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Avoiding Damage of CO_2 Injection Wells Caused by Temperature Variations

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Abstract

Well integrity is a prerequisite for safe geological storage of CO_2. Both active and abandoned wells are man-made channels between the storage reservoir and the atmosphere that can become leakage paths over time. The CO_2 injection wells are of special concern, as they are exposed to low temperatures and strong temperature variations. In oil/gas wells this is known to threaten well integrity, and it should therefore be investigated how the sealing ability of well barriers is affected in the temperature range relevant for CO_2 injection wells. This has been the main focus in a research project entitled "Ensuring well integrity during CO_2 injection" carried out in the period 2014-2016. This paper summarizes the major findings obtained within the project, and presents research-based recommendations for construction and operation of CO_2 injection wells.

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Keywords: CO_2 injection; well intergrity; thermal cycling; cement.

1. Introduction

Ensuring well integrity is important throughout a well's life cycle, including the abandonment phase, and therefore has an eternal perspective. Well integrity problems often arise due to failure of one or several well barrier materials. The well cement, which fills the annulus between the casing pipe and the rock – and is typically used to plug the well after abandonment, is an important barrier material. Its integrity can be compromised in several ways, e.g. by debonding along the cement-casing or cement-rock interfaces or by the formation of leakage paths through the cement

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itself [1]. The latter can be the case if the cement has been exposed to thermal [2, 3], mechanical [4] or chemical [5, 6] loads.

Previous studies have shed some light on how challenging it is to maintain the well integrity over longer periods of time. In the Gulf of Mexico it was found that older wells have a 50% probability of sustained casing pressure [7], and similar studies of active and temporarily abandoned wells on the Norwegian Continental Shelf show that a significant percentage of these have well integrity issues that cannot be ignored [8, 9]. If wells are operated outside their design envelope, e.g. are converted into injectors, they typically become more prone to damage [10], and CO_2 injection wells are likely to suffer from similar problems [11]. They can be exposed to low temperatures (e.g. during cold CO_2 injection or due to Joule-Thomson cooling) and to strong temperature variations (e.g. as a result of an on/off injection pattern) [12].

Thermal cycling results in expansion and contraction of well materials, which can cause cement cracking in the bulk, or debonding at interfaces with casing and formation. Cement debonding from the casing occurs due to radial tensile stresses at the interface, whereas radial cracks in the bulk cement originate from tensile circumferential (hoop) stresses. Such material failure may result in connected leakage pathways along the wellbore, making thermal cycling a potential threat towards well integrity.

The current paper summarizes the findings obtained in a soon-to-be finalized research project called "Ensuring well integrity during CO_2 injection". It has studied the effects of downhole temperature variations on CO_2 injection wells, and has been carried out in the period 2014-2016. The work has been done as a collaboration between SINTEF (Norway) and Lawrence Livermore National Laboratory (USA). Prior to the project, only a few experimental studies had focused on the effect of temperature variations on well integrity, and no studies had been performed in the temperature range relevant for CO_2 injection wells. The overall project objective was thus to gather experiment-based information on safe temperature intervals within which a CO_2 well can be operated without loss of well integrity. The main findings of the project are outlined in this paper, together with research-based recommendations for well construction and operation.

2. Cement bonding

In order to create relevant samples for thermal cycling experiments, the initial project task was to map how cement bonds with various rock and steel surfaces. Both the impact of surface geometry/topography, and the presence of drilling mud and filter cake were investigated. It was also studied how material interfaces were affected by CO_2 exposure. The bonding qualities were inspected mechanically, and by using computed tomography (CT) and Scanning Electron Microscopy (SEM), as outlined in [13-16]. Important findings were:

i. **Mud at interfaces causes higher interface porosity**. Composite cement-rock samples were created using a variety of different rock types, and by using no mud, oil-based mud or water-based mud at the interface. The full study is published in [15]. This revealed that mud at the interface will in any case lead to higher interface porosity. In the case of clay-containing shale rocks, it was observed that oil-based mud gave a lower interface porosity than water-based mud. This is in line with observations in literature that oil-based muds are preferred for drilling and cementing shale sections [17, 18].

ii. **Cement interfaces are weak points in well construction.** Unlike the bulk cement, the interfaces of cement sheaths or plugs are never homogeneous, but are affected by a *wall effect* known as the interfacial transition zone (ITZ). It is the region of the cement perturbed by the presence of the solid wall (rock/steel), where cement grains cannot obtain optimal packing configurations. Typically, it stretches up to 10-50 μm from the solid wall [19, 20]. Experiments were performed to study the ITZ in cement adjacent to steel and rock, and both convex and concave "walls" were studied [16]. In all cases, SEM images revealed depletion of large cement particles within the ITZ. The region between the ITZ and the bulk cement was also found to be weak, and this is typically where fractures develop (instead of at the interface itself). In addition to the geometrical packing explanation for the ITZ, our work proposed that hydrodynamic effects (such as lubrication) hinder larger cement particles in approaching the wall. It was also pointed out in our work that elimination of the ITZ is a good way of optimizing cement bonding. Application of electric field on model casing has recently demonstrated that it is possible to manipulate cement grain packing around a metal surface [21].

