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Identification and evaluation of well integrity and causes of failure of well integrity barriers (A review)

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ABSTRACT

Volatile markets and harsh locations and downhole conditions pose severe challenges for ensuring safe and long-lasting intact well conditions. Well integrity is a crucial issue in the life cycle of all sub-surface boreholes. Failure of wellbore integrity leads not only to negative financial consequences, but also potentially to significant environmental impacts, such as groundwater contamination, gas leakage to the atmosphere, and fluid spills and seepage at the surface. Many studies have specifically focused on well integrity issues related to particular types of conventional and unconventional oil and gas reservoirs. Specific types of wells and well operations (e.g., high pressure high temperature, enhanced oil and gas recovery, deepwater, water and gas injection, geothermal, and plugging and abandonment) pose their specific issues. To understand the barriers to well integrity, and what is required to sustain it, a holistic study encompassing a wide range of issues is highly required. From a practical point of view, there are several factors affecting well integrity issues which can be classified based on chemical, mechanical, and operational factors. The consequence of these well integrity issues is mainly the fluid migration over time within or escaping from the wells. Past studies reveal that well integrity barriers are highly impacted by cement carbonation and casing corrosion processes, fluid migration, in-situ conditions, cement and casing mechanical properties.

Cement is the main physical barrier able to seal fluid flow into unintended zones from the wellbore. The sealing efficiency of cement is highly dependent on in-situ environment conditions and cement chemical compositions, influencing the time-dependent stress geometry in the vicinity of wellbores. Casing corrosion is another challenging issue which is often unavoidable due to acidic environments imposed mainly by CO_2 and H_2S “sour” gasses. Modern studies have also shown the importance of cement fatigue degradation.

Pressure regulation during production and temperature variation are the most common influencing variables impacting the mechanical aspects of well integrity. These variables induce extra stresses on the established barriers which can initiate and/or promote fluid migration. In addition, to chemical and mechanical aspects of well integrity, operational interventions can play crucial roles in improving well integrity. This aspect contributes to establishing zonal isolation, not limited to, but specific requirements of plugging and abandonment operations.

Continuous evaluation and monitoring using different logging techniques and tests during drilling, completion, and production are required to address the issues that compromise the robustness of the well integrity. Nuances of the interpretation of multiple well logs must be understood in order to effectively respond to the potentially damaging situation, without risking the amplification of negative downhole conditions. Well integrity compensatory factors such as pressure, temperature, chemical changes, corrosion are interdependent. For instance, the variation in temperature or chemical changes will affect the extent of corrosion, hence a comprehensive design and monitoring system is essential to

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clearly understand the well integrity issues. This paper presents a broad review of research and field experiences related to well integrity.

Contents

1. Introduction

Pushing the boundaries of oil and gas exploration and development to more challenging locations and harsher environments leads to exposure to greater uncertainties and necessitates robust risk mitigation strategies and techniques. Millions of dollars are now spent on reservoir monitoring and production systems to minimize the risks and promote safe wellbore conditions during drilling, completion, and production operations. The preeminent objective is designing a wellbore which has the least potential for exposure to fluid migration, better longevity, and reliable and fit-for-purpose hydraulic and mechanical barriers. These aspects are generically referred to as wellbore integrity.

A worldwide study of more than 380,000 wells from Canada, China, Netherlands, Offshore Norway, UK, and US revealed that approximately 7 percent of the wells had wellbore integrity failure (Davies et al., 2014). Specific wellbore integrity issues vary depending upon the different types of conventional and unconventional reservoirs, vertical versus horizontal wells, onshore versus offshore, and special types of well designs, purpose and operations (e.g. gas and water injection, geothermal, high-pressure and high-temperature (HPHT), enhanced oil recovery (EOR), deepwater drilling, plugging and abandonment). Resolving well integrity issues enhances the potential to achieve optimum production, maximum reserves recovery, and cost-effective operations over a wellbore lifespan.

Well integrity issues are most commonly associated with the cement quality, casing corrosion, dynamic drilling and production pressures, and completion and abandonment complexities. Well barriers elements comprised of primary and secondary barriers are established to cater with these issues. Primary well barrier consists of fluid column and secondary barrier involves cement, casing, wellhead, high-pressure riser, and Blow-out Preventer (BOP). The fluid column is the main hydraulic barrier during drilling activities which helps in maintaining overbalance state of the borehole with regards to the formation. This overbalance pressure condition prevents any fluid influx in the wellbore (NORSOK D-010). Cement is a silica-based material commonly utilized for creating another permanent hydraulic barrier to prevent the communication of fluids between formations and wellbore, and cross flow of fluids via the wellbore between formations. Typical cement properties, such as tensile and compressive strength, porosity, and permeability can be altered due to cement compositional variation reacting with downhole fluids. Also, the dynamic pressure and temperature conditions during drilling and production exert a cyclic load on cured cement, and sometimes initiates cracks in the cement. These cracks then have the potential to act as pathways for fluid migration.

In addition to hydraulic barriers, mechanical barriers such as casing, casing shoes, connections, sealants, packers, wellhead, riser, and BOP provide extra safety layers to well construction. Casing, casing shoes, and connections are usually fabricated of steel, while sealants and packers typically also involve rubber or polymers. The nature of these materials makes them vulnerable to reaction with various chemicals present downhole, which often leads to their progressive corrosion and degradation. These issues ultimately compromise wellbore integrity by providing fluid leakage pathways at the cement-casing interface. The wellhead and BOP provide additional safety layer to well in case of failure of primary barrier. It helps in shut-in the well in case of the uncontrolled flow of fluid in the wellbore till other barriers are re-established (NORSOK D-010).

The lack of impeccable well integrity increases the risk of negative environmental impacts (e.g. greenhouse gas emissions, contamination of surface and ground water), accidents, production interruptions and costly remedial workover operations to repair damage as it occurs. It is noteworthy to mention that the advancement in production technology has extended the life of the well beyond its original design. Therefore time will play a major role in the well integrity assessment.

1.1. *Wellbore integrity issues*

1.1.1. *Conventional and unconventional reservoirs*

Conventional reservoirs typically involve porous sandstone, carbonate, and shaly sand formations, whereas unconventional reservoirs include low porosity/permeability shales and sandstones, bitumen and heavy oil sands, and coalbed methane resources. Conventional and unconventional reservoirs share many typical well integrity challenges.

The most common well integrity issues involve fluid migration through leakage pathways. Various safety barriers are employed in wells to minimize potential leakage. Cement is another main hydraulic barrier apart from the fluid column which provides isolation between wellbore and formation fluid. However, cement has certain limitations such as chemical degradation and strength reduction with time. In addition, mechanical barriers can provide significant isolation of reservoir formations, and completed zones, from each other thereby reducing potential fluid loss and influx. Such barriers improve wellbore integrity and facilitate the transition from well completion to production (Ceccarelli et al., 2009). However, the performance of mechanical barriers has certain limitations, such as property degradation causing their strength to be altered over time and dynamic conditions. The complexity of many unconventional reservoirs poses many well integrity challenges such as severe pressure and temperature conditions, the irregular chemical behavior of formation rocks. Therefore, more comprehensive tactics are required to facilitate high-quality well integrity in the unconventional reservoir.

Unconventional shale reservoirs often encounter specific problems due to unpredictable geological behavior during drilling operations. Oil-based mud (OBM) is the most common drilling fluid used in these reservoirs (Guo et al., 2012). The solubility of hydrocarbon gasses in OBM is considerable. This characteristic of OBM causes the evolution of dissolved gas when the mud reaches the bubble point pressure during circulation. This process provides a pathway for gas migration to shallower, uncased zones. This phenomenon can also result in sustained casing pressure in certain zones of a well during shale drilling operations. The robust casing can sustain the pressure differential between perforated zones and open hole, but in the case of an undetected leak, the pressure differential makes it difficult to set packers. Field observation in Marcellus shale indicates that sustained casing pressure mainly results from damaged cement rather than unset cement (McDaniel et al., 2014). Pipe whipping to casing during hydraulic fracturing is another common challenge in the unconventional reservoirs. This phenomenon potentially imparts additional force and stress to the cement resulting in cracks and the possible consequence of creating pathways for fluid migration (Elshehabi and Bilgesu, 2015). Such processes are constantly affecting the integrity of cement adjacent to the casing.

Gas-charged unconventional formations, particularly those at relatively shallow depths, such as coals, bitumen, and thin shale beds are classified as one of methane contamination sources in aquifers (King and King, 2013). One of the commonly used techniques to enhance the production of heavy oil and bitumen is enhanced thermal recovery. This technique reduces the viscosity, but it also induces thermal stresses which undermine the cement and cap rock integrity. Cement casing bond failure is prominent in these conditions due to thermal cyclic loading, casing buckling, and formation shear movements. Thermal cyclic loading typically results in extreme volumetric changes in the reservoir as a result of high temperature, cyclic dilation, fluid convection and contraction. Also, formation shear movements are mainly caused by in a reduction in friction due to heat transfer between the producing zones and thin surrounding impermeable beds (Xie and Liu, 2008).

Abnormally overpressure zones are created over geologic time scales due to the limited period for fluids to drain during the rapid burial of clay and shale formations in the sedimentary sequence. These zones can result in high annulus pressure. This high annulus pressure poses severe threat to well integrity pressure containment barriers. In addition, the cyclic stresses induced due to frequent change between production and injection accelerates the barrier degradation process and consequently leads to greater risk of casing deformation and collapse (Sultan, 2014). Also, a combination of sand production and reservoir compaction is another challenge to casing integrity. Sand production depletes the lateral support, while reservoir compaction adds axial compressive load. This loading perturbation results into an extra load on the casing and makes it susceptible to buckling. Thermal stimulation in the Canadian oil sands, reservoir compressibility coupled with substantial pressure depletion in the Gulf of Mexico deepwater operations, compaction in the highly porous weak reservoir in the North Sea and California during production poses a significant threat to casing integrity (Li et al., 2007).

Cavity completion incorporates repetitive injection of air or air/water mixtures into the wellbore. Following the injection stage, the surface valve is opened to reduce the pressure rapidly and suddenly, so that annulus is filled with the solid material, which is removed. This process is employed to potentially induce secondary fractures intersecting the natural fractures in the reservoir (Wang and Tremblay, 2001). However, the downside of cavity completion is its potentially adverse effect on cement and creation of connected leakage pathways between natural fractures and artificially induced fractures within the reservoir and surrounding formations.

1.1.2. *Geothermal and high-temperature water injection wells*

In geothermal wells, heat energy is derived from deep within the Earth by using artificially injected or formation fluids and circulating them through high-temperature zones. In contrast to typical oil and gas wells, such wells are typically exposed to much higher temperatures, in the range of 450 °F to 750 °F, which complicate the management of circulation fluids, casing design, and cement.

High downhole temperatures can significantly impact drilling fluid characteristics, leading to fluid flocculation, viscosity, and fluid flashing problems occurring during drilling operations (Carden et al., 1985). Also, high temperatures can escalate the corrosion of the metallic materials by increasing the concentration of chlorides in drilling fluids (Klapper and Stevens, 2013). Extreme temperature can cause cement casing debonding. Portland cement is brittle in nature and susceptible to cracking and shrinkage due to thermally induced stresses (Shadravan et al., 2015). In addition, cement strength retrogression and deterioration at elevated temperature pose vital concerns for the prolonged service life of this type of water well. Voids in cement behind casing can induce casing collapse during the well heat up phase, as the fluid behind the casing cannot expand, thus the generated pressure exceeding the collapse resistance of the strongest material. Most of the actual geothermal concepts require hydraulic fracture to enhance well productivity, and as the injected water is far colder than the wellbore, a massive failure of the casing and cement can be induced (Okech et al., 2015).

In high temperature environment, the water injection wells are more prone to well integrity issues. Specifically, in a subsea environment, the cold water is pumped into the well, which temperature depends on well length, water depth, injection line length, injection, and reservoir temperature. The high reservoir temperature and low injection fluid temperature results into the temperature cycle described as low temperature - high temperature - low temperature due to injection - shut in - injection. This temperature cycle induces differential stress between the casing and cement interface. The lack of shear bond strength at the interface can lead to debonding at this juncture and consequently result in the creation of fluid migration pathway along the casing (Therond et al., 2016). Degradation mechanisms of cement due to increased temperature, mechanical, and chemical influences also become more prominent and can result in a reduction of cement strength and/or permeability. Furthermore, these injection wells also consistently suffer corrosion and leakage issue in tubing due to highly aerated, and/or corrosive water injected (Al Khamis et al., 2014, Vignes et al., 2008). In these conditions, pitting corrosion is the common occurrence, which penetrates the metal in the localized domain very quickly and has the potential to form a leakage conduit for the fluid. Apart from the tubing, seal stem undergoes severe consequences of high temperature. The presence of high differential temperature between water injected and reservoir results in a significant movement of seal stem within polished bore receptacle and consequently demeans the sealing between the tubing and annulus. The presence of small particles aggravates the erosion issue in these wells, especially around the perforations. (Vignes et al., 2008).

