LONG TERM INTEGRITY OF CO₂ STORAGE – WELL ABANDONMENT

Background to the Study

CO₂ geological storage projects will likely incorporate a range of well types, from injection and production wells, to abandoned and previously completed wells. While newly drilled and completed wells are likely to be governed by and subject to regulations designed to uphold the integrity of storage sites, wells completed and abandoned in the past may have been subject to less strict governance, and it is these wells that are, therefore, considered to be the greater threat to long-term storage integrity.

The IEA Greenhouse Gas R&D Programme (IEA GHG) recently commissioned TNO in The Netherlands to conduct a review of abandonment procedures and methodologies from around the world in order to determine whether the predominant factor influencing the methods used is regional location and regulatory led, or if it is purely down to operator preference.

Storage in deep saline aquifers may be considered as a lower risk, as the number of wellbores expected to be encountered during a storage project should often be lower than those encountered in oil and gas fields. Depleted oil and gas reservoirs are likely to incorporate a greater number of wells perforating the caprock of the reservoir due to the historical exploration and exploitation of these fields.

While the historical exploration of oil and gas fields creates the very potential for geological storage of CO₂ to take place in these reservoirs, it may have given rise to the greatest risk to the storage operation by providing multiple pathways for injected CO₂ to migrate through wellbores to overlying, unbounded geological areas, or ultimately to the atmosphere. This study aims to address this issue, assessing the state of knowledge and identifying methodologies and best practices designed to minimise risks associated with injection into previously drilled and explored areas both on and off-shore.

Seepage, migration and leakage¹ can occur through faults and fractures in the caprock above the storage reservoir, and through poorly completed or abandoned wellbores from previous exploitation or exploration. While site selection criteria should work to minimise the risks posed by faults and fractures, a good understanding of well abandonment and remedial measures necessary to ensure secure storage is necessary to provide assurance to regulators and the general public that CCS is a safe option for greenhouse gas mitigation.

¹ For the context of IEA GHG studies, CO₂ escaping from the storage reservoir is termed seepage, movement through overlying strata and along abandoned wellbores is termed migration, and leakage is the escape of CO₂ from the subsurface to the atmosphere.
Results and Discussion

A Review of Well Plugging and Abandonment Techniques

The report includes a high-level review of the variety of techniques that are employed around the world to facilitate well abandonment. The report describes the preliminary work necessary, such as removal of equipment from the well and cleanout of the wellbore before plugging can take place. The report outlines the basic principles involved in each plugging method and highlights the drawbacks and limitations of the methods. These are summarised in table 1 below.

<table>
<thead>
<tr>
<th>Abandonment Method</th>
<th>Description</th>
<th>Benefits / Limitations</th>
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<tr>
<td>Balanced Plug</td>
<td>The more common method of abandonment, whereby the tubing is placed at the target plug depth, and the cement slurry is then injected onto a bridge plug device which forms the plug base. Cement is then pumped into the annulus until it is equal to the level inside the casing.</td>
<td>One of the simplest techniques, incurring lower costs than some, the main limitation is caused by the potential for cement contamination. This can be minimised by use of best practice and best suited plug base materials, as described later in this overview.</td>
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<td>Cement Squeeze</td>
<td>Squeeze cementing involves pressurised forcing of cement at a pre-determined depth coinciding with perforations in the casing. The pressure forces the liquid of the slurry into the formation, leaving the cement to form a seal.</td>
<td>Often used as a remedial measure for flawed or damaged primary cement, the exact quantity of cement required cannot always be calculated, leading to possible excess cement which can enter the casing above the packer. This would effectively stick the tubing into the hole, preventing future removal.</td>
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<tr>
<td>Dump Bailers</td>
<td>A known quantity of cement is lowered into the wellbore on a wireline, and the bailer is activated when it reaches the correct position, just over the bridge plug and raising the bailer releases the cement.</td>
<td>The stationary nature of the slurry during the descent can lead to premature setting, so this is more suited to setting plugs at shallower depths</td>
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<tr>
<td>Two-plug</td>
<td>A complex process whereby a top and bottom plug are set at calculated depths, the lower plug cleans the well as it is lowered, and the cement can then be placed with minimal contamination from other fluids.</td>
<td>Allows maximum accuracy of placement with minimum cement contamination. The isolation of the cement slurry from other fluids ensures predictable cement performance.</td>
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Table 1: Description of abandonment methods

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2 A plug is a mechanism whereby a quantity of cement or other mechanical plug effectively seals the wellbore at a given height, isolating permeable layers of the geological formation from each other, preventing migration of injected CO₂.