iii. **Cement defects heal upon CO_2 exposure.** Composite cement-sandstone cylinders were created and scanned by micro computed tomography (μ-CT) [22]. The defects within them were in this way digitalized, and the samples were thereafter flooded in a water-alternating-gas (WAG) scheme by CO_2 and brine. Subsequent μ-CT scanning showed that a continuous defect running through the cement had closed up, and that the cement porosity was lowered compared to before exposure. This is in line with previously published results showing that CO_2 exposure under certain conditions causes cement defects (like cracks and voids) to self-heal [6]. This is both due to cement carbonation and precipitation of $CaCO_3$.

iv. **Mud/filter cake hinders self-healing of cement defects upon CO_2 exposure**. An experimental study by Opedal et al. [13] focused on creating composite cores of rock and cement where a drilling fluid film or filter cake was present at the interface. The cores were flooded with CO_2-brine, and any changes in the samples were supervised using μ-CT. The three-dimensional (3D) visualization of CT data revealed complex leakage paths at the cement-rock interfaces, and a reduction in bonding quality with an increase of mud-film/filter cake thickness. The core-flooding experiments showed a correlation between the sizes of micro-annuli and the measured CO_2 flow. An important finding in this study was that drilling fluid deposited at the cement-rock interface altered the reaction kinetics of CO_2 with cement and rock. With a mud film or filter cake covering cement defects, no self-healing (as described in (iii)) could be observed.

v. **Permeability of connected cement defects can be high**. By using CT scanning to digitalize interface porosity and leakage paths, data is obtained that can be used directly in numerical software. In Kjøller et al. [23], such a methodology was used to estimate the *consequences* of connected defects in cement. Two composite shale-cement samples were prepared, and the defects within them were digitalized by CT scanning. The 3D leakage paths were thereafter used in ABAQUS for steady-state flow simulations. Subsequently, the samples were flooded with laboratory oil, to investigate their actual permeabilities. Oil was used instead of CO_2 to avoid chemical reactions during flooding. Experimentally measured permeabilities were thereafter compared to flow simulations, and permeabilities were estimated for the connected cement defects. Since the defect patterns were different in the two samples, the permeabilities were also differing – being 800 mD for one sample and 6000 mD for the other.

3. Thermal cycling experiments

In order to gain a better understanding of the stability of wells upon exposure to temperature changes relevant for CO_2 injection wells, thermal cycling experiments for downscaled well models were designed [24]. The objectives of these were to gather experimental data on:

- Whether strong temperature variations (down to temperatures as low as -80°C) threaten well integrity;
- At which conditions well failure occurs, and which dimensions/geometries the resulting defects have;
- What kind of failure can be expected (debonding at interfaces, cracks in the cement material or rock);

The thermal cycling experiments were performed on downscaled well samples consisting of rock, cement and steel casing. They were downscaled with a factor of 4 from a "typical" well with a 12 1/4" borehole and a 9 5/8" casing. The thickness ratio between the casing and cement was maintained in the downscaling, as it was essential for the reproduction of realistic thermally induced volumetric changes in a well. The rock used in the experiments was Berea sandstone, and all samples were cemented using ordinary Portland G cement. Radial temperature variations were induced in these samples by a computer-controlled thermal platform [3, 25]. This consisted of a copper rod inserted into the casing to transmit heat radially to the sample. Temperature variations at different locations of the sample were measured by thermocouples placed at the copper rod, at the cement/rock and cement/casing interfaces, and at the outside of the Styrofoam layer surrounding the sample. This is illustrated in Fig. 1. Damage introduced to the samples by the thermal cycling procedure was visualized by frequent CT scans.

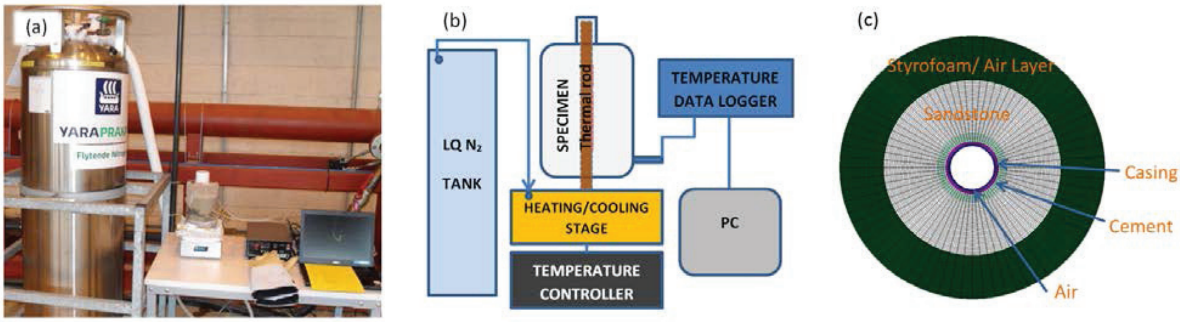

Fig. 1. (a) Picture of the thermal cycling set-up in the laboratory, (b) Schematic drawing of the constituents of the set-up, (c) Samples used for thermal cycling experiments as seen from above.

