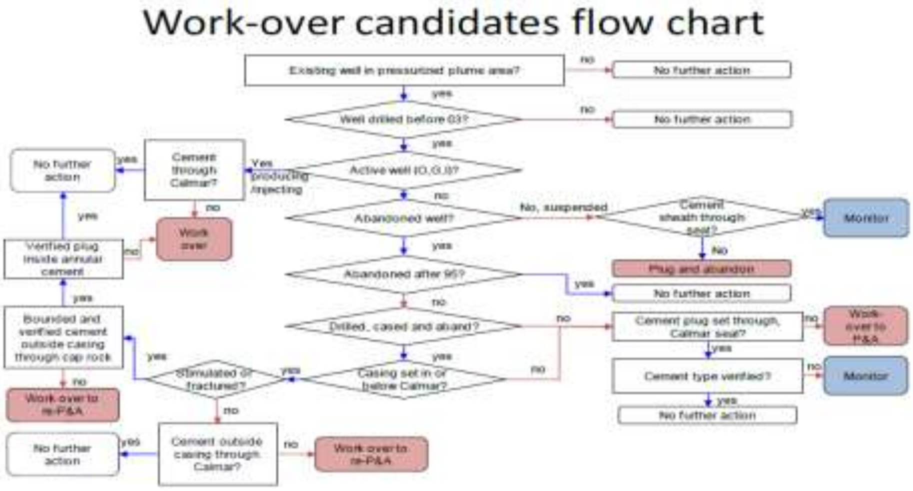

Fig. 3: Data mining (Reinicke & Fichter [1])

Table 1: Factors influencing well integrity investigated by ERCB (after Watson and Bachu [12, 13])

FEPs	Factors	Description
Features	Well age	Well age is expected to have a significant impact on wellbore leakage because of poorer wellbore-construction techniques and materials in the past and absent regulatory requirements.
	Well operational mode	Well operational mode, such as producing oil or gas, injecting water or solvents, disposal of liquid waste or acid gas, or observation, did not have any effect on the occurrence of wellbore leakage.
	Completion interval	It is proved that the majority of wells have good cement quality and zonal isolation deep in the wellbore, but in the shallower formations the cement is typically poor or non-existent.
	Surface casing depth	As the surface casing depth increases, the occurrence of leakage decreases.
	Total depth	The occurrence of leakage increases slightly with the well total depth, due to the relatively larger uncemented intervals in their upper part.
	Well density	Well density has a significant effect on the occurrence of wellbore leakage. In areas of high well density, well-to-well cross flow may occur and result in a single well leaking to surface through many nearby wellbores.
	Topography	River valleys may represent zones of higher leakage risks due to removal of overburden and decline of hydrostatic pressure.
	Wellbore deviation	Migration occurred significantly more often related to deviated wells, while the impact of well deviation on the ration of leakage to migration was minor.
	Well type	Cased abandoned wells account for 98 % of all leakage cases reported.
	Uncemented annulus	A low cement top was found to be the most important indicator for migration and leakage, as well as external casing corrosion.
Processes	Stimulation	Formation damage due to stimulation has a number of potential implications for assessing CO_2 storage, e.g., damaged regions themselves may provide flow paths for CO_2 migration, particularly if damage results in fracturing.
	Production	With production of gas the reservoir pressure decreases causing an increasing load acting on the storage rock. Such a compaction will cause strain in the cap rock, cement and casing, which could cause cracks and so on.
	Corrosion on casing /cement	Degradation of cement and corrosion of casing will form some pathways for CO_2 leakage into the biosphere.
	Abandonment	According to the data in Alberta, the method bridge plugs capped with cement will fail by 10% over a period of centuries allowing formation fluids to enter the wellbore.

Performance & Risk Management Methodology

To assess CO_2 leakage along wellbore in a storage project a Performance and Risk (P&R^{TM}) methodology was developed by Oxand S. A. This method represents a quantitative risk-based approach for well integrity management, allowing identification and quantification of risks within CO_2 injection and storage operations over various time scales. Figure 4 shows the process chain of this P&R assessment methodology. It consists of a data collection survey followed by a functional analysis of the system, serving as input for a static well model. This latter, in turn, acts as an input for a dynamic model, able to predict degradation of well components as a function of time and to quantify CO_2 leakage along the wellbore. Based on the parameters of the static and dynamic models, and associated uncertainties scenarios are defined and then evaluated numerically. Simulation results enable to identify leakage pathways along the wellbore and the amount of leaking gas towards different targets over time. The probability level of a risk is given by the probability of risks for all wells relevant to CO_2 injection and storage operations. Risk mapping is performed by filling a color coded grid with each couple corresponding to all scenarios which lead to CO_2 leakage. These results then lead to recommendation and conclusions to support decision making. The essential component of the approach is a well completion and leakage simulator (Simeo^{TM}-Stor) allowing the prediction of the quantitative impact of leakage paths along the wellbore. A detailed description of this method can be found in Le Guen *et al.* [14-16] and Houdu *et al.* [17].