1.1.3. *High-pressure and high-temperature (HPHT) wells*

High pressure and high temperature (HPHT) wells refer to the wells that have an expected wellhead shut-in pressure more than or equal to 690 bars (10,000 psi) and/or wells with a temperature higher than 150 °C (300 °F) (Junior et al., 2009). These prevailing high-pressure environments are conducive to fluid compression, which makes HPHT environment a suitable warehouse for oil and gas storage. However, HPHT wells pose high risks during drilling and completion operations (Yuan et al., 2013). During drilling, these wells exhibit the coupling effects of changes in stresses, pore pressure and temperature, which often lead to wellbore instability problems, such as a tight hole, stuck pipe, and differential sticking. The elevated temperature tends to decrease the equivalent circulating density (ECD) of the mud, due to thermal expansion, and consequently, narrows the margin for the fluid influx from the formation. This reduction in ECD will make the well more susceptible to kicks or collapse. Also, HPHT conditions reduce the thickening time of cement slurry, which accelerates the development of premature compressive strength and can promote cracking in post-set cement (Shadravan and Amani, 2012; Frittella et al., 2009). The rheological properties of cement, such as plastic viscosity and yield point, drops significantly which affects the wellbore pressure profile. In the absence of an accurate prediction of the wellbore's pressure profile, the casing and cement sheath may be unable to withstand the formation pressure potentially resulting in wellbore collapse (Shaughnessy and Helweg, 2002; Ravi et al., 2003). At temperatures above 450 °F, cement sets within a fortnight, but due to the formation of porous structure, Tobermorite exhibits strength retrogression (Gherardi et al., 2012).

HPHT wells exhibit higher pressure differentials inside the casing and formation over the production life than conventional wells (Stiles, 2006). Therefore, several other challenges such as casing eccentricity, channeling in cement, and cement voids are often associated with these environments (Guillot et al., 2008; Ferda and Al-Ghadban, 2004; Couturler et al., 1990). Ichim and Teodoriu (2016) have shown that casing eccentricity will increase the local stresses on cement increasing the chance to fail. Casing eccentricity results in non-uniform fluid velocity, which circumvents slow moving drilling fluid and leads to irregular cement work undermining the well integrity (Wilcox et al., 2016). Studies demonstrate that voids in cement and cement channeling have a higher impact on casing collapse resistance than casing eccentricity. Consequently, this behavior of casing affects the mechanical properties of the cement casing sheath behavior overall. The cement exhibits higher tensile failure probability in channeling condition, while higher compressive failure probability in situations involving casing eccentricity (Yuan et al., 2012).

1.1.4. *Enhanced oil recovery (EOR) and enhanced gas recovery (EGR)*

Enhanced oil and gas recovery operations are often employed, using a wide range of techniques to unlock the greater resource recovery from reservoirs. However, many of the techniques have severe potential consequences of demeaning wellbore integrity and causing formation damage due to the creation of pressure imbalance and associated chemical alteration in the prevailing conditions (Yuan et al., 2016). Widely employed, secondary recovery techniques for improving oil and gas recovery involve placement of water and gas injection wells in and around reservoirs. The injection wells commissioned in secondary recovery processes pose risks of migration of fluids to the surface, leakage, and subsidence or uplift and potentially resulting seismic tremors, because of the pressure differentials created (Yeck et al., 2016). After studying more than 50 wells in Santa Fe Springs oil field in California, Chillingar and Endres (2005) concluded that water flooding and hydraulic fracturing created avenues for the gas migration for more than 75% of wells which was attributed to reservoir pressurization. Besides pressurization, drilling stimulation, temperature variation, and natural tectonic activities exert detrimental effects on the casing cement-sheath integrity when wellbore sections are exposed to in excess of 8000 psi casing pressure (Shadravan et al., 2014). Another critical problem in such wells is long-term zonal isolation. This problem depends on several factors, such as the temperature increment during production, differential pressure adjustments due to fluid movements, cooling due to re-entry operations, changes in loading from the formation, and the extent of well stimulation operations (Hossain and Amro, 2010). Besides these problems, the sand production in water injection wells placed in poorly consolidated or highly porous formation also pose a threat to the integrity of the well. During the shutdown of these wells, pressure waves are generated. Sometimes due to sand production, the porosity of nearby formation increases which becomes susceptible to liquefaction and in-turn sand flows into the well. This sand can cover the perforated interval, and injectivity would be lost instantly (Santarelli et al., 2000; Yeow et al., 2004; Vaziri et al., 2007). In addition, the induced pressure on the in-situ system poses a threat to casing integrity.

CO_2 injection sometimes leads to the formation of a critical wet plume at the top of the reservoir, which impairs the cement due to its reaction with hydration agents in cement after prolonged exposure. Sulfate and Carboxyl ions, active during the hydration, improve the performance of cement in the initial phase, while prolonged exposure adversely impacts the cement's performance. Portland cement is mainly used in the CO_2 EOR wells. It is thermodynamically unstable in the aqueous CO_2-rich environment. The carbonic acid formed diffuses in the cement matrix, reacting with calcium hydroxide and calcium silicate, then migrating out of the matrix and subsequently increasing the cement's porosity and permeability, leading to loss of zonal isolation and gas migration. This cementing problem can also cause sustained casing pressure (Sweatman, 2006; Syed and Cutler, 2010). Apart from cement, the acidic environment also promotes erosion of casing and packers which can cause leakage through such intended integrity barriers (Durongwattana et al., 2011). In addition to these common phenomena, hydraulic shear bonding also reduces due to these chemical reactions. Reduced shear bonding increases the risk of creating pathways of leakage (Tarco and Asghari, 2010).

1.1.5. Deepwater drilling

Deepwater drilling introduces multiple additional risks and complex challenges compared to conventional onshore and shallow water drilling. For instance, deepwater environments typically contain gas hydrate zones at shallow depths below the seabed (Boswell et al., 2012). Typically gas hydrate zones are associated with over-pressured sand formations. Drilling through these zones can lead to exposure to high-pressure fluid flows that can compromise the structural integrity of the well, and consequently result in buckling and failure of the casing (Salehabadi et al., 2008). Ultimate consequences of this failure include wellbore collapse and/or leakage pathways created along the cement-casing interface. In addition, such failures can induce fluid flow from formations, which have the potential to result in the uncontrolled discharge of formation fluids and blow-outs (Flores et al., 2007; Kortekaas and Peuchen, 2008). In deepwater environments, this type of flows is difficult to predict and prevent (Smith et al., 2005). Heat development during cement hydration can also lead to hydrates destabilization and loss of well integrity.

Salt formations, encountered during deepwater drilling in many locations, poses several critical well integrity issues during drilling, completion, and throughout the well life cycle. Salt formation locally alters the stress fields and complicates the wellbore stability while drilling by imposing non-uniform forces, which can be tensile or compressible in nature. Salt is a relatively ductile and easily deformed rock formation in the subsurface, progressively moving and flowing over geologic time scales. Progressive deformation of salt formations post drilling increases the risks of the casing collapse during the production phase of wells drilled through it because the salt formation imparts varying lateral forces on the casing (Lao et al., 2012; Mackay et al., 2008). Also, the wellbore temperature profile impacts the behavior of salt formations. The change in temperature between the top and bottom of salt formations creates differential creep rates between the sections and consequently, creates enormous differential stresses (Mathur et al., 2010). This differential stress severely impacts the wellbore's cement and casing integrity, resulting in cracks in the set cement or fluid migration pathways created along cement-casing interface or formation-cement interface (Heidarian et al., 2014; Dusseault et al., 2004). Also, the effect of casing eccentricity caused by fast creeping stress results in a severe alteration in casing bearing stress in the salt zones over the life of the wells (Wang and Samuel, 2016). Recently, it has been found out that the salt formation poses non-uniform casing and cement load, which has been very little studied in the past.

1.1.6. Plugging and abandonment (P&A)

Plugging and abandonment operations are carried out to secure the integrity of the formations at the end of wells useful life. However, after an extended period, P&A'd wells can potentially suffer severe well integrity issues. The importance of plugging and abandonment of boreholes was not realized until after the 1890's (NPC, 2011). Prior to that date, several wells had been left unplugged, due to the absence of any regulation, resulting in sustained leakage to the surface. Prevailing regulations are intended to restore the functionality of cap rock and maintain the well integrity in perpetuity. The cement plugs have become mandatory at casing shoe level, across the oil, gas, and water bearing strata so that the risks of contamination and cross flow from P&A is avoided (NPC, 2011). Improper P&A operations result in orphaned or abandoned-unplugged wells in which the leakage pathways and natural seepage and cross flow of oil and gas can occur between the geological formation sand sometimes to the surface. P&A'd wells sometimes suffers from improper sealant placements, resulting in gas-cut cement, mud channels, and poor cement jobs.

Sequestration, underground gas storage and re-fracturing operations involving old isolated wells also show a potential for leaks in case of re-pressurization of the reservoir (King and Valencia, 2014; Warrick, 2015; Schultz et al., 2016). In the case of prolonged exposure to brine or gasses, such as CO_2 or H_2S, the properties of the casing, cement, and sealant severely deteriorate which can result in the establishment of leakage pathways for fluid to move to shallower unintended zones. Excessive pressure applied during P&A operation can lead to fractures in cement which can provide a way for fluid migration. Also, if mud is not properly removed during P &A operations from the well, a channel can be created through which the liquid or gas can pass through other zones (Lockyear et al., 1990). Water flooding in nearby wells can potentially exert a significant amount of unexpected, and unplanned for, pressure on already placed cement in plugged wells, and this pressure can negatively impact the cement creating fractures in it. In addition, plugged and abandoned wells can suffer from casing leaks, differential casing elongation, and seal failure over time due to dynamic changes in reservoir pressures (Loizzo and Sharma, 2008; Watson, 2013; Calosa et al., 2010).

Thermal induced stresses and pressure alteration during production stage exerts stress variation on cement sheath, but the progressive weakening effects induced by these stresses and mechanical loading persist after plugging of a well, and can contribute to extra stress on cement placed during P&A operations and increase the risk of breaches of well integrity (Thiercelin et al., 1998; Bosma et al., 1999; Mainguy et al., 2007).

1.1.7. CO_2 sequestration

CO_2 capture and sequestration (CCS) in depleted, or partially depleted, reservoirs provides some attractive opportunities for mitigating greenhouse-gas levels in the atmosphere, and in some cases can additional be combined with EOR activities. Levels of atmospheric CO_2 have increased to 400 ppm above the industrial level 280 ppm in recent years (NOAA, 2016). The success of CCS in sub-surface formations is highly dependent on the proper injection of supercritical CO_2 without leaking, in the short term or long term, from the target formations. The critical issues for its implementation are the cost of CO_2 capture, transportation, and the reliability of sealants for zonal isolation. Poor quality zonal isolation in the wellbores is likely to lead to pathways for buoyant CO_2-rich fluids to escape into unintended zones and make its way back to the surface. This leakage is primarily dependent on the cement permeability, its capillary properties, and the quality of bonding between casing and cement (Carey et al., 2007). CO_2 has a tendency to migrate through natural fractures and defects prevailing in the cement due to operational pressure and temperature fluctuations, shrinkage during hydration, mechanical shock from pipe movements, solid cuttings and drilling fluid residuals in the cement, and poor cementing jobs. Also, the prevailing reservoir formation temperature is likely to be higher in CCS operations than the borehole temperature. This temperature differential can induce fractures especially in depleted zones, and reactivate nearby faults. The fractures and faults act as migration pathways for fluid which compromises the well integrity (Fang et al., 2012).

As CO_2 in contact with water is acidic in nature, it has potential to alter the behavior of cement chemically. Experiments have been conducted to characterize the geochemical effects and mass transfer due to the flow of brine and supercritical CO_2 mixtures from Illite-rich shales of the Wolfcamp formation into cement at the reservoir rock and cement interface. The increased pH due to cement–brine reactions and subsequent cement-brine-CO_2 reactions immobilizes the silica present in the cement (Wigand et al., 2009). Hydration reactions of cement with supercritical CO_2 results in calcite precipitation at the surface of a longitudinal fracture induced in the cement. This alteration increases fracture opening and the cement permeability, but also simultaneously heals the fracture to a degree. The reactive transport model developed by Brunet et al. (2016) suggested that residence time is the main contributing factor for the evolution of fracture property such as self-healing and fracture opening behavior of cement fractures. Residence time refers to the ratio of initial fracture volume and flow rate in the fracture which accounts for the combined effect of fracture length and flow rate. The long residence time encourages better self-healing of fractured cement while the short residence time favors the fracture opening. However, in this model geomechanical effects are not accounted.

2. Mechanisms for failure of wellbore integrity

Loss of wellbore integrity is mainly a consequence of time-dependent formation leakage caused by fluid flow, solute transport, and chemical reactions, mechanical stresses, annulus quality and integrity, casing degradation, seal degradation, and defective abandonment operation over a wellbore's life cycle. These parameters can be divided into three high-level categories: - chemical; mechanical; and, physical. Ultimately, these aspects contribute to the evolution of leakage pathways along and through wells, and potentially assist the movement of fluid migration to the surface, as shown in Fig. 1.

Potential leakage pathways can be mainly attributed to casing corrosion and thread leakage, casing-cement interfaces, gas migration through the cement due to micro-annuli, void spaces and fractures, mud channels, fluid communication between the formations and the cement, gas migration through damaged cap rock, fluid communication between the cap rock and the wellbore cement. Acidic environment caused by the presence of CO_2, H_2S, and water promote corrosion of casing and dissolution of cement. Thread leaks are mainly reported as connection failures. 90% of the tubular failures recorded are associated with connection failures (Schwind et al., 2001). The poor placement or presence of cement and non-proper removal of filter cake leads to gaps at cement-casing and cement-formation interfaces. Poor quality of cement often leads to mud channels or existence of micro-annuli within the cement. Extra mechanical stresses due to pressure change over time, thermal stresses induced by fluid injection, chemical stresses due to the chemical reaction of downhole and injected fluids with cement, and steel result in fractures being formed. Also, the stresses translate to increased permeability of cement and eventually pathways for fluid to move into unintended zones.