The heating/cooling rod was programmed to run the following temperature cycle: (1) cooling from room temperature down to -50°C at a rate of 1°C/min, (2) the temperature of -50°C maintained for 4 hours, (3) heating from -50 to 80°C at a rate of 1°C/min, (4) the temperature of 80°C maintained for 4 hours, (5) cooling from 80°C down to room temperature at a rate of 1°C/min. All the stages of the set program are depicted in Fig. 2. (red curve) together with the registered temperature values at the thermal rod and deeper inside the specimen (casing/cement, cement/rock interfaces and outside). The minimum temperature at the thermal rod was about 15°C higher compared to the lowest set temperature (-50°C) and about 10°C lower compared to the maximum set temperature (80°C). The minimum temperatures reached inside the specimens were -19 and -9°C at casing/cement and cement/rock interfaces respectively. This cycle was repeated 20 times in total with a good repeatability of temperature curves for each thermocouple. The experiment was suspended after the 1st, 6th, 13th and 20th cycle in order to perform CT scanning. Fig. 3. shows three-dimensional visualization of pores inside cemented annulus before thermo-cycling and after 20 thermal cycles. As the CT scanning did not reveal any structural changes inside the specimen we hypothesized that either: (1) the temperature range applied might have been insufficient to create stresses that would cause serious damage in the cement sheath, or (2) the changes were beyond the resolution limit of the used CT scanner, or (3) the debonding at the casing/cement interface did occur in-situ when the casing was cooled down, however, subsequent re-heating to room temperature (for CT scanning) could restore the casing/cement contact to its pristine state.

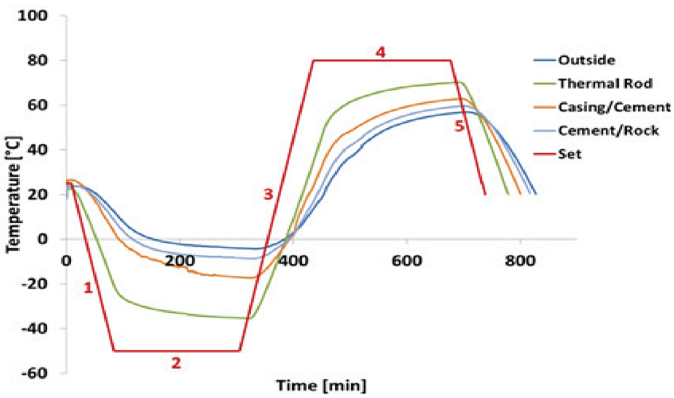

Fig. 2. Temperature profiles during the first cycle.

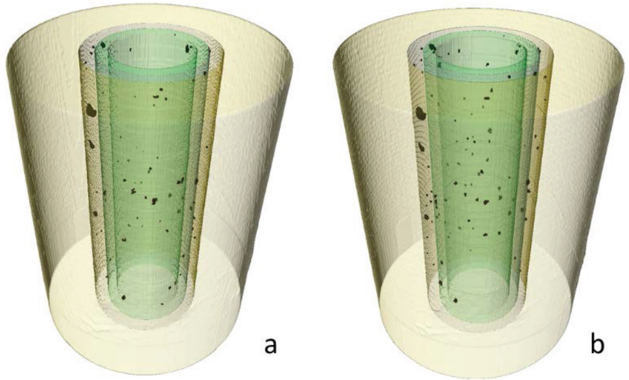

Fig. 3. 3D visualization of CT data from the specimen (a) before and (b) after 20 thermal cycles. Sample diameter and height was about 20 cm. The dark dots in the green cement sheath are defects. The sample is not strongly affected by the thermal cycling.

Harsh cooling experiments (T down to -90°C) were performed to evaluate the lower temperature tolerance limit for CO_2 injection wells. Well models similar to those used for thermo-cycling were cooled down using dry ice or liquid nitrogen by pouring cooling agents inside the bottom-plugged casing. The lowest temperatures achieved inside the specimens were -15 and -40°C on cement/rock and casing/cement interfaces, respectively. These conditions have not induced any changes within dry specimens. Cooling with liquid nitrogen decreased the temperature inside specimens to approximately -80°C at the cement/rock interface. The dried specimen remained unperturbed but the wet specimen lost its integrity. In this sample, a crack formed and propagated through both the cement and the rock along the whole length of the specimen [24]. Based on theoretical/analytical considerations, we proposed that the radial fracture in this water-saturated specimen was caused by combined effects of tensile hoop stresses and stresses due to water freezing. Our experiments were, however, carried out with zero confining stress on the specimen. In a real well, in-situ hoop stress caused by overall compression might reduce the risk of in-situ thermal fracturing during cooling.

The take-home message from thermal cycling experiments was that the well cement may become significantly damaged if the temperature in the well drops to the point of freezing of the pore fluid in cement/rock.