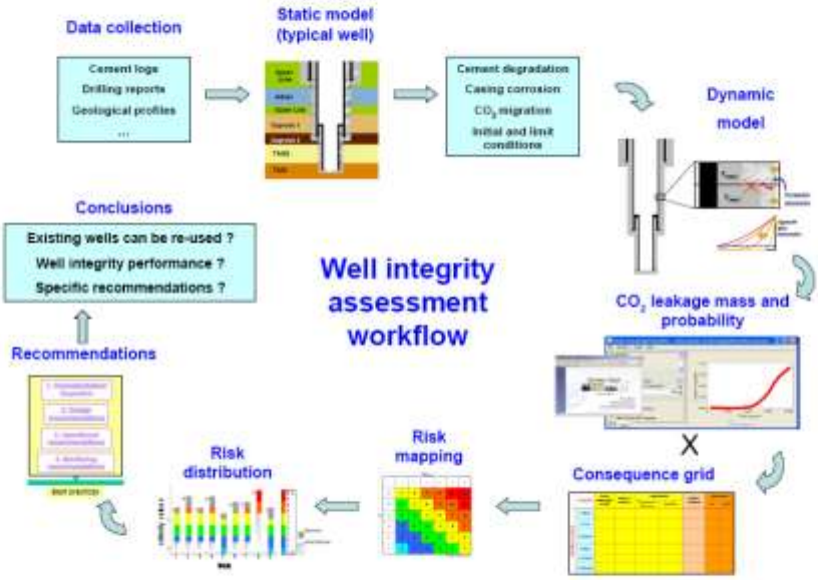

Figure 4: Chain of a P&R assessment

CO_2-PENS (CO_2-Predicting Engineered Natural System)

CO_2-PENS is a probabilistic simulation tool designed to incorporate CO_2 injection and sequestration knowledge from the petroleum industry to perform risk assessment [18-20]. The model links high level system models (reservoir model) to the process level (wellbore leakage, chemical interaction of CO_2) and thus represents a hybrid coupled process and system designed to simulate different CO_2 pathways. Simulation of wellbore leakage is complicated since the associated interactions and processes are not yet entirely understood. Wellbore cement permeability is identified as a key parameter in a wellbore leakage scenario and is difficult to estimate. Additionally, as the storage sites are usually intersected by numerous wells, simulation approaches require probability distribution functions (PDF) with respect to potential failure mechanisms as input parameters to take account of uncertainties. A conceptual model of CO_2 leakage may be developed relying on PDFs of the quantities of the following processes:

- Flow at cement-casing interface
- Flow through the cement matrix
- Flow through pathways created by bulk chemical dissolution of the cement
- Flow through fractures in the cement
- Flow through an open annular region due to inadequate cement placement
- Flow at the cement caprock interface

The CO_2-PENS wellbore release module is capable of predicting CO_2 release based on the given wellbore cement effective permeability. Simulations can be performed in two ways: (1) Finite Element Heat and Mass Transfer (FEHM) which represents a multi-dimensional multiphase reservoir simulator; (2) calculation of leakage rates by a semi-analytical model which is introduced in Nordbotten *et al.* [21, 22].