In the following sub-sections, the evolution of leakage pathways associated with the wellbore-integrity-failure mechanisms is evaluated.

2.1. Chemical

Chemical reactions are the most common aspect of all well integrity issues prevailing in any conditions. Several chemical reactions continuously occur during various processes like the dissolution of cement components, corrosion of casing, and degradation of sealants. The basic compounds in cement consist of various oxides of calcium and silicon. In particular, calcium oxides react with CO_2. The kinetic rate of reactions between calcium compounds and CO_2 are very fast and governed by the rates of equilibrium of the associated reaction (Lesti et al., 2013). Hence, the behavior of cement depends significantly on the byproducts produced over the course of these reactions. Different types of cement are composed of the different molecular combinations of calcium, silicon, and oxygen. This variation in composition makes the type and extent of reactions experienced by each type of cement to some extent unique. However, some of the reactions are generic to all kinds of cement as suggested by equations (1)–(4). The escalating chemical degradation of cement due to its contact with CO_2 in an aqueous environment is referred to as “carbonation” (Strazisar et al., 2009). As denoted by equation (1), the CO_2 dissociates and forms carboxyl ions (HCO_3^-) in the presence of aqueous environment. Calcium oxide exists as calcium hydroxide in aqueous solutions, which is the prevalent compound in nature. With the formation of carboxyl ions, the medium becomes acidic due to the presence of H^+ ions. In the presence of HCO_3^-, the calcium hydroxide reacts and forms calcium carbonate, which in the presence of acidic media progressively dissociates (as denoted by equations (2)–(4)). This dissociation results into the ionic form of Ca which tends to remain in the solution phase and becomes the main reason for the deterioration of stable cement compounds. These four reactions divide the cement formation interface into five zones: the aqueous zone closest to the formation, the unaltered cement zone within the cement, and three transition zones (depicted in Fig. 2). The extent of the cement dissociation fronts propagates with time and degrades cement in the presence of persisting acidic conditions. Due to these reactions, the strength of cement increases and permeability and porosity reduce in the initial stage, but over time the effect reverses significantly, and the strength of the cement becomes much degraded (Rimmele et al., 2008; Kutchko et al., 2007; Duguid et al., 2011).

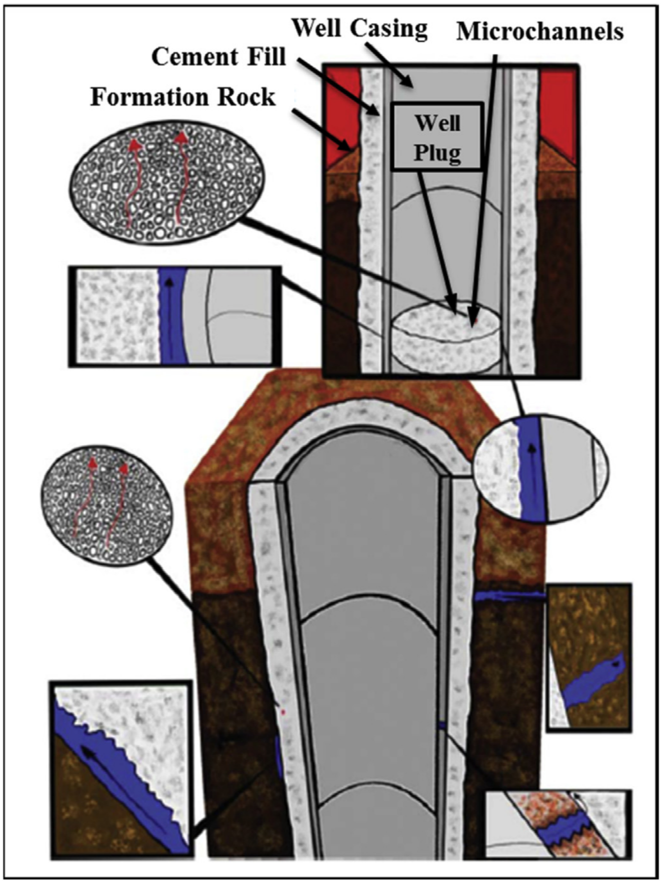

Fig. 1. Potential leakage pathways in wellbores (Nygaard et al., 2014).

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \tag{1}$$

$$Ca(OH)_2 + H^+ + HCO_3{}^- \leftrightarrow CaCO_3 + 2H_2O \tag{2}$$

$$C - S - H + H^+ + HCO_3{}^- \leftrightarrow CaCO_3 + SiO_2 \cdot H_2O \tag{3}$$

$$2H^+ + CaCO_3 \leftrightarrow Ca^{2+} + H_2CO_3 \tag{4}$$

Additionally, the cement matrix experiences chemical changes which can be characterized by a two-step process in the case of interactions with acidic fluids. Firstly, cement leaching occurs which initiates casing corrosion. Cement alteration commences with the occurrence of clogging due to the precipitation of calcite and progresses to pore volume reopening due to re-dissolution of minerals, in particular, calcium based minerals. Carbonation process initially creates weak acidic solutions rich in dissolved carbonate species, which lowers the pH and consequently dissolves many cement phases such as portlandite, silicates, sulfates, and aluminates. The extent and rate of these alterations in cement in the wellbore depends on initial composition, age, the range of downhole reactive conditions experienced. Table 1 summarizes the carbonation effect over time for different types of cement. Experimental investigations from various sources reveal that the carbonated depth predicted is almost twice as deep for fresh water conditions compared to brine-saturated, CO_2-rich downhole environments (Um et al., 2014; Barlet-Gouedard et al., 2006). Also, as the downhole conditions become more acidic, the penetration of CO_2 and the carbonation process becomes more extensive. Increasing temperature and supercritical CO_2 also enhance the carbonation process (Duguid et al., 2005; Kutchko et al., 2008).

The geochemical reactions at the cement formation interface tend to induce clogging at cement – base of caprock domains, primarily due to enhanced precipitation and increase porosity in the cement at the top of the caprock interface. In the vicinity of cement–caprock interface, porosity initially decreases and then increases (Viswanathan et al., 2008). Moreover, the presence of sulfur-related impurities in cement drives another set of redox and sulfidation reactions, which tend to promote the dissolution of iron and aluminum based minerals as shown in equations (5) and (6) (Zhang et al., 2014; Carroll et al., 2016). Iron has a high affinity for sulfide ions (HS^-) and, in the presence of aqueous environment, the iron dissolves as a ferrous ion (Fe^{2+}). Aluminum sulfate is added to cement to improve (reduce) its setting time, increase the drying shrinkage and improve its early strength; however, it also tends to dissolve very fast forming Al^{3+} ions in acidic fluid solutions as depicted by equation (6). This reaction weakens the late cement strength and reduces the fluidity of cement (Han et al., 2015).

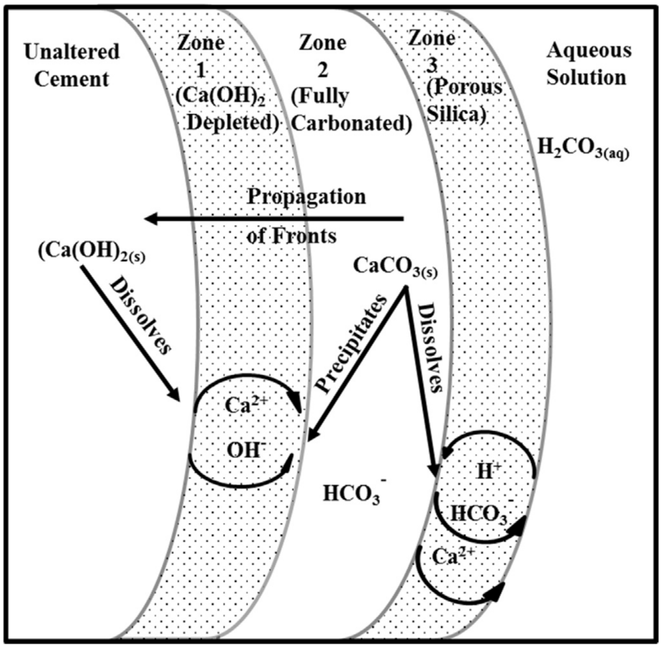

Fig. 2. Cement interaction with aqueous CO_2-Rich environments (After Kutchko et al., 2007).

$$8Fe(OH)_3(am) + HS^- \leftrightarrow 8Fe^{2+} + SO_4{}^{2-} + 5H_2O + 15OH^- \tag{5}$$

$$Ca_4Al_2O_6(SO_4) \cdot 12H_2O + 12H^+ \leftrightarrow 4Ca^{2+} + 2Al^{3+} + 18H_2O + SO_4{}^{2-} \tag{6}$$

In addition to cement behavior in the CO_2 environment, laboratory experiments have concluded that cement paste gets severely attacked by H_2S saturated brine, and its porosity increases by several folds when exposed to such conditions for an extended period (Brunet et al., 2013, 2016). The different impacts on the cement of exposure to an environment rich only in CO_2 and those rich in CO_2-H_2S combinations are illustrated in Fig. 3. In region I (Fig. 3), CO_2, H_2S, and SO_2 only interacts with water; whereas, region II is mainly dominated by the precipitation and dissolution of cement materials, while region III depicts unreacted cement. As the pH in the cement increases, the carbonation depth of penetration into the cement increases and more and more unreacted cement is altered. The presence of H_2S with CO_2 drives sulfidation reactions in addition to oxidation-reduction reactions. The carbonated zone exhibits the presence of secondary ettringite and pyrite on the outer face of carbonation zone. Iron ions become oxidized, and some form sulfate compounds. Sulfate ions react with aluminum compounds to form ettringite (Kutchko et al., 2011; Zhang et al., 2013; Jacquemet et al., 2008, 2012).

In highly acidic conditions, the cement mechanical strength tends to decrease at very rapid rates (Lecolier et al., 2010). The degradation mechanism involves the carbonation process, which depletes the calcium at the cement interface in a time-dependent manner, leading to a progressive reduction in its compressive strength. In highly acidic environments (pH of order 4–6), the hydronium ion (the aqueous cation H_3O^+, the type of oxonium ion produced by protonation of water) penetrates the matrix structure of the cement and dissolves ions like Fe^{3+} and Al^{3+} (Benge and Dew, 2006; Krilov et al., 2000). Overall, these mineralogical transformations in cement are induced because of the penetration of acidic fluids, which increase its porosity, leading to the formation of a vertical ascent route for gasses. Moreover, the pozzolanic additives, which are not active in CO_2-rich environments, suffer severe chemical attacks under reducing conditions (presence of SO_2 and H_2S) leading to the formation of pyrites, siderite, and ankerite (Zhang et al., 2013). However, several researchers have concluded that the carbonation reaction provides better insulation in the context of permeability decrease over time (Carroll et al., 2016). Table 2 summarizes the previous studies conducted on fractured cement and cement rock interfaces.

Furthermore, acidic environments, caused by the presence of H_2S and CO_2 are conducive to corrosion and embrittlement of casing. Casing is typically made of various grades of steel, which in the absence of corrosion resistive alloys, is susceptible to chemical alteration due to the presence of sulfates, chlorides, and acid stimulating agents. In addition, increased temperature and pressure act as a catalyst for the chemical reactions involved in steel casing corrosion, as shown by equation (7). Due to the presence of acidic environment and high affinity of iron, the redox reaction

Table 1
Summary of carbonation effects on different types of cement over time.

Cement Types	Predicted Carbonation Depth in 30 Years (mm)	Experimental Conditions	References
Ordinary Portland Cement, w/c 0.33	219	CO_2 saturated brine	Um et al., (2011)
Portland cement with antifoaming agent, dispersant, retarder, and water	113	CO_2 saturated fresh water	Barlet-Gouedard et al., (2006)
	133	Presence of supercritical CO_2	
Class H cement, w/c 0.38	2630	pH 2.4, 50 °C	Duguid et al., (2005)
	723	pH 3.7, 50 °C	
Class H cement, w/c 0.38	1.68	Presence of supercritical CO_2	Kutchko et al., (2008)
	1.0	CO_2 saturated brine	
Class H cement in sandstone cylinder, w/c 0.38	0.93	pH 3, 20 °C	Duguid (2008)
	0.40	pH 5, 20 °C	
	1.21	pH 3, 50 °C	

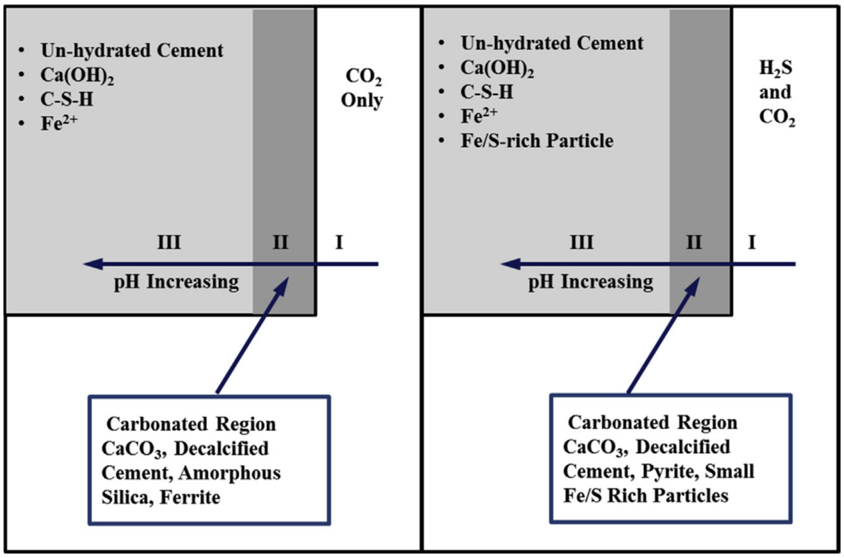

Fig. 3. Cement interactions with CO_2 and CO_2+H_2S/SO_2 environments.