4. Thermal cycling simulations

4.1. Simulations using GEOS

The response of wellbore materials to thermal loading was studied with numerical simulations performed using the LLNL-GEOS code, a multi-physics, multi-scale simulator. A linear elastic stress model coupled with a conduction heat transfer model was used to represent the thermo-mechanical behavior of each material in the well and surrounding host rock (Fig. 1c). The initial objectives of the simulations were to predict the temperature profiles for prescribed thermal boundary conditions and compare them with the experimental results. The model was also used to assess the effects of heating or cooling rates, to assess the effects of confinement and to study potential modes of failure. The virtual wellbores employed in the numerical models have the same sample dimensions as in the experiments described in Section 3. The initial temperature of the well and host rock was set to 24°C (~ room temperature) at the beginning of each simulation. Then, the temperature at the inner radius of the casing was increased or decreased instantaneously or at a specific heating/cooling rate, depending on the nature of the numerical test.

The simulation results were used to study the modes and amount of heat transfer within the sample materials, and to specify the appropriate thermal boundary conditions representing actual physical conditions. Early simulations, which assume perfect thermal contact between the casing and the copper rod, were found to result in an overestimation of heat transfer in the materials compared to the experimental data. When a contact resistance was introduced between the two materials (as might arise, for example, due to an air gap or an imperfect contact), the numerical results matched well with the thermocouple readings (Fig. 4). Further improvement was achieved by assuming a variable thermal conductivity at the contact surface, varying it from 0.05 to 0.10 W/m/K during cooling and heating respectively. The variation of thermal conductivity is representative of the improved contact during the heating process due to the thermal expansion of the copper and steel. From the experimental data, it was also evident that, in spite of using the insulating material around the sample during the experiment, there was considerable heat loss along the radial direction. Thus a constant temperature boundary condition was applied at the outer boundary in the numerical modeling, which produced a better match with the experimental results than a zero heat flux or insulating boundary condition. Moreover, the heat transfer process was found to be very sensitive to the thermal properties of the materials, especially the thermal conductivity.

Upon achieving good agreement between the experimental data and the numerical results, the calibrated model was used to investigate the effect of thermal stresses produced by predetermined heating and cooling rates. The numerical results showed that some radial cracking is likely to occur because of the thermal expansion of wellbore materials during the heating stage. Similarly, the thermal contraction of the materials during the cooling stage may result in interfacial debonding. These results qualitatively agree with Lecampion et al. [26], where the authors described the possible failure modes for different well operations including thermal loading. A confinement pressure applied along the periphery of the sample can delay the initiation of fracture, and at times can even suppress it. High tensile circumferential stress is developed in cement during the early stages when the inner casing is instantaneously heated to a constant temperature. For a gradual heating scenario, high circumferential stresses are developed at the outer periphery of the rock (Fig. 5). During cooling, the maximum radial stress occurs almost always at the cement-casing interface, as shown in Fig. 6. The detailed results of this study were discussed by Roy et al. [27].

The extent of the fractures predicted by the simulations was between 10-100 µm, which was well below the resolution of the CT scanner. This explains why they were not observed in the experiments described in Section 3. From the geochemical modeling of wellbore-cement/carbonated-brine systems, Iyer et al. [28] showed that in a CO_2 storage environment, fractures with such small apertures are likely to be sealed by the interactions between carbonated brine and cement. Further information on chemical and mechanical alteration of leakage pathways in cement is presented in [6, 29-32].

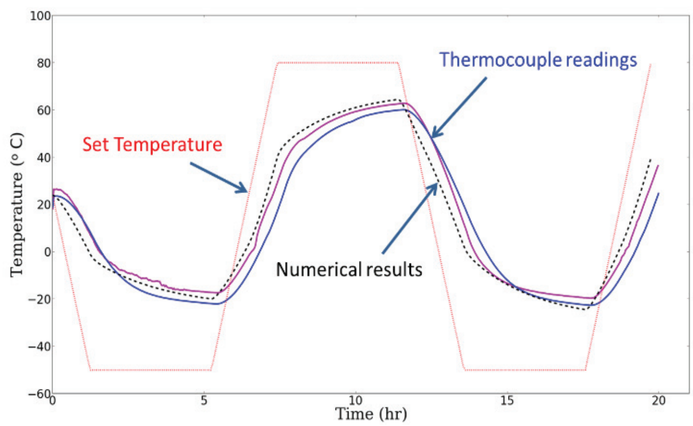

Fig. 4. Comparison of cement-casing interface temperature with top and bottom thermocouple readings.

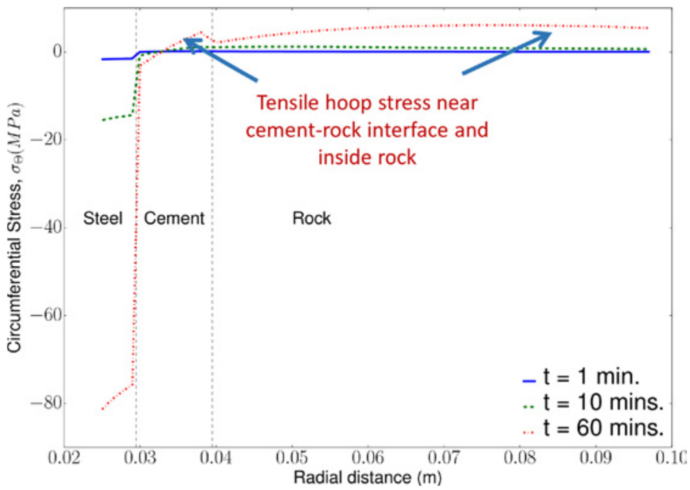

Fig. 5. Circumferential stress profiles as a function of radial distance for heating at 1°C/min.