Lab experiments for well integrity evaluation

The methods stated above are often used together with some lab experiments for some case-specific conditions. Bachu and Bennion [23] performed two sets of experiments to study brine and CO_2 leakage through well cement at reservoir conditions. The results show: (1) in case the cement and the bond are of good quality, the effective permeability of the casing-cement-rock assemblage is extremely low and it will constitute a good and reliable barrier to the upward flow of CO_2 or brine; (2) in case an annular gap at the interface or micro-cracks occur, the effective permeability will increase which pose a great risk for leakage. Carey *et al.* [24] performed an experimental investigation on CO_2-brine flow along casing-cement micro-annulus through core-flood experiments. The experiments were conducted on a synthetic wellbore system consisting of cement and steel embedded with a certain size. The results show that cement is not significantly eroded by the CO_2-brine mixture confirming the durability of neat Portland cement in CO_2-brine environments while the carbon steel shows a significant corrosion and precipitation which lead to self-sealing of the interface of casing and cement. Another famous method is Schacht Konrad test in areas of Konrad repository which is a storage facility for radioactive waste [25]. In this area there are some abandoned boreholes. The radioactive contaminated salt water in the storage formation is not allowed to reach the aquifers in the upper parts of the geological settings. Goal of this method is to evaluate, if the abandoned wells are tight enough to prevent saline water from moving upwards and reaching overlying aquifer. The developer tried then to determine the permeability of the two possible pathways: inner space of the casing and the annulus. The methodology applied in Konrad repository consists of a set of different experiments and tests. The test apparatus is shown in Fig. 5, with which the permeability and the sedimentation process can be simulated.

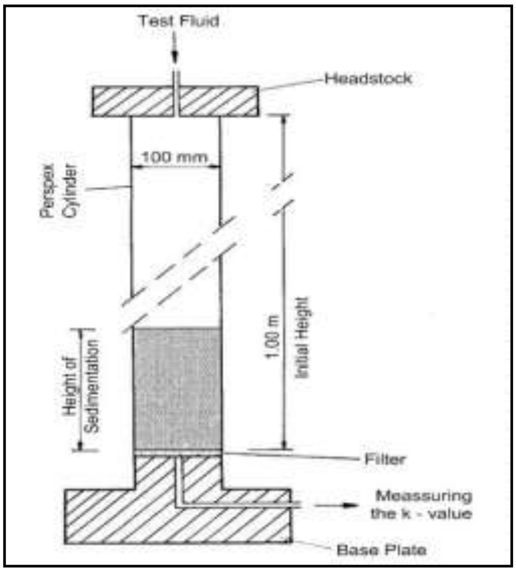

Fig. 5: Schacht Konrad test unit (Wittke [25])

CONCLUSIONS AND OUTLOOK

Existing methodologies for risk assessment of well integrity have been reviewed. A FEP database cannot solve all the questions and problems of a storage project. 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. Data mining technique is suitable for measuring uphole leakage. It is a decision tool for distinguishing between zones in intended storage area exhibiting different risk levels. Schlumberger and Oxand P&R method is a relatively comprehensive risk assessment. However, for old abandoned wells, which do not have much data available, some assumptions have to be made. Assessment results will therefore have very high uncertainties. The method used by Konrad repository is based mainly on determination of the hydraulic conductivity and transmissivity of the flow path, which can be determined by field and lab investigation of all materials existed in the bore hole or in the annulus, such as drilling fluids, drilled solids, cement, swelling and decomposition of minerals due to contact with mud. This method is very complex in collecting all necessary parameters, however, it is a deterministic approach compared with the Oxand probabilistic approach. A brief comparison of these methods mentioned above is shown in Table 2.

Table 2: Risk assessment methods available (after IEA [6])

Methods	Description	Simulator	Decision tool
FEP	Quantitative	Yes	Yes
Data mining	Semi-quantitative	No	Yes
Oxand	Probabilistic	Yes	Yes
Schacht Konrad	Quantitative	Yes	No
CO_2 PENs	Probabilistic	Yes	No

Based on all the approaches described, a new comprehensive assessment method will be developed with the application in one pilot CCS area in Germany. 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. From well construction till injection phase, the wellbore experienced mainly the geomechanical processes, including drilling, completion, stimulation, production and abandonment. In the storage phase, the wellbore experiences mainly the geomechanical and geochemical processes (Fig. 6). Fig. 7 illustrates the whole process of risk assessment proposed in this paper.