Table 2
Summary of experiments on fractured cement and cement-rock interfaces.

Experimental Conditions	Effects	Reasons	References
High pressure and high temperature, supercritical CO_2, and brine fractured cement	Drop in permeability of cement	Relative permeability, carbonation	Bachu and Bennion (2009); Liteanu and Spiers (2011); Luquot et al., (2013)
Ambient temperature and pressure, fractured cement	Permeability drop	Carbonation	Huerta et al., (2015)
High pressure and high temperature, supercritical CO_2, cement rock interface	Permeability drop	Relative permeability, fines migration, cement deformation	Newell and Carey (2013), Walsh et al., (2013)

takes place at the surface of the casing, and it is exacerbated at sites of stress induced defects and mechanical damages. The byproduct of this redox reaction results in the formation of carbonate scales at the surface and eventually over time consumes the casing.

$$Fe + H^+ \rightarrow Fe^{2+} + H_2 \tag{7}$$

Hydrogen damage, galvanic, crevice, and biological corrosion are major contributors to steel casing corrosion and lead to the formation of iron scales on the metal surface (Zhang et al., 2014). Casing strings, tubing, and packers are vulnerable to corrosion, especially in the case of severe downhole corrosive environments, such as water alternating gas (WAG) injection for enhanced oil recovery. Finally, these chemical reactions lead to the creation of micro-annuli in the cement as well as at the casing-cement interface which act as downhole fluid migration pathways, as shown in Fig. 1 (Viswanathan et al., 2008).

In addition to the standard practices typically deployed in oil well cementing, several measures have been tested in attempts to improve the operational resistance to well integrity failures. These actions include the alteration of the material properties of cement and/or casing. Despite being deployed with the intention of improving well integrity, these alterations can sometimes suffer some negative consequences. Changing the properties of cement is often considered as a potential means of combating wellbore integrity-related problems. For example, lightweight cement slurries having high compressive strength, low fluid contents, and better-lost-circulation-control properties, provided a superior cement bond quality and worked effectively in the highly natural fractured reservoirs in Mesa Verde Formation of San Juan Basins (Posey and Purvis, 2004). Although lightweight cement exhibits these positive aspects in the controlled environments, in the field such lightweight cement formulas tend to be generated by adding foam to standard grades of cement. In the field, it is quite difficult to achieve a consistent mixing of foam and cement, and this can severely damage its performance. Apart from this operational problem, lightweight cement tends to suffer fast carbonation reactions (Zhang and Talman, 2014).

Another measure adopted over the time is the use Flexible Expandable Cement Systems (FECS). The operational intricacies of using FECS in Marcellus shale wells is based on the promotion of the bulk cement expansion during hydration (Williams et al., 2011). Sustained casing pressure has been reported to be a common occurrence in this formation, and it has been reported that 25% of wells still produce (leak) a considerable amount of annular gas to the surface. This technology coupled with good mud removal and proper cementing enabled rapid static gel strength (SGS) development, long-term zonal isolation, minimal sustained casing pressure over time, adequate compressive strength, low wait-on-cement (WOC) time, and improved elastic and expansion properties. FECS exhibited better chemical expansion compared to conventional Portland cement though showed a reduction in Young's modulus of the order of 40–70%, decreased compressive strength which was acceptable for the well conditions (Williams et al., 2011). One of the major limitation of this technique is its cost effectiveness. Apart from cost, this technology also has issues with its late compressive strength (De Andrade and Sangesland, 2016).

2.2. *Mechanical*

Existing and induced geomechanical stresses are a major challenge to well integrity. The changing stress regimes have been attributed to several parameters such as pressure differential created in the system during consistent production and injection, changes in temperature, impacts of tectonic activities, the eccentricity of the casing, existing fractures, leakage at casing shoes, and chemical alteration. The mechanism for initiation and propagation of mechanical degradation is due to radial cracking, plastic deformation in cement, de-bonding between cement and casing or formation, and voids in the cement (Yuan et al., 2013; Fleckenstein et al., 2001). The localized stresses impacting the cement, casing, and formation are dependent on their modulus properties. Casing has higher elastic modulus than the cement sheath, which is significantly influenced by cement composition and the cement curing process. The difference in the moduli causes the variation of stress along the radial and tangential directions. At the cement-casing interface, the change in moduli affects the casing collapse resistance by up to 10%. This stress distribution exhibits non-uniform behavior and is susceptible to fracture initiation and propagation in the cement at the interface. The combined effect of the variation of cement moduli and that in neighboring rock formations can promote the onset of radial fracture propagation and plastic deformation in cement (Gray et al., 2009). Additional thermal load alters the hoop stress significantly and mechanical loads imposed due to injection effect radial stresses. Thermal cooling initiate debonding and tensile failure due to increased contraction in the case of cement with high Poisson's ratio. Hoop stress is more sensitive to Poisson's ratio values than radial stresses. Higher Young's modulus typically leads to more radial fractures in the cement. (Jo and Gray, 2010; Shen and Beck, 2012; Nygaard et al., 2014; Nygaard and Lavoie, 2010).

Poor cementing, compaction, tubular loading and thermal stresses, surface roughness, casing eccentricity, wellbore inclination, and shrinkage in cement over time lead to de-bonding at interfaces which transform into channels for fluid migration (Yuan et al., 2013; Shahri et al., 2005; Nelson, 1990). Cement shrinkage can cause significant stress perturbation in the formation and casing and result in the creation of plastic zones in the cement and the formation and debonding at the cement/casing interface (Chenevert and Jin, 1989; Gray et al., 2009). Casing collapse resistance is highly dependent on the presence of voids and cement channels and can exhibit reduction up to 60%; while eccentricity exhibits only minor effects on casing collapse (Rodriguez et al., 2003; Berger et al., 2004). Such failures typically occur in the production and completion stage of a well's life cycle. At both completion and production stages, stresses consistently change with time due to dynamic loading, leakage, casing perforation, variable flow rates, leak-off tests. (Nygaard et al., 2014; Vignes and Aadnoy, 2010; Pickle and Swan, 2012; Lecampion et al., 2011). When CO_2 is injected in horizontal wells, the caprock above the well becomes tensile and becomes susceptible to tensile failure. In addition to tensile failure, the probability of shear failure also increases due to the spread of temperature profile in the well. As the time progresses and CO_2 is injected, the mobilized friction angle around the injection well also increases, which results in an increase of shear stress. Ultimately as the temperature difference between the injected fluid and the in-situ temperature increases, the risk of shear failure also increases (Gor et al., 2013). Also, thermal expansion of the formation increases the stress developed by pressure build up. This condition assists onset of fracture formation and, due to high-pressure conditions, fractures tend to propagate rapidly. However, low-permeability formations tend to limit the rate of fracture propagation. (Goodarzi et al., 2012; Buscheck et al., 2012).

Various analytical and numerical models have been developed to study these effects as summarized in Table 3. High wellhead casing pressure tends to lower the safety factor of the casing sheath experiencing a range of temperature and pressure conditions (Honglin et al., 2015). Thermo-mechanical simulations of CO_2 injection well show that the initial thermal expansion of casing causes a rapid increase in tangential and radial stresses at inner surfaces of both internal and external cement annuli. The inner surface of cement annulus has greater tangential strength than the outer surface, but casing eccentricity can add it up to the tensile strength limit. The centralizers are set to ensure the proper positioning of casings, but it can also induce local micro-annulus opening. In addition, the probability of occurrence of the opening of micro-annulus at cement and casing interfaces during CO_2 injection is low (Yvi et al., 2012). However, casing eccentricity can increase the stresses towards the tensile strength limits. Better low cycle fatigue behavior of cement having higher Poisson's ratio and lower young's modulus was observed in finite element analysis studies (Yuan et al., 2013). The opening and interconnection of cement fractures under mechanical loads increases fluid flow and permeability in the cement. However, commencement of cement fractures due to crystallization-induced pressure or dissolution of cement phases tends to decrease the fracture permeability (Jung et al., 2014). The cement rigidness, normal and shear strength at the interfaces and formation properties have major impacts on arresting fracture propagation according to numerical simulations conducted by Wang and Taleghani (2014). Also, the failure mechanism can in some cases be quantified using numerical models. Numerical studies suggest that cement integrity is severely compromised in cases of the high ratio of Young's moduli of cement and formation. Interface debonding mechanism at cement/casing interface dominates in a cooler environment. Casing offset or eccentricity tends to result in localized damage to cement-sheath (Andrade and Sangesland, 2016).

In addition, mechanical instabilities occurred during drilling operation poses a threat to wellbore integrity. The instabilities manifest in the form of compressive and tensile failure such as

Table 3
Summary of Analytical and Numerical Models related to Well Integrity and their Areas of Study.

Model Types	Summary	References
Analytical	Effect of wellhead casing pressure and downhole temperature	Honglin et al., 2015
Axisymmetric FEA	Effects of expansion of casing caused by internal burst pressures, study of radial cracking due to tensile and tangential stress induced in cement sheath	Fleckenstein et al., 2001
FEA	Effect of micro-annulus at casing cement interface on induced stress	Yvi et al., 2012
FEA	Effect of low and high cycle fatigue in high-pressure and high-temperature environment	Yuan et al., 2013
Cohesive Crack Model FEA	Study of fracture initiation and propagation, sensitivity analysis of cement rigidness, normal and shear strength at the interface	Wang and Taleghani (2014)
XMT imaging Coupled with CFD Model	Quantification of fracture evolution and change in permeability and behavior during carbon sequestration, hydraulic fracturing, and geothermal wells	Jung et al., 2014
FEA	Assessment of casing-cement-formation material properties, geometric parameters and characteristic well-loading events on cement sheath failure mechanisms	Andrade and Sangesland (2016)

*FEA: Finite Element Analysis; XMT: X-Ray Microtomography; CFD: Computational Fluid Dynamics.

breakouts and fracturing. The breakout imposes extra stresses on well components such as casing, casing shoe, and cement. The integrity of these elements is crucial in maintaining the overall integrity of the system in place (Ottesen and Kwakwa, 1991; Chen et al., 2002).

2.3. Physical

Failure of integrity barriers are not only attributed to chemical and mechanical alteration but are heavily dependent on in-situ, physical, factors. Physical factors are often related to methods of operational procedure and use of materials. Drilling is the basic operation, and filtered mud cakes are formed at the borehole interfaces during continuous circulation of drilling fluids. Particularly in deviated wells, the presence of mud cake is of significant and regular concern (Keller et al., 1987). Mud conditioning, pumping of chemical washes and spacers at turbulent flow velocity are usually adopted to remove as much of the filter cake as possible. However, non-removal of mud cake formed along the walls of the wellbore during drilling tends to result in the improper bonding of cement and casing. Besides drilling, completion is another operation essential for the preparation of wells for sustained production. Hydrochloric acid (HCl) and hydrofluoric acid (HF) are used in certain types of the reservoir to improve formation permeability by dissolution of acid-soluble minerals, which tends to enhance the flow of formation fluids by increasing the fluid conductivity in the reservoir during completion. However, the HCl and HF, or mixtures of those acids tend to be very destructive to cement. It damages the cement or creates channels by dissolving residual calcium carbonate along with the mud cake. A case study in Prudhoe Bay showed that 37% of primary cement jobs developed zonal-isolation problems and 73% of squeeze cement jobs broke down after HCl/HF treatment (Boyd et al., 2006).

Cementing is also an important part of wellbore operations. Cement usually takes time to set, and during this setting period, if gas invades it, channels can be created that consequently hamper the cement properties. Cement setting times are mainly influenced by slurry compositions and characteristics and its displacement efficiency during pumping. The slurry is the fluid form of cement before it sets. Slurry characteristics can be inflicted by various mechanisms such as gelation, shrinkage, separation of water from cement, and fluid loss. Gelation and shrinkage of cement dictate certain properties of hardened cement such as permeability, porosity, and strength. These properties directly affect the integrity of a well by providing resistance to fluid flow and in-situ loading. Separation of water from cement and fluid loss reduces the in-situ hydrostatic pressure and potentially escalates gas invasion of the cement (Bonett and Pafitis, 1996). The gas invasion has a tendency to create micro-annuli, small fractures, weaken the cement strength, which, over time, tend to amplify large scale gas migration. Another influence on the effectiveness of casing cement jobs is the placement of casing centralizers. Improper placement of casing centralizers ultimately creates induced stresses in the cement, which enhances fracture formation within the cement (Nelson and Guillot, 2006).

Apart from drilling and completion, successful abandonment operations prevent the cross-flow of formation fluids between different strata after the end of life cycle of a well. Key factors in abandonment operations are well type, abandonment methods, and materials used. Wells converted to acid gas injection wells have shown higher susceptibility to integrity compromise than the wells converted to CO_2 injection wells after abandonment. Analysis of risk during abandonment reveal that the execution quality and the kind of the well involved after the abandonment operation has the greatest impact on the quality of the materials used in the abandonment process (Bachu and Watson, 2009). The effective stress change in cap rock is either governed by the pressure increase during abandonment or by compressive stress induced during abandonment. These stresses are based on the sealing material properties. The thermal expansion coefficient of the plugging material generates extra tensile or compressive stresses at the interface depending on the coefficient relative to the formation. The inept material can severely pose a threat to the well integrity leading to plugging failure or micro-annuli formation (Mainguy et al., 2007). Besides these issues, sandy condition in combination with corrosive environment exacerbates the damage to the casing which adds to the integrity barrier threat. The effect of sand on corrosion under High Pressure High Temperature (HPHT) conditions depend on the relative velocity of the erosive corrosive fluid (Dai et al., 2012).