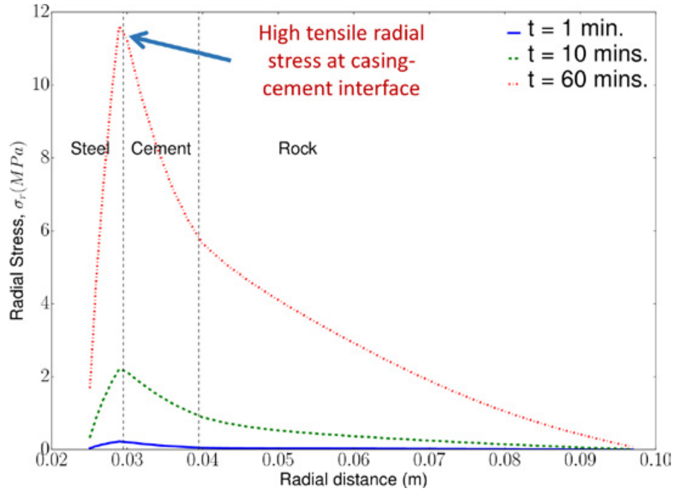

Fig. 6. Radial stress profiles as a function of radial distance for cooling at 1°C/min.

4.2. Numerical use of CT data from experiments

The use of CT to digitalize defects within samples in the experimental work proved to be useful for subsequent numerical simulations. The CT data was used in Finite Element Method (FEM) simulations with the ABAQUS software, by applying a methodology described in [33]. This is also schematically illustrated in Figure 7. The numerical studies were performed to understand in more detail the experimental results described in Section 2 and 3. Important findings were:

i. **Isolated defects may act as stress concentrators and thereby facilitate bulk failure of cement.** A numerical stress analysis was performed with input on defect sizes and geometries from experiments [34]. This was done to gain insight into possible effects of such imperfections on the stress distribution and fracturing in the annular cement during mechanical or thermal loading. A two-dimensional finite-element model of a cemented well (including casing, cement and rock) was set up in ABAQUS. Idealized circular voids were placed in the cement in the model with the objective to demonstrate the overall role of voids as stress concentrators. Two simulations were performed: (1) radial stress of 1 MPa was applied at the outer boundary of the model; (2) no mechanical stress was applied, but the entire system was cooled down by 10 °C. This resulted in an increase of von Mises stress in simulation (1), and in positive tensile stresses in simulation (2). The main conclusion of this work is that isolated voids and channels may serve as fracture nucleation sites (stress concentrators) during mechanical or thermal loading if the induced stresses are sufficiently high.

ii. **Thermal and mechanical properties of defects are important.** It is difficult to measure the properties of cement defects experimentally, and numerical simulations were therefore performed to study how these properties impact well integrity [35]. The stiffnesses (Young's moduli) and thermal conductivities were varied in simulations. This revealed that defect properties are *crucial* for predicting the effect of thermal cycling on well integrity. With respect to the damage the defects can introduce in the intact materials (rock and cement), it is beneficial if they have a low stiffness and/or a high thermal conductivity.

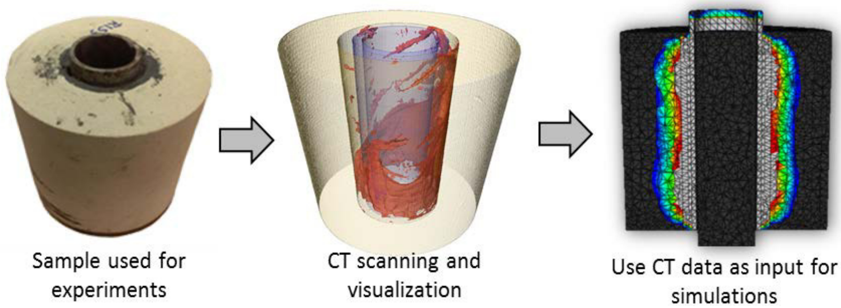

Fig. 7. An illustration of how samples used in experiments were first CT scanned, then reconstructed in 3D (including all defects), and finally used as input in numerical simulations of stress/stain effects.

4.3. Simulations using SINTEF finite volume software

In order to study temperature variations in wells constructed using other materials than cement, a finite volume software for heat conduction in wells was developed. This was validated against previously published experiments using the SINTEF thermal cycling set-up [25], where a reasonable agreement with experimental results was obtained. Lund et al. [36] performed simulations where cement was exchanged with different types of annular sealant materials, and the effect of thermal cycling was studied. The materials considered were: (i) sand slurry, (ii) thermosetting polymer, (iii) bismuth-tin alloy, (iv) ordinary Portland cement. For all these, the rock formation type was varied between sandstone, halite and shale.