3 A dump bailer is a tool that delivers a prescribed quantity of cement that can be lowered into the well by a wireline and deployed on top of the permanent plug.
Case Studies
The study covered case studies of abandonment practices at three locations around the world:

- Proposed storage of CO₂ in the depleted De Lier field, The Netherlands,
- Well evaluation at Gulf Coast and SACROC, Texas, USA,
- The Alberta Basin, Alberta, Canada.

These case studies present a range of aspects of wellbore integrity, and the potential impact these have on storage operations.

De Lier field, The Netherlands
The De Lier case illustrated several concerns that are often raised when considering second life applications for depleted hydrocarbon fields. The integrity of the previously abandoned wells gave rise to health, safety and environmental concerns, often a consideration when dealing with second life applications.

The De Lier study provides a good example of the implications of regulatory regimes. Of the 51 abandoned wells, 3 were abandoned before 1967 when regulations were enforced. These wells are typified by significantly shorter cement plugs than current standards recommend, despite conforming to the Dutch Mining Regulations and Decree with regard to isolation of the low pressure depleted gas reservoir.

The stacked nature of the De Lier field adds complexities to proposed storage, as many wells transect the proposed storage reservoir, and due to the methods prevalent at abandonment, no cement plugs are present at the caprock level. The abandonment status alone is unlikely to present the potential for gas migration to the surface, but if corrosive fluids were introduced additional abandonment measures would be needed.

Additional issues were encountered due to urban and industrial development over and around abandoned wellbores, presenting accessibility issues for monitoring and any necessary recompletion.

Following the well evaluations, storage in the De Lier field was not considered economically feasible – expensive work-over measures would be required on numerous wells to safeguard CO₂ storage satisfactorily.

Gulf Coast and SACROC, Texas, USA
Texas is an area often used as a case study for CO₂ storage due to the high number of abandoned wells, and the history of hydrocarbon exploitation and production. Here the issues are with well densities, and completion methods. Many wells were completed before 1930, and were not plugged with cement and abandonment methods were not subject to governance by the site operators. These wells are known as ‘orphan wells’⁴. Other political influences have made the area a popular case study, including the oil crisis in the mid 1980’s where many deeper wells were not plugged with cement due to operator companies becoming insolvent. Data quality is identified as another issue, with the exact details of many wells being unknown, or of poor quality.

Field samples from wellbores comprising of steel casing and portions of cement obtained from the SACROC (see figure 1) region have been vigorously studied and make a strong case for the

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⁴ An orphan well is classified as a well that is not abandoned adequately and no longer falls under the jurisdiction of the operating company.
argument of using Portland\(^5\) cements. On obtaining samples, it appears that the wells were completed using a neat Portland cement which has served to prevent degradation of the casing which showed very little evidence of corrosion. There are however clear signs of cement alteration in 2 locations.

Figure 1: Photograph of samples retrieved from well 49-6, showing (from left to right) casing, cement with alteration zones at both interfaces, a zone of fragmented shale and shale caprock (Carey et al., 2007).

Collaborative studies have determined that the cement in the SACROC sample will have retained its initial structural integrity, and would be suitable for containing injected CO\(_2\) in a storage activity. The sample also shows that migration along interfaces is likely to occur, leading to the alteration zones\(^6\) evident in figure 1. This suggests that further work is required to maximise the integrity of the interfaces of wellbore completions.

**The Alberta Basin, Canada**

Alberta is another region that has seen extensive drilling and oil and gas production, but unlike Texas, the Alberta Basin has a very high quality and complete database on oil and gas wells. Similar to many regions of the world, monitoring is required by regulations during a sites active lifetime, but following adequate abandonment, no further monitoring is required.

Again, we see that earlier wells were not required to be cemented to the same standards that later wells were, and this is evident in many older shallower wells having inadequate primary cement sheaths. Sustained casing pressure\(^7\) has been recorded at various locations from shallow gas resources, and these leakage pathways could present potential pathways for CO\(_2\) migration from lower levels.

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\(^5\) The Portland cement used in this well was Portland Class H cement, with 50% fly ash and 3% Bentonite gel, and a density of 1710kg/m\(^3\), from Crow et al., 2008.

\(^6\) The alteration zones are shown as the areas with a colour change from the adjacent area. This is due to carbonation of the minerals in the cement. In this image, the alteration zones are seen on the left-hand edge of the left hand cement sample as a white rind, and as the orange area on the right-hand cement sample, both indicated by the red circles.