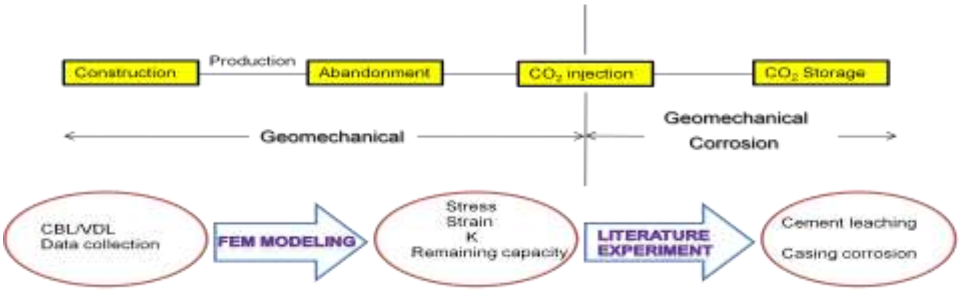

Fig. 6: Process affecting well integrity in the well life

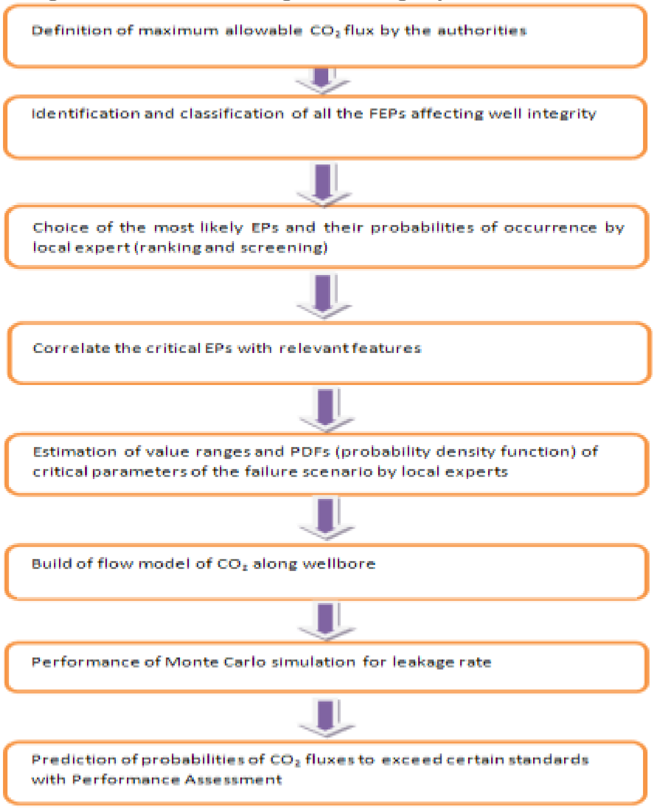

Fig. 7: Workflow of risk assessment for well integrity

As the method is still under the development process, more details are available in future. Several points are noteworthy:

- The FEPs have been screened and grouped according to the risks based on published work and expert judgment.
- CO_2 leakage model needs to be built and simplified.
- Estimation of value ranges and probability density function for the key parameters are based on expert opinions and lab experiments.
- Treating the uncertainties in the parameter values requires a stochastic approach with the help of ***Monte Carlo*** simulations, which can be used to predict probabilities of CO_2 leakage rate to exceed the predefined maximum allowable rate.

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REFERENCES

1. Reinicke KM, Fichter C; Measurement strategies to evaluate the integrity of deep wells for CO_2 applications. Proc. Sino-German Conference on Underground Storage of CO_2 and Energy, Beijing, July 6-13, 2010.