3. Evaluation of wellbore integrity

Wellbore integrity can be evaluated at several levels. It commences with laboratory experiments on suitable materials, evaluation, and implementation of consistent operating procedures, and continues with monitoring systems over the life cycle of the well, and following well abandonment. Several methods are now applied to identify and quantify potential leaks or damage to the well integrity barriers. Experiments can be conducted to quantify the chemical and mechanical behavior of materials such as cement, casing, tubing and packers, with typical experimental findings discussed in previous sections. Analytical and numerical modeling can be conducted to provide more insight into the effects of different parameters, as elaborated in the preceding sections. In order to enhance operational performance with respect to sustainable well integrity and to minimize the risks of adverse consequences of failures of well integrity barriers, government and industrial guidelines and best practice are outlined in different sets of published standards, such as API STD 65−2 and NORSOK D-010, and their adherence is now monitored and enforced in many jurisdictions. However, these standards are upgraded from time to time to address technological and materials developments and consideration of research findings relating specific harsh environments not previously encountered. For instance, Li et al. (2016) demonstrated that relying on static gel strength to evaluate the potential of gas migration is imperfect, though the API STD 65−2 standard suggests the shortening of transition time to minimize the risk of gas migration.

Apart from the quantification and quality analysis of materials and procedures, statistical analysis of historical wellbore performance can help to evaluate the effectiveness of certain aspects for wellbore integrity. Statistical analysis of reliable databases tends to boost the efficiency, interpretation of and confidence in the results of experimental tests and numerical models. Moreover, analysis of such information also assists in providing some insight into the results in the cases where standards are unavailable or provide inconclusive guidance. In the petroleum industry, there is a lack of standard guidelines for testing procedures for the tensile strength of material, in contrast, to direct tensile strength tests using dog bone and the Brazilian test as applied in the construction industry (ACI 207, 1989; Houghton, 1976). Such cases can be dealt with using a statistical approach. Since there is a statistical variation of cement's tensile strength, a probabilistic approach is often most suitable to evaluate its risk of failure under certain conditions (Ashby and Jones, 1998). The Weibull statistical approach can also be used to capture the effects of inorganic fibers as additives to Class G cement for the estimation of original tensile strength (Quercia et al., 2016).

Statistical modeling is not only limited to experimental and numerical simulation interpretation but can also be extended to risk modeling efforts to quantify the effectiveness of well integrity barriers. Commonly used quantitative and qualitative risk modeling methods include fault tree, bow-tie, failure mode and effect analysis, event tree, if-else, Monte Carlo simulation and Bayesian network analysis. The mapping of bow tie analysis to Bayesian networks can be used to model the time-dependent nature of integrity issues. Drilling system designs, logging tool designs, cement slurry designs, casing running methods, swab and surge pressures are major elements of well integrity models that can benefit from such analysis (Oladipo and Houlbrook, 2016). Risk assessment studies using Monte-Carlo simulation can stochastically address the uncertainty through time-dependent risk analysis of well integrity involving probabilistic distributions of input uncertainties (Soeder et al., 2014). Probabilistic distributions analyzed by Monte Carlo Simulation to address the uncertainties of the sustained casing pressure calculation concept can be helpful to estimate the potential wellbore leakage-pathway conductivity, which in turn can be useful in quantifying the unknown wellbore permeability. However, several assumptions are needed for this approach, such as the similarity between natural fractures and vertically aligned channels penetrating through the cement, and comparable characteristics for the gaps between steel and cement same and the gaps between cement and formation (Tao et al., 2014). The validity of such assumptions is yet to be thoroughly verified.

Besides insights into the behavior of the material and system incorporated to ensure intact wellbore integrity, continuous monitoring and evaluation techniques are required during production and after operations cease and a well has been plugged and abandoned. Periodic wireline logging is one of the common techniques widely used to monitor the performance of wellbores. A range of wireline tools, such as cement bond log (CBL), variable density log (VDL), ultrasonic imager (USI), radioactive tracer survey (RATS), standard annulus pressure test (SAPT), and ultrasonic casing imager (UCI) are commonly employed to assess the prevailing conditions based on specific downhole requirement (Froelich et al., 1982; Griston, 1990; Crow et al., 2010; Alaref et al., 2016). In addition, some other methods such as the noise log (the spectral noise logging (SNL) is an acoustic noise measuring technique that records acoustic noise generated by fluid or gas flow through the reservoir or leaks in downhole well components), production logging, and, temperature log (TL) are capable of providing insight into dynamic well conditions (Jalan et al., 2013). Table 4 shows the uses and limitations of different logs.

CBL and VDL are used to determine the isolation between reservoir units by evaluating the cement quality behind casing. CBL measures the loss of acoustic energy which is proportional to the fraction of the casing perimeter covered by cement. The ratio of CBL/VDL gives an average volumetric assessment of cement in the casing-to-formation annular space, while ultrasonic logs provide a high-resolution scan in real-time about the condition of the casing to cement bond and casing quality (Van Kuijk et al., 2005). Moreover, these logs are capable of identifying the presence of gas and liquid channels in cement, and tubular damage, hence providing insight into the zonal isolation status. The inference is based on the difference in thresholds of acoustic impedance between different materials. However, the ultrasonic log recordings also have some limitations such as they are prone to errors in certain circumstances such as gas contamination in cement. The acoustic impedance of gas contaminated cement varies as per the amount of contaminated gas or a mixed gas of cement. Ultrasonic log usually doesn't offer a contrast to distinguish between contaminated cement from gas or fluid acoustic impedance (Coelho de Souza Padilha and da Silva Araujo, 1997; Johns et al., 2011). In addition, the ultrasonic log provides post-operational assessments without directly measuring the strength. Several factors such as micro-annuli, eccentricity, casing dimension and coating, fast formations, lightweight cement, cement setting time, the permeability of the formation, and viscosity and compressibility of saturated fluid affect the quality of data and its interpretation (Bybee, 2007). Micro annuli filled with liquid caused by temperature, mud cake deposits, pipe coatings, and constraining forces can produce anomalous results in CBL/VDL data. Eccentric casing and erratic movement of the tool can also have negative quality impacts on logging data recorded. Lightweight cement slurries lead to the very low contrast between liquid and hardened cement's acoustic properties. Cement setting time dictates the interpretation of well-log data. Several factors such as contamination, in-situ temperature, and pressure, material composition impact the setting time. Running the tool on the proper settings to reflect the setting status of the cement is preferable to obtain reliable log data, but this is often not the case at operational sites (Contraires et al., 2009).

Cement jobs in gas injection wells can be very complicated, and require careful interpretation of well log data such as CBL, corrosion log, cased hole-neutron log in combination with cement evaluation test (CET). Neglecting CET data indications can lead to failures of cement jobs (Al-Ashhab et al., 2006; Frisch et al., 2005). The electromagnetic technique, known as the corrosion log, involves a short, high-energy electromagnetic pulse from a transmitter coil which induces a charge to the surrounding concentric pipes. Following the excitation pulse, a receiver coil measures the collapsing eddy currents. This decay involves a complex signature characteristic of the pipe geometry and its electromagnetic properties. An inversion technique is used to derive prevailing casing thicknesses, which provides insight about the corrosion or defects affecting the casing or tubular since its installation. The evaluation of surface casing behind the cemented production string is possible

Table 4
Uses and limitations of different wellbore logs for determining well integrity.

Methods	Uses	Limitations
CBL/VDL	Predicts well-bonded cement, debonding at wet casing and formation	No prediction of mud channels, vertical cracks, gas chimney, and radial variation in cement
Ultra-Sonic Imaging Log	Shows well-bonded cement, mud channel in good cement, gas chimney, and debonding at wet casing	Unable to figure out mud channels in weak cement, vertical cracks, debonding at dry casing and formation, and radial variation in cement
Isolation Scanner	Capable of showing good cement, mud channels, gas chimneys, thick vertical cracks, debonding at wet casing and formation, and cement radial variation	No prediction on thin vertical cracks and debonding at dry casing
Radioactive Tracer Survey	Used to detects leaks	Incapable of predicting the quality of cement or casing
Temperature Log/Acoustic Log	Detects anomalies due to leak	No insight on cement
Corrosion Log	Can predict the corrosion in the casing, tubular, and even casing after the cemented zone such as surface casing.	No insight on cement
SAPT/VIT	Assessment of the hydraulic properties of the cemented annulus zone under study	No evaluation of cement and casing quality

using this technique (Brill et al., 2011; Zhang et al., 2013). The cased-hole-neutron log can be used to provide insight about the density of the cement. This log is useful in detecting anomalies in the cement placed in a wellbore (Harness and Frank, 1996). The standard production logging tool (PLT) reveals fluid flow contributions from different formations and, in particular, it is useful in the identification of water contributing layers, which can help to understand the potential for integrity barrier failures (Jalan et al., 2013).

Apart from logging tools, certain tests are conducted on site to evaluate the intactness of the integrity barrier. Well annular barrier evaluation by SAPT and vacuum insulated tubing (VIT) assesses the seal integrity (Frisch et al., 2015). The SAPT test involves the application of pressure on a closed system, such as the annulus between casing and cement, and detects potential leaks via pressure depletion once the applied pressure is removed. The main limitation of SAPT is its inability to detect faulty cement jobs and/or leakages through the casing shoe. However, VIT is based on perforating two separated downhole intervals and isolating them from each other using casing packers (Nordbotten et al., 2005). In this test, the downhole pressure is fixed to some degree in the upper zone, and pressure is monitored in the lower zone. This pressure monitoring gives an indication about the fluid migration overall, but cannot specifically identify that recorded flow is occurring along microchannels (Gasda et al., 2008). In the RATS technique, radioactive tracers are introduced into the fluid, and then a radioactive detector is used to detect the tracer elements in the system (Griston, 1990). Leaks produce anomalies in the sensor and generate noise at different frequencies. Leaks, if they are present, also disturbs the temperature profile of the well. The TL provides the temperature gradient of a well in relation to the geothermal gradient during shut-in conditions. The noise log acquires acoustic data at low and high frequencies. Noise and temperature logs are frequently used together to provide insight into the fluid movements inside the annulus originating from the formations (i.e., “leaks”) based on the reference log data obtained before the initiation of production (Alaref et al., 2016).

4. Conclusions

In order to maintain safe wellbore integrity over a well's life cycle (drilling through to post-abandonment), chemical, mechanical and physical factors impacting integrity need to be thoroughly assessed and periodically monitored.

Chemical impact assessment such as cement property evaluation, corrosion in cement is required to minimize the degradation in cement and casing properties across the possible spectrum of wellbore environments. Awareness of acid gas concentrations is essential as these tend to aggressively degrade cement, requiring more rigorous monitoring of the cement's condition and characteristic properties over time to maintain safe operations.

Casing is susceptible to corrosive environments, which again are more significant in the presence of acid gasses and also require careful evaluation and monitoring of casing conditions over time in order to verify that it continues to provide an integrity barrier.

The mechanical integrity of wellbore systems is dependent on the various prevailing downhole conditions and is affected by temperature, pressure, stresses, and material properties. These properties, in turn, have an impact on the strength and chemical resistance of mechanical integrity barriers. The extent of impact depends on the specific type of in-situ environment and/or operation. Hence, a comprehensive procedure for execution of well construction is required to ensure the impeccable wellbore which can improve the sustainability of integrity over the life cycle and beyond.

Evaluation and regular periodic monitoring techniques are necessary to provide insight into the evolution of wellbore integrity over time. Well integrity evaluation techniques are based on experiments, logging, analytical and numerical modeling, statistical modeling, and risk analysis. Monitoring of the operational system including barrier elements, production and completion systems provides the assessment of the well integrity over time in order to develop a sustainable system. The evaluation of dynamic in-situ conditions such as pressure and temperature variation can improve designing a suitable system to cater with the anomalies.

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Nomenclature

CO_2	Carbon-di-Oxide
H_2S	Hydrogen Sulfide
HCO_3^-	Hydrogen Carbonate Ion
Ca	Calcium
H^+	Hydronium Ion
H_2O	Water
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonate
SiO_2	Silicon-di-Oxide
H_2CO_3	Carbonic Acid
$Fe(OH)_3$	Ferric Hydroxide

HS^-	Hydrogen Sulphide Ion
SO_4^{2-}	Sulfate Ion
OH	Hydroxide Ion
$Ca_4Al_2O_6(SO)_4 \cdot 12H_2O$	Hydrated Calcium Aluminum Sulfate
Ca^{2+}	Calcium Ion
Al^{3+}	Aluminum Ion
SO_2	Sulfur-di-Oxide
HCl	Hydrochloric Acid
HF	Hydrofluoric Acid

Abbreviations

BOP	Blow-out Preventer
OBM	Oil Based Mud
HPHT	High Temperature and High Pressure
ECD	Equivalent Circulating Density
EOR	Enhanced Oil Recovery
EGR	Enhanced Gas Recovery
P&A	Plugging and Abandonment
P&A'd	Plugged and Abandoned
CCS	CO_2 Capture and Sequestration
w/c	Water Cement Ratio
FECS	Flexible Expandable Cement System
SGS	Static Gel Strength
FEA	Finite Element Analysis
XMT	X-Ray Micro Tomography
CFD	Computational Fluid Dynamics
CBL	Cement Bond Log
VDL	Variable Density Log
USI	Ultrasonic Imager
RATS	Radioactive Tracer Survey
SAPT	Standard Annulus Pressure Test
UCI	Ultrasonic Casing Imager
TL	Temperature Log
CET	Cement Evaluation Test
PLT	Production Logging Test
VIT	Vacuum Insulated Tubing

References

ACI 207, 1989. Mass Concrete, ACI Manual of Concrete Practice. Part 1-207-4R, Farmington Hill, USA.