\(^7\) Sustained casing pressure is a term used, mainly in Canada, to describe the increase in pressure and subsequent leakage at the surface of a wellbore following migration of CO\(_2\) along the wellbore.
Extensive reviews of well failures have been carried out in Alberta, and it is noted that post 1994 well failures are much less frequent due to the improvements in regulatory requirements. The review also highlighted the variation in causes of well failures, from tubing or casing failure, packer failure, zonal isolation failure and sustained casing pressure. These variations represent different aspects of the wellbore suffering failure, with converted wells suffering greater incidences of failure than wells drilled for purpose, again highlighting the influence of regulation on the minimisation of leaks through wellbores.

**Regulatory Review**

The report also looks at several examples of regulatory regimes in place around the world aimed at controlling CO₂ storage operations and making operators accountable for leakage and problems over the longer site lifetime. Assessment of current regulatory frameworks can help to determine and evaluate initial abandonment practices only, and subsequent changes to legislation mean that during the lifetime of a commercial scale CO₂ storage project it is conceivable that well abandonment practices would change. However, it is also unlikely that regulatory regimes will stipulate the exact abandonment methods for all wells encountered in a field, rather they would allow operators to assess and make informed judgements as to which methods are necessary to fulfil the regulatory requirements, ensure safety, but not entail excessive or prohibitive costs. It is accepted that a site specific survey would be required for each potential storage site, and site selection criteria would likely remove some potential sites from the reckoning due to excessive remedial costs for abandoned wells.

The report looks at 11 different regulatory regimes from European, Australasian and American countries, and also assesses the London Convention and Protocol and the OSPAR Convention, with the role they play as International Conventions.

From this review, it is clear that there is a large repository of regulatory information and tools available to regulators of CO₂ storage activities, and much of this has evolved from the legislation governing well abandonment in the hydrocarbon and petroleum extraction industries.

Generally, the regulations in place provide guidance on abandonment methods for existing wells, and although the review shows that there is always a need for a cement plug, the length of cement plug varies greatly, from a minimum of 15m in Canada, to up to 100m in some European scenarios. Other areas where variation is apparent include verification of abandoned wells, provisions made for CO₂ storage, and data availability.

The single most difficult hurdle encountered by the contractor when assessing international regulatory positions, was the language barrier that exists. Many countries do not offer their regulations in anything but their native language, and any translation is deemed unofficial.

**Specific Impacts of CO₂ on Wellbore Integrity**

While the similarities between hydrocarbon production and geological storage of CO₂ mean that operators can learn greatly from previous oil and gas industry experience, there are

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8 This is extrapolated from results showing fewer instances of sustained casing pressure following the introduction of regulations stipulating abandonment methods. Sustained casing pressure is much more likely to be observed in a well lacking in cement, suffering from degradation from formation fluids, deformations or poor cementing procedures.

9 It should be noted that this review is not intended to relay information on all regulatory regimes in place globally, rather it should reflect the wide range of legislative tools in place, and likewise, the review is not exhaustive, and there are many other legislator tools in use that are not included in this review.
significant contrasts of discrete characteristics that can have severe implications on wellbore integrity. Such characteristics include re-pressurisation of exploited reservoirs, the need for long-term containment over 1000’s of years, and the potential for chemical reactions between aqueous phase CO2 and formation geology and wellbore materials.

Impacts that must be specifically investigated for CO2 storage purposes can be classified as:

- **Mechanical deformation of wellbore cement;**
  This is generally caused by operational activities such as drilling new wells, and changes in the temperature and pressure cycles. Natural stresses can also occur, and any of these factors can lead to the development of cracks, small or large, or shear strain. Either of these scenarios can create highly permeable pathways for leakage of the injected CO2.

- **Chemical degradation of wellbore cement;**
  The injected CO2 will not be corrosive, but when it mixes with formation water, it can form a corrosive form of carbonic acid. This dissolution process and the resulting acid will degrade the solid constituents of the cement to produce carbonates.

- **Corrosion of the wellbore casing steel;**
  Steel corrosion is an electrochemical process, and requires the presence of a cathodic and anodic reaction. The more prevalent conditions in CO2 storage reservoirs involve the corrosion of iron metals under the influence of dissolved hydrogen ions. Hydrogen gas generated by the cathodic and anodic reactions drives the corrosion process.

**Risk Management Methodologies**

Risk management is defined in the context of this study as comprising of all the activities involved in assessment, mitigation and monitoring of risks.