2. Reinicke KM, Bai M, Fichter C, Weichmann MJ, Weinlich FH; Leckagerisiko von Bohrungen unter Einfluss von CO_2: Von den FEPs bis zu den Szenarien. DGMK/ÖGEW-Frühjahrstagung, 2011, Celle, 11./12.
3. Benge G; Improving wellbore seal integrity in CO_2 injection wells. SPE 119267, SPE/IADC Drilling Conference and Exhibition, Amsterdam, The Netherlands, Mar. 17-19, 2009.
4. Fakhreldin Y, Al-Sharji H, Ruwehy AM, Saadi K, Taoutaou S, Al-Kalbani S; Advanced cement system for acid gas injection wells. SPE 132345, SPE Asia Pacific Oil & Gas Conference and Exhibition, Queensland, Australia, Oct. 18–20, 2010.
5. Carey JW, Wigand M; Analysis and performance of oil well cement with 30 years of CO_2 exposure from the SACROC Unit, West Texas, USA, Intl J Greenhouse Gas Control, 2007; 1: 75–85.
6. IEA Greenhouse Gas R&D Programme. Long term integrity of CO_2 storage – well abandonment report 2009/08.
7. Savage D, Maul PR, Benbow S, Walke RC; A generic FEP database for the assessment of long-term performance and safety of the geologic storage of CO_2. Quintessa Document QRS-1060A-1, 2004: 73.
8. Leijnse A, Wildenborg AFB, Kreft E, Obdam A, Nepveu M, Wipfler L; CO_2 capture project – an integrated, collaborative technology development project for the next generation CO_2 sequestration, capture and geologic sequestration. Safety assessment methodology for CO_2 sequestration (SAMCARDS). DOE Award Number DE-FC26-01NT41145, August 2003.
9. Maul P, Savage D, Egan M; A generic FEP database for the assessment of long-term performance and safety of the geological storage of CO_2, Quintessa Ltd., Oxfordshire, 2004.
10. Thomas DC, Benson SM; Carbon Dioxide capture for storage in deep geologic formations. Elsevier, Volume 2, 2005: 1293-1316.
11. Wildenborg AFB, Leijnse AL, Kreft E, Nepveu MN, Obdam ANM, Orlic B *et al.*; Risk assessment methodology for CO_2 storage: the scenario approach. Carbon Dioxide Capture for Storage in Deep Geologic formations, 2005; 2: 1293–1316.
12. Watson TL, Bachu S; Evaluation of the potential for gas and CO_2 leakage along wellbores. SPE 106817 presented at the E&P Environmental and Safety Conference, Galveston, Texas, Mar. 5–7, 2007.
13. Watson TL, Bachu S; Identification of wells with high CO_2 leakage potential in mature oil fields developed for CO_2-enhanced recovery. SPE 112924 presented at the SPE/DOE Improved Oil Recovery Symposium in Tulsa, Oklahoma, April 19–23, 2008.
14. Le Guen Y, Huot H, Loizzo M, Poupard O; Well integrity risk assessment of Ketzin injection well (ktzi-201) over a prolonged sequestration period GHGT 10, Elsevier, Energy Procedia, 2010.
15. Le Guen Y, Le Gouevec JL, Chammas R, Gerard B; CO_2 storage: managing the risk associated with well leakage over long time scales. SPE 116424 presented at the 2009 SPE Asia Pacific Oil and Gas Conference and Exhibition held in Perth, Australia, 20–22 October, 2008.
16. Le Guen Y, Meyer V, Poupard O, Houdu E; A risk-based approach for well integrity management over long term in a CO_2 geological storage project. SPE 122510 presented at the 2009 SPE Asia Pacific Oil and Gas Conference and Exhibition held in Jakarta, Indonesia, 4–6 August, 2009.
17. Houdu E, Poupard O, Meyer V; Supercritical CO_2 leakage modeling for well integrity in geological storage project. Excerpt from the Proceedings of the COMSOL Conference, Hannover, 2008.
18. Viswanathan H, Pawar RJ; Development of a hybrid process and system model for the assessment of wellbore leakage at a geologic CO_2 sequestration site. Environment Science & Technology, 2008; 42: 7280–7286.
19. Stauffer PH, Viswanthan HS, Pawar R, Guthrie GD; CO_2-PENS: A system model for geologic sequestration of carbon dioxide. Environmental Science and Technology, 2009; 43: 565–570.
20. Celia M, Bachu S, Nordbotten JM, Gasda SE, Dahle HK; Quantitative estimation of CO_2 leakage from geological storage: analytical models, numerical models and data needs. Proc. GHGT-7 Meeting, Vancouver, September 2004.
21. Nordbotten JM, Celia A, Bachu S, Dahle HK; Semi-analytical solution for CO_2 leakage through an abandoned well. Environmental Science & Technology, 2005; 39(2): 602–611.
22. Nordbotten JM, Kavetski D, Celia MA, Bachu S; A semi-analytical model estimating leakage associated with CO_2 storage in large-scale multi-layered geological systems with multiple leaky wells, Environmental Science & Technology, 2009; 43(3): 743–749.
23. Bachu S, Bennion DB; Experimental assessment of brine and /or CO_2 leakage through well cements at reservoir conditions. Intl J Greenhouse Gas Control, 2009; 3(4): 494–501.
24. Carey JW, Svec R, Grigg R, Zhang J, Crow W; Experimental investigation of wellbore integrity and CO_2–brine flow along the casing–cement microannulus. International J. of Greenhouse Gas Control, 2010: 272–282.
25. Wittke W; Beratende Ingenieure für Grundbau und Felsbau GmbH: Endlager Konrad Schachtverfüllung / Alte Bohrungen, Bericht Nachweis der Dichtigkeit alter Bohrungen, Aachen , 1991.