Al-Ashhab, J.K., Yar Khan, N.S., Boyd, D., 2006, January 1. Restoring well integrity in a critical gas pilot injection well. Soc. Pet. Eng. http://dx.doi.org/10.2118/101398-MS.

Alaref, O., Rourke, M., Khabibullin, M., Yakupov, A., 2016, March 22. Comprehensive well integrity solutions in challenging environments using latest technology innovations. Offshore Technol. Conf. http://dx.doi.org/10.4043/26560-MS.

Al Khamis, M.N., Al Khalewi, F.T., Al Hanabi, M., Al Yateem, K., Al Qatari, A., Al Muailu, H., 2014, January 19. A comprehensive approach of well integrity surveillance. Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-17465-MS.

Andrade, J.D., Sangesland, S., 2016, August 1. Cement sheath failure mechanisms: numerical estimates to design for long-term well integrity. J. Pet. Sci. Eng. ISSN 0920–4105 http://dx.doi.org/10.1016/j.petrol.2016.08.032.

API STD 65–2, 2010. Standard for Isolating Potential Flow Zones during Well Construction, second ed. API, Washington, DC.

Ashby, M.F., Jones, D.R.H., 1998. Chapter 20-special topic: cements and concretes. In: International Series on Materials Science and Technology. Butterworth-Heinemann, Oxford, pp. 207–215. ISSN 0362479X, Engineering Materials (Second Edition), ISBN 9780080545653. http://dx.doi.org/10.1016/B978-0-08-054565-3.50023-X.

Bachu, S., Bennion, D.B., 2009. Experimental assessment of brine and/or CO_2 leakage through well cements at reservoir conditions. Int. J. Greenh. Gas Control 3 (July (4)), 494–501. http://dx.doi.org/10.1016/j.ijggc.200811.002.

Bachu, S., Watson, T.L., 2009. Review of failures for wells used for CO_2 and acid gas injection in Alberta, Canada. Energy Procedia 1 (1, 2009), 3531–3537. ISSN 1876-6102. http://dx.doi.org/10.1016/j.egypro.2009.02.146.

Barlet-Gouedard, V., Rimmele, G., Goffe, B., Porcherie, O., 2006, February 21–23. Mitigation strategies for the risk of CO_2 migration through wellbores. In: IADC/SPE98924. IADC/SPE Drilling Conference, Miami, FL, USA.

Benge, G., Dew, E.G., 2006, September 1. Meeting the challenges in completion liner design and execution for two high rate acid gas injection wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/91861-PA.

Berger, A., Fleckenstein, W.W., Eustes, A.W., Thonhauser, G., 2004, January 1. Effect of eccentricity, voids, cement channels, and pore pressure decline on collapse resistance of casing. Soc. Pet. Eng. http://dx.doi.org/10.2118/90045-MS.

Bonett, A., Pafitis, D., Spring 1996. Getting to the Root of Gas Migration, Oilfield Review.

Bosma, M., Ravi, K., van Driel, W., Schreppers, G.J., 1999, January 1. Design approach to sealant selection for the life of the well. Soc. Pet. Eng. http://dx.doi.org/10.2118/56536-MS.

Boswell, R., Collett, T., Frye, M., Shedd, W., McConnell, D., Shelander, D., 2012. Subsurface gas hydrates in the northern Gulf of Mexico. J. Mar. Pet. Geol. 34, 4–30.

Boyd, D.A., Al-Kubti, S.A.-R., Khedr, O.H., Khan, N., Al-Nayadi, K.G., Degouy, D., Al-Kindi, Z.L., 2006, January 1. Reliability of cement bond log interpretations compared to physical communication tests between formations. Soc. Pet. Eng. http://dx.doi.org/10.2118/101420-MS.

Brill, T.M., Demichel, C., Nichols, E.A., Zapata Bermudez, F., 2011, January 1. Electromagnetic casing inspection tool for corrosion evaluation. Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-14865-MS.

Brunet, J.-P.L., Li, L., Karpyn, Z.T., Kutchko, B.G., Strazisar, B., Bromhal, G., 2013. Dynamic evolution of cement composition and transport properties under conditions relevant to geological carbon sequestration. Energy Fuels 27, 4208–4220. http://dx.doi.org/10.1021/ef302023v.

Brunet, J.P.L., Li, L., Karpyn, Z.T., Huerta, N.J., 2016. Cement fracture opening or self-sealing: critical residence time as a unifying parameter for cement-CO_2-brine interactions. Int. J. Greenh. Gas Control. http://dx.doi.org/10.1016/j.ijggc.2016.01.024.

Buscheck, T.A., Sun, Y., Chen, M., Hao, Y., Wolery, T.J., Bourcier, W.L., Court, B., Celia, M.A., Friedmann, S.J., Aines, R.D., 2012. Active CO_2 reservoir management for carbon storage: analysis of operational strategies to relieve pressure buildup and improve injectivity. Int. J. Greenh. Gas Control 6, 230–245.

Bybee, K., 2007, February 1. Cement-bond-log interpretation reliability. Soc. Pet. Eng. http://dx.doi.org/10.2118/0207-0064-JPT.

Calosa, W.J., Sadarta, B., Ronaldi, R., 2010, January 1. Well integrity issues in Malacca Strait contract area. Soc. Pet. Eng. http://dx.doi.org/10.2118/129083-MS.

Carden, R.S., Nicholson, R.W., Pettitt, R.A., Rowley, J.C., 1985, May 1. Unique aspects of drilling and completing hot, dry rock geothermal wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/11373-PA.

Carey, J.W., Wigand, M., Chipera, S., WoldeGabriel, G., Pawar, R., Lichtner, P.C., Wehner, S., Raines, M., Guthrie, G.D., 2007. Analysis and performance of oil well cement with 30 Years of CO_2 exposure from the SACROC field, west Texas, USA. Int. J. Greenh. Gas Control 1, 75–85.

Carroll, S., Carey, J.W., Dzombak, D., Huerta, N.J., Li, L., Richard, T., Um, W., Walsh, S.D.C., Zhang, L., 2016, June. Review: role of chemistry, mechanics, and transport on well integrity in CO_2 storage environments. Int. J. Greenh. Gas Control 49, 149–160. ISSN 1750-5836. http://dx.doi.org/10.1016/j.ijggc.2016.01.010.

Ceccarelli, T.U., Albino, E.H., Watson, G.M., Deffieux, D., 2009, January 1. Deepwater completion designs: a review of current best practices. Soc. Pet. Eng. http://dx.doi.org/10.2118/122518-MS.

Chen, X., Tan, C.P., Haberfield, C.M., 2002, December 1. A comprehensive, practical approach for wellbore instability management. Soc. Pet. Eng. http://dx.doi.org/10.2118/80146-PA.

Chenevert, M.E., Jin, L., 1989, January 1. Model for predicting wellbore pressures in cement columns. Soc. Pet. Eng. http://dx.doi.org/10.2118/SPE-19521-MS.

Chillingar, G., Endres, B., 2005. Environmental hazards posed by the Los Angeles Basin urban oilfields: a historical perspective of lessons learned. Environ. Geol. 47, 302–317.

Coelho de Souza Padilha, S.T., da Silva Araujo, R.G., 1997, January 1. New approach on cement evaluation for oil and gas reservoirs using ultrasonic images. Soc. Pet. Eng. http://dx.doi.org/10.2118/38981-MS.

Contraires, S., Loizzo, M., Lecampion, B., Sharma, S., 2009, February. Long-term wellbore integrity in Otway: integrating ultrasonic logs, cement petrophysics, and mechanical analysis. Energy Procedia 1 (1), 3545–3552. ISSN 1876-6102. http://dx.doi.org/10.1016/j.egypro.2009.02.148.

Couturler, M., Guillot, D., Hendriks, H., Callet, F., 1990, January 1. Design rules and associated spacer properties for optimal mud removal in eccentric annuli. Soc. Pet. Eng. http://dx.doi.org/10.2118/21594-MS.

Crow, W., Carey, J.W., Gasda, S., Williams, D.B., Celia, M., 2010, March. Wellbore integrity analysis of a natural CO_2 producer. Int. J. Greenh. Gas Control 4 (2), 186–197. ISSN 1750-5836. http://dx.doi.org/10.1016/j.ijggc.2009.10.010.

Dai, J., Liu, W., Wu, Y.L., Lin, X.Q., Fan, X., Yang, M., Lu, M.X., 2012. Effect of sand in fluids at different velocities on CO_2 erosion corrosion behavior of X70 steel under high temperature and high pressure. In: Corrosion 2012. NACE. Paper no. 1241.

Davies, R.J., Almond, S., Ward, R.S., Jackson, R.B., Adams, C., Worrall, F., Herringshaw, L.G., Gluyas, J.G., Whitehead, M.A., 2014, September. Oil and gas wells and their integrity: implications for shale and unconventional resource exploitation. Mar. Pet. Geol. 56, 239–254. ISSN 0264-8172. http://dx.doi.org/10.1016/j.marpetgeo.2014.03.001.

De Andrade, Jesus, Sangesland, Sigbjørn, November 2016. Cement sheath failure mechanisms: numerical estimates to design for long-term well integrity. J. Pet. Sci. Eng. ISSN: 0920-4105 147, 682–698. https://doi.org/10.1016/j.petrol.2016.08.032.

Duguid, A., Radonjic, M., Scherer, G., 2005, May 2–5. Degradation of Well Cements

Exposed to Carbonated Brine. Presented at the 4th Annual Conference on Carbon Capture and Sequestration DOE/NETL, Alexandria, Virginia, USA.

Duguid, A., 2008, January 1. The effect of carbonic acid on well cements as identified through lab and field studies. Soc. Pet. Eng. http://dx.doi.org/10.2118/119504-MS.

Duguid, A., Radonjic, M., Scherer, G.W., 2011. Degradation of cement at the reservoir/cement interface from exposure to carbonated brine. Int. J. Greenh. Gas Control 5, 1413–1428.

Durongwattana, N., Toempromraj, W., Jedsadawaranon, P., Sompopsart, S., 2011, January 1. Well integrity remediation - a challenge for swellable technology. Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-15205-MS.

Dusseault, M.B., Maury, V., Sanfilippo, F., Santarelli, F.J., 2004, January 1. Drilling Around Salt: Risks, Stresses, and Uncertainties. American Rock Mechanics Association. ARMA-04-647. https://www.onepetro.org/conference-paper/ARMA-04-647.

Elshehabi, T., Bilgesu, I., 2015, October 13. Impact of drilling with oil based mud on well control in horizontal shale gas wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/177294-MS.

Fang, Z., Khaksar, A., Gibbons, K., 2012, September 1. Geomechanical risk assessments for CO_2 sequestration in depleted hydrocarbon sandstone reservoirs. Soc. Pet. Eng. http://dx.doi.org/10.2118/133994-PA.

Ferda, A., Al-Ghadban, H.H., 2004, January 1. Simulation investigation of casing eccentricity estimation for different inclination angles and tensile forces using finite element method. Soc. Pet. Eng. http://dx.doi.org/10.2118/91811-MS.

Fleckenstein, W.W., Eustes, A.W., Miller, M.G., 2001, June 1. Burst-induced stresses in cemented wellbores. Soc. Pet. Eng. http://dx.doi.org/10.2118/72059-PA.

Flores, W., Garner, J., Scarborough, C., 2007. Deepwater blowout, a case history: shallow gas hazards hide in the weeds. In: Proceedings IADC. SPE/IADC 105914-PA.

Frisch, G.J., Fox, P.E., Hunt, D.A., Kaspereit, D., 2005, January 1. Advances in cement evaluation tools and processing methods allow improved interpretation of complex cements. Soc. Pet. Eng. http://dx.doi.org/10.2118/97186-MS.

Frisch, G., Fox, P., Hospedales, D., Lutchman, K., 2015, September 28. Using radial bond segmented waveforms to evaluate cement sheath at varying depths of investigation. Soc. Pet. Eng. http://dx.doi.org/10.2118/174829-MS.

Frittella, F., Babbo, M., Muffo, A.I., 2009, January 1. Best practices and lesson learned from 15 Years of experience of cementing HPHT wells in Italy. Soc. Pet. Eng. http://dx.doi.org/10.2118/125175-MS.

Froelich, B., Dumont, A., Pittman, D., Seeman, B., 1982, August 1. Cement evaluation tool: a new approach to cement evaluation. Soc. Pet. Eng. http://dx.doi.org/10.2118/10207-PA.

Gasda, S.E., Nordbotten, J.M., Celia, M.A., 2008. Determining effective wellbore permeability from a field pressure test: a numerical analysis of detection limits. Environ. Geol. 54, 1207–1215.

Gherardi, F., Audigane, P., Gaucher, E.C., 2012, February 14. Predicting long-term geochemical alteration of wellbore cement in a generic geological CO_2 confinement site: tackling a difficult reactive transport modeling challenge. J. Hydrol. 420–421, 340–359. ISSN 0022-1694. http://dx.doi.org/10.1016/j.jhydrol.2011.12.026.