The results from the study show that a thermally insulating material such as a polymer can lead to much larger temperature variations in the well than other materials, as depicted in Fig. 8. The Figure shows the temperature at the casing/sealant interface as a function of time while injecting CO_2 at 10°C in a typical well. After 24 hours, the temperature has dropped 20-30°C more if a polymer is used as the annular seal compared to the three other materials. If the goal is to minimize temperature gradients at the casing/sealant interface to avoid debonding, a thermally conductive sealant should be used during well construction. This is further discussed in [36].

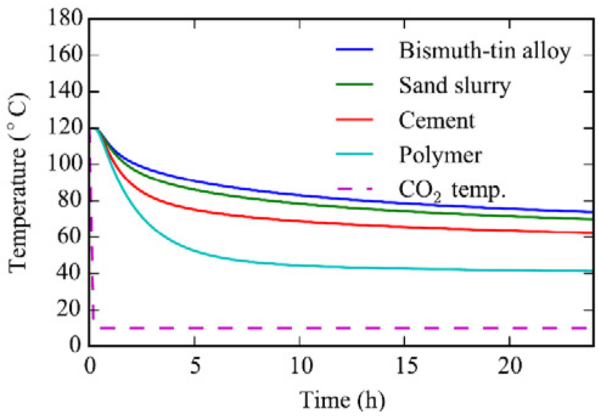

Fig. 8. Temperature at the casing/sealant interface as a function of time while injecting CO_2 at 10°C.

5. Operational parameters

In order to investigate realistic temperature ranges in a well as a function of injection parameters, a sophisticated and accurate model for vertical CO_2 flow was developed in the project by Linga and Lund [37]. It is a two-phase vertical flow model which is coupled to the SINTEF heat transfer model described in Section 4.3. The model specifically handles various flow regimes such as bubbly, annular and mist flow. Using the code, different CO_2 injection scenarios were simulated including well shut-in and blowout. The main finding was that **very low temperatures, down to -30°C and below, may occur very quickly in a CO_2 well during a blow-out**. As seen from the experiments on thermal cycling described in Section 3, such temperatures would lead to freezing and expansion of pore fluid in cement and rock and thus be highly damaging for well integrity.

A combination of the vertical CO_2 flow model and the heat transfer model was also used by Aursand et al. [38] to investigate in more detail challenges that are related to ship transport and injection of CO_2. Studies have shown that ships may be the most cost-effective way to transport CO_2 from many sources in the Nordic countries to offshore storage sites [39]. In this case, the CO_2 is likely to be transported at low temperatures close to the triple point, around -50°C and 7 bar. This means that unless significant heating is made topside before injection, an on/off injection pattern can cause strong thermal variations in the injection well. The study evaluated the influence of several important parameters, such as: (i) injection rate, (ii) injection time, meaning the time to unload one ship, (iii) the time between injections, meaning the time between two subsequent ships, and (iv) injection temperature. The paper concludes that **the time between injections (shut-in time) and the injection temperature are the main factors that affect downhole temperature variations**. Longer pauses between subsequent injections leads to an increased heating of the well by the surrounding formation and hence larger temperature variations when the well is again cooled by CO_2 injection. Lower injection temperature also gives larger variations, since the formation is then significantly warmer than the injected fluid. Thermal stresses resulting from the temperature variations were also evaluated, and it was concluded that for the worst-case scenario considered in the paper (injection temperature of 4°C, injection rate of 100 kg/s, injection pattern of 24h on – 24h off), the compressive stress at the cement-rock interface was reduced by a few MPa. This means that if the initial stress in cement (which is an unknown parameter) is not sufficiently compressive, debonding may occur at the interface resulting in loss of well integrity.

6. Research-based recommendations

The work summarized in this paper makes it possible to draw up some research-based recommendations for how to construct and operate CO_2 injection wells to maximize long-term well integrity. These are:

- **Material and fluid choices for well construction:** To minimize interface porosity between cement and formation, it is recommended to drill clay-containing sections with oil-based mud. The fluids chosen for drilling have impact on subsequent well integrity, and compatibility tests between formations and fluids should thus be performed. The fluids used for drilling will also be present in some types of cement defects, such as bypassed mud channels/pockets in the annulus. It is therefore important to know the properties of the fluids to estimate defect properties in the well. Additionally, annular seal materials with high thermal conductivity may reduce amplitudes of thermal variations in the well.
- **Cement placement:** Primary cementing operations should focus on minimizing the number, size and extent of defects (channels, cracks, voids). These act as stress concentrators in the cement, and reduce the well's resistance towards thermal cycling and cooling. Since the occurrence of defects created during primary cementing is strongly relying on casing centralization, borehole shape and fluid rheologies [40, 41], it is recommended to further develop cement placement codes. A strong focus should also be directed towards mud removal, since mud layers at cement interfaces reduce cement bonding. Innovative techniques for optimizing cement bonding should also be considered.
- **Safe temperature ranges:** Experiments show that temperature variations introduce only small defects in wells, even when cycling from very low to high temperatures. It was demonstrated, however, that freezing of pore water in the well is strongly detrimental to well integrity, as it may radially crack both cement and surrounding rock formations. The crack apertures are in this case hundreds of microns in size. It is thus recommended that all sections of the well always have temperatures above the freezing point of the brine at that particular depth. Numerical simulations show that even in the normal well operating range (15-70°C), heating can lead to radial fracturing and cooling to cement debonding. The extent of damage is, however, small (on the order of tens of microns). In a CO_2 storage environment, such defects are likely to be sealed by chemical interactions between carbonated brine and cement. Careful choice of annular sealant material (especially its thermal conductivity) is also a way of controlling the amplitudes of thermal cycling.
- **Operational parameters:** Injection from ships could lead to excessive temperature variations if the CO_2 is not sufficiently heated before injection. The required heating can depend on the well depth, geometry and materials, as well as the initial stress state after cementing. In any case, too many long periods without injection should be avoided (this applies to both ships and pipelines) as this will give rise to thermal cycling in the well. Heating of CO_2 before injection will also reduce thermal cycling risks.
- **Low probability, high risk:** A blow-out situation in a CO_2 well will cause strong cooling. Our simulations show that well temperatures can quickly go as low as at least -30°C. This will involve freezing of pore fluid in both well cement and surrounding rock formations, and thus cause significant damage to wells. It is thus not recommended to reuse or try to repair a CO_2 well after a blow-out has occurred.