Goodarzi, S., Settari, A., Keith, D., 2012. Geomechanical modeling for CO_2 storage in Nisku Aquifer in Wabamun Lake Area in Canada. Int. J. Greenh. Gas Control 10, 113–122.

Gor, G.Y., Elliot, T.R., Prevost, J.H., 2013. Effects of thermal stresses on caprock integrity during CO_2 storage. Int. J. Greenh. Gas Control 12 (January 2013), 300–309. ISSN 1750-5836. http://dx.doi.org/10.1016/j.ijggc.2012.11.020.

Gray, K.E., Podnos, E., Becker, E., 2009, March 1. Finite-element studies of near-wellbore region during cementing operations: Part I. Soc. Pet. Eng. http://dx.doi.org/10.2118/106998-PA.

Griston, S., 1990, January 1. Evaluation of radioactive tracer surveys for steam injection wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/20031-MS.

Guillot, D.J., Froelich, B.G., Caceres, E., Verbakel, R., 2008, January 1. Are current casing centralization calculations really conservative? Soc. Pet. Eng. http://dx.doi.org/10.2118/112725-MS.

Guo, Q., Ji, L., Rajabov, V., Friedheim, J.E., Wu, R., 2012, January 1. Marcellus and haynesville drilling data: analysis and lessons learned. Soc. Pet. Eng. http://dx.doi.org/10.2118/158894-MS.

Han, J., Wang, K., Wang, Y., Shi, J., 2015. Study of aluminum sulfate and anhydrite on cement hydration process. J. Mater. Struct. 49 (4), 1105–1114. ISSN 1871-6873. http://dx.doi.org/10.1617/s11527-015-0561-2P, 1105-1114.

Harness, P.E., Frank, W.E., 1996, December 1. Neutron logs improve interpretation of foamed cement, even in concentric casing. Soc. Pet. Eng. http://dx.doi.org/10.2118/35681-PA.

Heidarian, M., Jalalifar, H., Schaffie, M., Jafari, S., 2014, December 1. New analytical model for predicting the unstable zone around the borehole. Soc. Pet. Eng. http://dx.doi.org/10.2118/169899-PA.

Honglin, X., Zhang, Z., Shi, T., Xiong, T., 2015, February. Influence of the WHCP on cement sheath stress and integrity in HTHP gas well. J. Pet. Sci. Eng. 126, 174–180. ISSN 0920-4105. http://dx.doi.org/10.1016/j.petrol.2014.11.028.

Hossain, M.M., Amro, M., 2010, January 1. Drilling and completion challenges and remedies of CO_2 injected wells with emphasis to mitigate well integrity issues. Soc. Pet. Eng. http://dx.doi.org/10.2118/133830-MS.

Houghton, D.L., 1976. Determining tensile strain capacity of mass concrete. Am. Concr. Inst. J. Proc. 73 (6), 691–700. http://dx.doi.org/10.14359/11108.

Huerta, N.J., Hesse, M.A., Bryant, S.L., Strazisar, B.R., Lopano, C., 2015. Reactive transport of CO_2-saturated water in a cement fracture: application to wellbore leakage during geologic CO_2 storage. Int. J. Greenh. Gas Control. http://dx.doi.org/10.1016/j.ijggc.2015.02.006.

Ichim, A.C., Teodoriu, C., 2016, November 28. Revisiting thermal well integrity through a closer look at casing-cement-formation interaction. Soc. Pet. Eng. http://dx.doi.org/10.2118/182525-MS.

Jacquemet, N., Pironon, J., Lagneau, V., Saint-Marc, J., 2012. Armouring of well cement in H_2S–CO_2 saturated brine by calcite coating – experiments and numerical modelling. Appl. Geochem 27, 782–795. http://dx.doi.org/10.1016/j.apgeochem.2011.12.004.

Jacquemet, N., Pironon, J., Saint-Marc, J., 2008. Mineralogical changes of a well cement in various H_2S-CO_2 (-Brine) fluids at high pressure and temperature. Environ. Sci. Technol. 42, 282–288. http://dx.doi.org/10.1021/es070853s.

Jalan, S.N., Al-Humoud, J., Al-Sabea, S.H., Gazi, N.H., Al-Azmi, K., Al-Haddad, S.M., Fahrizal, A., 2013, October 8. Well integrity: application of ultrasonic logging, production logging and corrosion logs for leak detection in wells - a case study. Soc. Pet. Eng. http://dx.doi.org/10.2118/167279-MS.

Jo, H., Gray, K.E., 2010, January 1. Mechanical Behavior of Concentric Casing, Cement, And Formation Using Analytical And Numerical Methods. American Rock Mechanics Association. ARMA-10-142. https://www.onepetro.org/conference-paper/ARMA-10-142?sort=&start=0&q=ARMA-10-142&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=10#.

Johns, J.E., Aloisio, F., Mayfield, D.R., 2011, January 1. Well integrity analysis in Gulf of Mexico wells using passive ultrasonic leak detection method. Soc. Pet. Eng. http://dx.doi.org/10.2118/142076-MS.

Jung, H.B., Kabilan, S., Carson, J.P., Kuprat, A.P., Um, W., Martin, P., Dahl, M., Kafentzis, T., Varga, T., Stephens, S., Arey, B., Carroll, K.C., Bonneville, A., Fernandez, C.A., 2014, August. Wellbore cement fracture evolution at the cement–basalt caprock interface during geologic carbon sequestration. Appl. Geochem. 47, 1–16. ISSN 0883–2927.

Junior, R.R., Ribeiro, P.R., Santos, O.L.A., 2009, January 1. HPHT drilling—new frontiers for well safety. Soc. Pet. Eng. http://dx.doi.org/10.2118/119909-MS.

Keller, S.R., Crook, R.J., Haut, R.C., Kulakofaky, D.S., 1987, August 1. Deviated-wellbore cementing: part 1-problems. Soc. Pet. Eng. http://dx.doi.org/10.2118/11979-PA.

King, G.E., King, D.E., 2013, November 1. Environmental risk arising from well-construction failure-differences between barrier and well failure, and estimates of failure frequency across common well types, locations, and well age. Soc. Pet. Eng. http://dx.doi.org/10.2118/166142-PA.

King, G.E., Valencia, R.L., 2014, October 27. Environmental risk and well integrity of plugged and abandoned wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/170949-MS.

Klapper, H.S., Stevens, J., 2013, March 17. Challenges for Metallic Materials Facing HTHP Geothermal Drilling. NACE International. NACE-2013-2252. https://www.onepetro.org/conference-paper/NACE-2013-2252?sort=&start=0&q=Challenges+for+Metallic+Materials+Facing+HTHP+Geothermal+Drilling&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=10#.

Kortekaas, S., Peuchen, J., 2008. Measured swabbing pressures and implications for shallow gas blow-out. In: Proceedings, Offshore Technology Conference. OTC-19280.

Krilov, Z., Loncaric, B., Miksa, Z., 2000, January 1. Investigation of a long-term cement deterioration under a high-temperature, sour gas downhole environment. Soc. Pet. Eng. http://dx.doi.org/10.2118/58771-MS.

Kutchko, B.G., Strazisar, B.R., Dzombak, D.A., Lowry, G.V., Thaulow, N., 2007. Degradation of well cement by CO_2 under geologic sequestration conditions. Environ. Sci. Technol. 41, 4787–4792.

Kutchko, B.G., Strazisar, B.R., Lowry, G.V., Dzombak, D.A., Thaulow, N., 2008. Rate of CO_2 attack on hydrated Class H well cement under geologic sequestration conditions. Environ. Sci. Technol. 2, 6237–6242, 42(16).

Kutchko, B.G., Strazisar, B.R., Hawthorne, S.B., Lopano, C.L., Miller, D.J., Hakala, J.A., Guthrie, G.D., 2011. H_2S–CO_2 reaction with hydrated Class H well cement: acid-gas injection and CO_2 Co-sequestration. Int. J. Greenh. Gas Control 5 (4, July 2011), 880–888. ISSN 1750-5836. http://dx.doi.org/10.1016/j.ijggc.2011.02.008.

Lao, K., Bruno, M.S., Serajian, V., 2012, April 30. Analysis of salt creep and well casing damage in high pressure and high temperature environments. Offshore Technol. Conf. http://dx.doi.org/10.4043/23654-MS.

Lecolier, E., Rivereau, A., Ferrer, N., Audibert, A., Longaygue, X., 2010, March 1. Durability of oilwell cement formulations aged in H_2S-containing fluids. Soc. Pet. Eng. http://dx.doi.org/10.2118/99105-PA.

Lecampion, B., Quesada, D., Loizzo, M., Bunger, A., Kear, J., Deremble, L., Desroches, L., 2011. Interface debonding as a controlling mechanism for loss of well integrity: importance for CO_2 injector wells. Energy Procedia 4, 5219–5226.

Lesti, M., Tiemeyer, C., Plank, J., 2013, March. CO_2 stability of Portland cement based well cementing systems for use on carbon capture & storage (CCS) wells. Cem. Concr. Res. 45, 45–54. ISSN 0008-8846. http://dx.doi.org/10.1016/j.cemconres.2012.12.001.

Liteanu, E., Spiers, C.J., 2011, February, 24. Fracture healing and transport properties of wellbore cement in the presence of supercritical CO_2. Chem. Geol. 281 (3–4), 195–210. ISSN 0009-2541. http://dx.doi.org/10.1016/j.chemgeo.2010.12.008.

Li, X.Q., Zhu, T.G., Fang, L.T., Yuan, Y., 2007, December 1. Effect of sand production on casing integrity. Pet. Soc. Can. http://dx.doi.org/10.2118/07-12-TN3.

Li, Z., Vandenbossche, J., Iannacchione, A., Brigham, J., Kutchko, B., 2016, May 1. Theory-based review of limitations with static gel strength in cement/matrix characterization. Soc. Pet. Eng. http://dx.doi.org/10.2118/178923-PA.

Lockyear, C.F., Ryan, D.F., Gunningham, M.M., 1990, September 1. Cement channeling: how to predict and prevent. Soc. Pet. Eng. http://dx.doi.org/10.2118/19865-PA.

Loizzo, M., Sharma, S., 2008, January 1. Assessing long-term CO_2 containment performance: cement evaluation in Otway CRC-1. Soc. Pet. Eng. http://dx.doi.org/10.2118/115707-MS.

Luquot, L., Abdoulghafour, H., Gouze, P., 2013. Hydro-dynamically controlled alteration of fractured Portland cements flowed by CO_2-rich brine. Int. J. Greenh. Gas Control 16, 167–179. http://dx.doi.org/10.1016/j.ijggc.2013.04.002.

Mackay, F., Inoue, N., da Fontoura, S.A.B., Botelho, F., 2008, January 1. Analyzing geomechanical effects while drilling sub salt wells through numerical modeling. Soc. Pet. Eng. http://dx.doi.org/10.2118/113216-MS.

Mathur, R., Seiler, N., Srinivasan, A., Pardo, N.O., 2010, January 1. Opportunities and challenges of deepwater subsalt drilling. Soc. Pet. Eng. http://dx.doi.org/10.2118/127687-MS.

Mainguy, M., Longuemare, P., Audibert, A., Lecolier, E., 2007. Analyzing the risk of well plug failure after reservoir abandonment. Oil Gas Sci. Technol.-Rev. IFP 62 (3), 311–324. http://dx.doi.org/10.2516/ogst:2007026.

McDaniel, J., Watters, L., Shadravan, A., 2014, February 4. Cement sheath durability: increasing cement sheath integrity to reduce gas migration in the Marcellus shale play. Soc. Pet. Eng. http://dx.doi.org/10.2118/168650-MS.

Nelson, E.B., 1990. Well Cementing. Developments in Petroleum Science Series, Elsevier, Oxford, UK.

Nelson, E.B., Guillot, D., 2006. Well Cementing. Schlumberger.

Newell, D.L., Carey, J.W., 2013. Experimental evaluation of wellbore integrity along the cement–rock boundary. Environ. Sci. Technol. 47, 276–282. http://dx.doi.org/10.1021/es3011404.

NOAA: Carbon Dioxide Levels Race past Troubling Milestone. A report published September 30, 2016, National Oceanic and Atmospheric Administration. http://www.noaa.gov/stories/carbon-dioxide-levels-race-past-troubling-milestone. (Accessed 5 December 2016).

Nordbotten, J., Celia, M.A., Bachu, S., Dahle, H.K., 2005. Analytical solution for CO_2 leakage between two aquifers through an abandoned well. Environ. Sci. Technol. 39, 602–611.

Norsok D-010 Rev3, Aug 2004. Standard Norge. http://www.standard.no/pagefiles/1315/d-010r3.pdf.

NPC, 2011, September, 15. Plugging and Abandonment of Oil and Gas Wells. Paper 2-25. Technology Subgroup of Operations and Environmental Task Group, National Petroleum Council. downloaded 5 December 2016, 21 pages. http://www.npc.org/Prudent_Development-Topic_Papers/2-25_Well_Plugging_and_Abandonment_Paper.pdf.

Nygaard, R., Lavoie, R.G., 2010, January 1. Well integrity and workover candidates for existing wells in the wabamun area CO_2 sequestration project (WASP). Soc. Pet. Eng. http://dx.doi.org/10.2118/137007-MS.

Nygaard, R., Salehi, S., Weideman, B., Lavoie, R.G., 2014, January 1. Effect of dynamic loading on wellbore leakage for the wabamun area CO_2-sequestration project. J. Can. Pet. Technol. Soc. Pet. Eng. http://dx.doi.org/10.2118/146640-PA.

Okech, R.R., Liu, X., Falcone, G., Teodoriu, C., 2015, November 18. Unconventional completion design for deep geothermal wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/177228-MS.

Oladipo, A., Houlbrook, A., 2016, September 6. Risk-based prioritization abandonment strategy for inactive subsea wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/181020-MS.

Ottesen, S., Kwakwa, K.A., 1991, January 1. A multidisciplinary approach to in-situ stress determination and its application to wellbore stability analysis. Soc. Pet. Eng. http://dx.doi.org/10.2118/21915-MS.

Posey, D.B., Purvis, D.L., 2004, January 1. Application of a lightweight cement slurry for the naturally fractured Mesa Verde formations. Soc. Pet. Eng. http://dx.doi.org/10.2118/90489-MS.

Pickle, B., Swan, T., 2012, April 30. Slickline-retrievable wellhead plugs and downhole plugging system provides wellbore integrity for extreme HPHT environments. Offshore Technol. Conf. http://dx.doi.org/10.4043/23630-MS.

Quercia, G., Chan, D., Luke, K., 2016, October. Weibull statistics applied to tensile testing for oil well cement compositions. J. Pet. Sci. Eng. 146, 536–544. ISSN 0920-4105. http://dx.doi.org/10.1016/j.petrol.2016.07.012.

Ravi, K., Bosma, M., Hunter, L., 2003, January 1. Optimizing the cement sheath design in HPHT shearwater field. Soc. Pet. Eng. http://dx.doi.org/10.2118/79905-MS.

Rimmele, G., Barlet-Gouedard, V., Porcherie, O., Goffe, B., Brunet, F., 2008. Heterogeneous porosity distribution in Portland cement exposed to CO_2-rich fluids. Cem. Concr. Res. 38, 1038–1048.

Rodriguez, W.J., Fleckenstein, W.W., Eustes, A.W., 2003, January 1. Simulation of collapse loads on cemented casing using finite element analysis. Soc. Pet. Eng. http://dx.doi.org/10.2118/84566-M.

Salehabadi, M., Jin, M., Yang, J., Haghighi, H., Ahmed, R., Tohidi, B., 2008, January 1. Finite element modelling of casing in gas hydrate bearing sediments. Soc. Pet. Eng. http://dx.doi.org/10.2118/113819-MS.

Santarelli, F.J., Skomedal, E., Markestad, P., Berge, H.I., Nasvig, H., 2000, June 1. Sand production on water injectors: how bad can it get? Soc. Pet. Eng. http://dx.doi.org/10.2118/64297-PA.

Schwind, B.E., Payne, M.L., Otten, G.K., Pattillo, P.D., 2001, January 1. Development of leak resistance in industry standard OCTG connections using finite element analysis and full scale testing. Offshore Technol. Conf. http://dx.doi.org/10.4043/13050-MS.

Schultz, R.A., Mutlu, U., Bere, A., 2016, June 26. Critical Issues in Subsurface Integrity. American Rock Mechanics Association. ARMA-2016-037. https://www.onepetro.org/conference-paper/ARMA-2016-037?sort=&start=0&q=Critical+Issues+in+Subsurface+Integrity&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=10#.

Shadravan, A., Amani, M., 2012, January 1. HPHT 101: what every engineer or geoscientist should know about high pressure high temperature wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/163376-MS.

Shadravan, A., Ghasemi, M., Alfi, M., 2015, January, 26–28. Zonal isolation in geothermal wells. In: Proceedings of Fortieth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California. SGP-TR-204-1.

Shadravan, A., Schubert, J., Amani, M., Teodoriu, C., 2014, March 17. HPHT Cement Sheath Integrity Evaluation Method for Unconventional Wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/168321-MS.

Shahri, M., Schubert, J.J., Amani, M., 2005, January 1. Detecting and modeling cement failure in high-pressure/high-temperature (HP/HT) wells, using finite element method (FEM). Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-10961-MS.

Shaughnessy, J., Helweg, J., 2002, January 1. Optimizing HTHP cementing operations. Soc. Pet. Eng. http://dx.doi.org/10.2118/74483-MS.

Shen, Z., Beck, F.E., 2012, January 1. Three-Dimensional modeling of casing and cement sheath behavior in layered, nonhomogeneous formations. Soc. Pet. Eng. http://dx.doi.org/10.2118/156469-MS.

Smith, M., Kou, W., Ahmed, A., Kuzela, R., 2005. The significance of gas hydrate as a geohazard in Gulf of Mexico exploration and production. In: Proceedings, Offshore Technology Conference. OTC-17655.

Soeder, D.J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A., Capo, R., 2014, June 1. An approach for assessing engineering risk from shale gas wells in the United States. Int. J. Coal Geol. 126 (1 June 2014), 4–19. ISSN 0166-5162. http://dx.doi.org/10.1016/j.coal.2014.01.004.

Strazisar, B., Kutchko, B., Huerta, N., 2009. Chemical reactions of wellbore cement under CO_2 storage conditions: effects of cement additives. Energy Procedia 1, 3603–3607.

Stiles, D., 2006, January 1. Effects of long-term exposure to ultrahigh temperature on the mechanical parameters of cement. Soc. Pet. Eng. http://dx.doi.org/10.2118/98896-MS.

Sultan, A.A., 2014, January 19. An abnormally high pressure zone have been detected to be the culprit of many well integrity issues in Dukhan Khuff wells. Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-17349-MS.

Sweatman, R., 2006, March 28-29. Studies on wellbore integrity. In: Proceedings of the 2nd Wellbore Integrity Network Meeting, Princeton, NJ.

Syed, T., Cutler, T., 2010, January 1. Well integrity technical and regulatory considerations for CO_2 injection wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/125839-MS.

Tao, Q., Checkai, D., Huerta, N., Bryant, S., 2014, April 1. Estimating CO_2 fluxes along leaky wellbores. Soc. Pet. Eng. http://dx.doi.org/10.2118/135483-PA.

Tarco, J.C., Asghari, K., 2010, October 1. Experimental study of stability and integrity of cement in wellbores used for CO_2 storage. Soc. Pet. Eng. http://dx.doi.org/10.2118/142004-PA.

Therond, E., Bois, A.-P., Whaley, K., Murillo, R., 2016, September 26. Large scale testing & modelling for cement zonal isolation of water injection wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/181428-MS.

Thiercelin, M.J., Dargaud, B., Baret, J.F., Rodriquez, W.J., 1998, December 1. Cement design based on cement mechanical response. Soc. Pet. Eng. http://dx.doi.org/10.2118/52890-PA.

Um, W., Jung, H.B., Martin, P.F., McGrail, B.P., 2011. Effective Permeability Change in Wellbore Cement with Carbon Dioxide Reaction. PNNL-20843. Pacific Northwest National Laboratory, Richland, WA.

Um, W., Jung, H., Kabilan, S., Fernandez, C.A., Brown, C.F., 2014. Geochemical and geomechanical effects on wellbore cement fractures. Energy Procedia 63 (2014), 5808–5812. ISSN 1876-6102. http://dx.doi.org/10.1016/j.egypro.2014.11.613.

Van Kuijk, R., Zeroug, S., Froelich, B., Allouche, M., Bose, S., Miller, D., Pagnin, A., 2005, January 1. A novel ultrasonic cased-hole imager for enhanced cement evaluation. Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-10546-MS.

Vaziri, H.H., Nouri, A., Hovem, K.A., Wang, X., 2007, January 1. Computation of sand production in water injectors. Soc. Pet. Eng. http://dx.doi.org/10.2118/107695-MS.

Vignes, B., Tonning, S.A., Aadnoy, B., 2008, January 1. Integrity issues in Norwegian injection wells. Soc. Pet. Eng. http://dx.doi.org/10.2118/118101-MS.

Vignes, B., Aadnoy, B.S., 2010, May 1. Well-integrity issues offshore Norway. Soc. Pet. Eng. http://dx.doi.org/10.2118/112535-PA.

Viswanathan, H.S., Pawar, R.J., Stauffer, P.H., Kaszuba, J.P., Carey, J.W., Olsen, S.C., Keating, G.N., Kavetski, D., Guthrie, G.D., 2008. Development of a hybrid process and system model for the assessment of wellbore leakage at a geologic CO_2 sequestration site. Environ. Sci. Technol. 42, 7280–7286. http://dx.doi.org/10.1021/es800417x.

Walsh, S.D.C., Frane, W.L.D., Mason, H.E., Carroll, S.A., 2013. Permeability of wellbore-cement fractures following degradation by carbonated brine. Rock Mech. Rock Eng. 46, 455–464. http://dx.doi.org/10.1007/s00603-012-0336-9.

Wang, H., Samuel, R., 2016, September 1. 3D geomechanical modeling of salt-creep behavior on wellbore casing for presalt reservoirs. Soc. Pet. Eng. http://dx.doi.org/10.2118/166144-PA.

Wang, W., Taleghani, A.D., September 2014. Three-dimensional analysis of cement sheath integrity around wellbores. J. Pet. Sci. Eng. 121, 38–51. ISSN 0920-4105. http://dx.doi.org/10.1016/j.petrol.2014.05.024.

Wang, Y., Tremblay, B., 2001, January 1. Enhanced production in horizontal wells by the cavity failure well completion. Soc. Pet. Eng. http://dx.doi.org/10.2118/68835-MS.

Warrick, J., 2015, December 24. New infrared video reveals growing environmental disaster in L.A. Gas Leak. Washington Post, available online at: https://www.washingtonpost.com/news/energyenvironment/wp/2015/12/23/new-infrared-videoreveals-growing-environmental-disaster-in-la-gas-leak.

Watson, T.L., 2013, October 16–17. Alberta Regulations: Wellbore Integrity Issues Driving Regulatory Changes. North America Wellbore Integrity Workshop, Denver, CO, USA.

Wilcox, B., Oyeneyin, B., Islam, S., 2016, August 2. HPHT well integrity and cement failure. Soc. Pet. Eng. http://dx.doi.org/10.2118/184254-MS.

Williams, R.H., Khatri, D.K., Keese, R.F., Le Roy-Delage, S., Roye, J.M., Leach, D.L.R., Rodriguez, J., 2011, January 1. Flexible, expanding cement system (FECS) successfully provides zonal isolation across Marcellus shale gas trends. Soc. Pet. Eng. http://dx.doi.org/10.2118/149440-MS.

Wigand, M., Kaszuba, J.P., Carey, J.W., Hollis, W.K., July 15, 2009. Geochemical effects of CO_2 sequestration on fractured wellbore cement at the cement/caprock interface. Chem. Geol. 265 (1–2), 122–133. ISSN 0009-2541. http://dx.doi.org/10.1016/j.chemgeo.2009.04.008.

Xie, J., Liu, Y., 2008, May. Analysis of Casing Deformations in Thermal Wells. Abaqus Users' Conference, Newport, Rhode Island, USA, pp. 542–553.

Yeck, W.L., Weingarten, M., Benz, H.M., McNamara, D.E., Bergman, E.A., Herrmann, R.B., Rubinstein, J.L., Earle, P.S., 2016. Far-field pressurization likely caused one of the largest injection induced earthquakes by reactivating a large preexisting basement fault structure. Geophys. Res. Lett. 43, 10,198–10,207. http://dx.doi.org/10.1002/2016GL070861.

Yeow, L.-M., Johar, Z., Wu, B., Tan, C., Yaakub, M.A., 2004, January 1. Sand production prediction study using empirical and laboratory approach for a multi-field gas development. Soc. Pet. Eng. http://dx.doi.org/10.2118/87004-MS.

Yuan, B., Bedrikovetsky, P., Huang, T., Moghanloo, R.G., Dai, C., Venkatraman, A., Sun, B., Thomas, D., Lei, W., Wood, D.A., 2016. Special issue: formation Damage during enhanced gas and liquid recovery. J. Nat. Gas Sci. Eng. 36 2016, 1051–1054.

Yuan, Z., Schubert, J., Esteban, U.C., Chantose, P., Teodoriu, C., 2013, March 26. Casing failure mechanism and characterization under HPHT conditions in south Texas. Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-16704-MS.

Yuan, Z., Schubert, J., Teodoriu, C., Gardoni, P., 2012, January 1. HPHT gas well cementing complications and its effect on casing collapse resistance. Soc. Pet. Eng. http://dx.doi.org/10.2118/153986-MS.

Yvi, L.G., Shingo, A., Emmanuel, H., Olivier, P., 2012. Well integrity: modeling of thermo-mechanical behavior and gas migration along wells-application to Ketzin injection well. Energy Procedia 23 (2012), 462–471. ISSN 1876-6102. http://dx.doi.org/10.1016/j.egypro.2012.06.042.

Zhang, S., Guergueb, N., Garcia, J., Yateem, K.S., Sethi, N., 2013, March 26. Successful application of a new electromagnetic corrosion tool for well integrity evaluation in old wells completed with reduced diameter tubular. Int. Pet. Technol. Conf. http://dx.doi.org/10.2523/IPTC-16997-Abstract.

Zhang, M., Talman, S., 2014. Experimental study of well cement carbonation under geological storage conditions. Energy Procedia 63 (2014), 5813–5821. ISSN 1876-6102. http://dx.doi.org/10.1016/j.egypro.2014.11.614.

Zhang, L., Dzombak, D.A., Nakles, D.V., Hawthorne, S., Miller, D.J., Kutchko, B., Lopano, C., Strazisar, B., 2014, August. Effect of exposure environment on the interactions between acid gas (H_2S and CO_2) and Pozzolan-amended wellbore cement under acid gas Co-sequestration conditions. Int. J. Greenh. Gas Control 27, 309–318. ISSN 1750-5836. http://dx.doi.org/10.1016/j.ijggc.2014.06.030.