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References

[1] Celia MA, Bachu S, Nordbotten JM, Gasda SE, Dahle HK. Quantitative estimation of CO_2 leakage from geological storage: Analytical models, numerical models, and data needs. In: Greenhouse Gas Control Technologies. 2005. p. 663-71.
[2] Carpenter RB, Brady JL, Blount CG. Effects of Temperature and Cement Admixes on Bond Strength. Journal of Petroleum Technology 1992; 44: 880-5.
[3] De Andrade J, Torsæter M, Todorovic J, Opedal N, Stroisz A, Vralstad T. Influence of Casing Centralization on Cement Sheath Integrity During Thermal Cycling. In: IADC/SPE. Society of Petroleum Engineers; 2014.
[4] Boukhelifa L, Moroni N, James SG, Le Roy-Delage S, Thiercelin MJ, Lemaire G. Evaluation of cement systems for oil- and gas-well zonal isolation in a full-scale annular geometry. SPE Drilling and Completion 2005; 20: 44-53.
[5] Kutchko BG, Strazisar BR, Dzombak DA, Lowry GV, Thauiow N. Degradation of well cement by CO_2 under geologic sequestration conditions. Environmental Science and Technology 2007; 41: 4787-92.
[6] Carroll S, Carey JW, Dzombak D, Huerta NJ, Li L, Richard T, Um W, Walsh SDC, Zhang L. Review: Role of chemistry, mechanics, and transport on well integrity in CO_2 storage environments. International Journal of Greenhouse Gas Control 2016; 49: 149-60.
[7] Brufatto C, Cochran J, Conn L, Power D, El-Zeghaty SZAA, Fraboulet B, Griffin T, James S, Munk T, Justus F, Levine JR, Montgomery C, Murphy D, Pfeiffer J, Pornpoch T, Rishmani L. From Mud to Cement - Building Gas Wells. Oilfield Review 2003; 15: 62-76+7-80.
[8] King GE, King DE. Environmental risk arising from well-construction failure: Difference between barrier and well failure, and estimates of failure frequency across common well types, locations, and well age. SPE 166142 2013.
[9] Vignes B, Aadnøy BS. Well-Integrity issues offshore Norway. SPE/IADC-112535 2008.
[10] Randhol P, Carlsen IM. Assessment of Sustained Well Integrity on the Norwegian Continental Shelf. In. http://www.ieaghg.org/docs/wellbore/Wellbore%20Presentations/4th%20Mtg/01.pdf
[11] Carey JW, Wigand M, Chipera SJ, WoldeGabriel G, Pawar R, Lichtner PC, Wehner SC, Raines MA, Guthrie Jr GD. Analysis and performance of oil well cement with 30 years of CO_2 exposure from the SACROC Unit, West Texas, USA. International Journal of Greenhouse Gas Control 2007; 1: 75-85.
[12] Krogh E, Nilsen R, Henningsen R. Liquefied CO_2 Injection Modelling. Energy Procedia 2012; 23: 527-55.
[13] Opedal N, Todorovic J, Torsæter M, Akervoll I, Jafarzade G. Filter Cake Behavior during Leakage at the Cement-Rock Interface in Wellbores. In: ARMA. American Rock Mechanics Association; 2015.
[14] Opedal N, Todorovic J, Torsæter M, Vralstad T, Mushtaq W. Experimental Study on the Cement-Formation Bonding. In: SPE. Society of Petroleum Engineers; 2014.
[15] Opedal NvdT, Torsæter M, Vrålstad T, Cerasi P. Potential Leakage Paths along Cement-formation Interfaces in Wellbores; Implications for CO_2 Storage. Energy Procedia 2014; 51: 56-64.
[16] Torsæter M, Todorovic J, Lavrov A. Structure and debonding at cement–steel and cement–rock interfaces: Effect of geometry and materials. Construction and Building Materials 2015; 96: 164-71.
[17] Mody FK, Hale AH. Borehole-Stability Model To Couple the Mechanics and Chemistry of Drilling-Fluid/Shale Interactions. 1993.
[18] Torsæter M, Todorovic J, Stenebråten JF, Fjær E, Gabrielsen GK. Shale Smearing at the Borehole Wall During Drilling. In: ARMA. American Rock Mechanics Association; 2014.
[19] Bentur A, Diamond S, Mindess S. The microstructure of the steel fibre-cement interface. Journal of Materials Science 1985; 20: 3610-20.
[20] Scrivener KL, Crumbie AK, Laugesen P. The Interfacial Transition Zone (ITZ) Between Cement Paste and Aggregate in Concrete. Interface Science 2004; 12: 411-21.
[21] Lavrov A, Gawel K, Torsæter M. Manipulating cement-steel interface by means of electric field: Experiment and potential applications. AIMS Materials Science 2016; 3: 1199-207.
[22] Kjøller C, Sigalas L, Frykman P, Bjørge R, Torsæter M. Cement Self-Healing as a Result of CO_2 Leakage. Energy Procedia 2016; 86: 342-51.
[23] Kjøller C, Torsæter M, Lavrov A, Frykman P. Novel experimental/numerical approach to evaluate the permeability of cement-caprock systems. International Journal of Greenhouse Gas Control 2016; 45: 86-93.
[24] Todorovic J, Gawel K, Lavrov A, Torsæter M. Integrity of Downscaled Well Models Subject to Cooling. In: SPE. Society of Petroleum Engineers; 2016.
[25] Albawi A, De Andrade J, Torsæter M, Opedal N, Stroisz A, Vrålstad T. Experimental Set-Up for Testing Cement Sheath Integrity in Arctic Wells. In.: Offshore Technology Conference; 2014.
[26] Lecampion B, Quesada D, Loizzo M, Bunger A, Kear J, Deremble L, Desroches J. Interface debonding as a controlling mechanism for loss of well integrity: Importance for CO_2 injector wells. Energy Procedia 2011; 4: 5219-26.
[27] Roy P, Walsh SDC, Morris JP, Iyer J, Hao Y, Carroll S, Gawel K, Todorovic J, Torsæter M. Studying the Impact of Thermal Cycling on Wellbore Integrity during CO_2 Injection. In: ARMA. American Rock Mechanics Association; 2016.
[28] Iyer J, Walsh SDC, Hao Y, Carroll SA. Incorporating reaction rate dependence in reaction front models of wellbore-cement/carbonated-brine systems. Submitted to the International Journal of Greenhouse Gas Control on July 5th 2016.
[29] Walsh SDC, Mason HE, Du Frane WL, Carroll SA. Experimental calibration of a numerical model describing the alteration of cement/caprock interfaces by carbonated brine. International Journal of Greenhouse Gas Control 2014; 22: 176-88.
[30] Walsh SDC, Mason HE, Du Frane WL, Carroll SA. Mechanical and hydraulic coupling in cement–caprock interfaces exposed to carbonated brine. International Journal of Greenhouse Gas Control 2014; 25: 109-20.
[31] Mason HE, Walsh SDC, DuFrane WL, Carroll SA. Determination of Diffusion Profiles in Altered Wellbore Cement Using X-ray Computed Tomography Methods. Environmental Science & Technology 2014; 48: 7094-100.
[32] Mason HE, Du Frane WL, Walsh SDC, Dai Z, Charnvanichborikarn S, Carroll SA. Chemical and Mechanical Properties of Wellbore Cement Altered by CO_2-Rich Brine Using a Multianalytical Approach. Environmental Science & Technology 2013; 47: 1745-52.
[33] Lavrov A, Torsæter M, Albawi A, Todorovic J, Opedal N, Cerasi P. Near-Well Integrity and Thermal Effects: A Computational Road from Laboratory to Field Scale. In: ARMA. American Rock Mechanics Association; 2014.
[34] Lavrov A, Todorovic J, Torsæter M. Impact of Voids on Mechanical Stability of Well Cement. Energy Procedia 2016; 86: 401-10.

[35] Lavrov A, Todorovic J, Torsæter M. Numerical Study of Tensile Thermal Stresses in a Casing-Cement-Rock System with Heterogeneities. In: ARMA. American Rock Mechanics Association; 2015.
[36] Lund H, Torsæter M, Munkejord ST. Study of Thermal Variations in Wells During Carbon Dioxide Injection. SPE Drilling and Completion 2016.
[37] Linga G, Lund H. A two-fluid model for vertical flow applied to CO_2 injection wells. International Journal of Greenhouse Gas Control 2016; 51: 71-80.
[38] Aursand P, Hammer M, Lavrov A, Lund H, Munkejord ST, Torsæter M. Well integrity for CO_2 injection from ships: Simulation of the effect of flow and material parameters on thermal stresses. To be submitted 2016.
[39] Kjærstad J, Skagestad R, Eldrup NH, Johnsson F. Recommendations on CO_2 transport solutions. In: Technical Report, NORDICCS report D20. Trondheim: SINTEF Energy Research; 2015.
[40] Lavrov A, Torsæter M. Effect of Rheology on Annular Sealing: From Placement to Failure. In: SPE. Society of Petroleum Engineers; 2016.
[41] Lavrov A, Torsæter M. Physics and Mechanics of Primary Well Cementing. Springer; 2016.