Risk management methodologies should include site selection and characterisation, and storage system design. Risk assessment should investigate the likely and actual performance of a storage site over geological time periods. Within the CO2 storage environment, as an industry very much in the developmental stage, there are many options for risk management, and these can be classified as qualitative or quantitative.

Table 2 below shows the range of well assessment methodologies available, and the aspects they address.
Table 2: Characteristics of well assessment methodologies

The report analyses these to some depth to relate a number of well features to the level of impact they pose to the risk of leakage. These are grouped into factors of: no impact, minor impact and major impact. The results of this assessment are summarised in the table below. For full details, see section 6.3 in the main report.
<table>
<thead>
<tr>
<th>Impact</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No impact</td>
<td>Well age</td>
<td>The expectation of higher leakage rates of older wells due to less elaborate construction and materials was not supported by the data. For example, in Alberta, compulsory testing was not put into place until 1995, very little data is available before this date, resulting into a serious distortion of the analysis of the age factor.</td>
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<tr>
<td></td>
<td>Well operational mode</td>
<td>The distinction between oil and gas production, water and solvent injection, disposal of liquid waste or acid gas did not reveal any effect with respect to wellbore leakage. Some operational modes were expected to present more impact, but as many wells are still operational, data is again not available.</td>
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<tr>
<td></td>
<td>Completion interval</td>
<td>Depth of the source of migrated gas and depth of completion intervals revealed no correlation, and this was supported by cement logs and other measured data.</td>
</tr>
<tr>
<td></td>
<td>H₂S or CO₂ presence</td>
<td>The presence of hydrogen sulphide and CO₂ in produced hydrocarbons was investigated for a possible impact on internal and external casing corrosion, and again, the data did not support this.</td>
</tr>
<tr>
<td>Minor Impact</td>
<td>Licensee</td>
<td>Various operators using different abandonment practices may result in different sealing efficiencies of wells subject to abandonment.</td>
</tr>
<tr>
<td></td>
<td>Surface casing depth</td>
<td>Surface casing depth was not found to influence the quantity of leakage, however, there is an influence on whether leakage occurs.</td>
</tr>
<tr>
<td></td>
<td>Total depth</td>
<td>Gas migration increases slightly with total well depth, attributed to the generally increasing un-cemented upper interval of deeper wells, providing enhanced hydraulic communication with source formations.</td>
</tr>
<tr>
<td></td>
<td>Well density</td>
<td>In areas exhibiting high well densities, occurrence of well-to-well crossflow can potentially result in enhanced leakage rates of wells. This hypothesis was not supported by the available data but was indicated from other work.</td>
</tr>
<tr>
<td></td>
<td>Topography</td>
<td>River valleys may represent zones of higher leakage risks due to removal of overburden and corresponding decline of hydrostatic pressure, potentially resulting in shallow over-pressured zones.</td>
</tr>
<tr>
<td>Major Impact</td>
<td>Geographic area</td>
<td>In certain areas within the province of Alberta testing of all wells is required, whereas in other areas the requirements are less strict. One area within the province subject to testing requirements for all wells exhibited a more frequent occurrence of leakage compared to the entire province. However, it is not clear whether this finding refers to the different testing conditions.</td>
</tr>
<tr>
<td></td>
<td>Wellbore deviation</td>
<td>Migration occurred significantly more often related to deviated wells, while the impact of well deviation on the ratio of leakage to migration was minor.</td>
</tr>
<tr>
<td></td>
<td>Well type</td>
<td>Cased abandoned wells account for 98% of all leakage cases reported. The rest refers to wells drilled and abandoned. This significant difference may rely on more stringent abandonment requirements for drilled and abandoned wells.</td>
</tr>
<tr>
<td></td>
<td>Abandonment Method</td>
<td>In Alberta, cased and completed wells are predominantly abandoned by bridge plugs capped with cement. Based on the data set and experience 10% of these bridge plugs will fail over a period of centuries allowing formation fluids to enter the wellbore.</td>
</tr>
<tr>
<td></td>
<td>Oil prices and</td>
<td>The data set reveals a significant positive correlation between leaks and migration occurrence and oil price between 1973 an 1999. This can be explained by the relation between exploitation activity and equipment availability. Satisfaction of a high demand with limited equipment resources impacts on primary cement placement practices.</td>
</tr>
<tr>
<td></td>
<td>regulatory changes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uncemented casing / hole annulus</td>
<td>A low cement top was found to be the most important indicator for migration and leakage. Low cement top is also the main cause for external casing corrosion.</td>
</tr>
</tbody>
</table>

*Table 3: Summary of factors impacting leakage risk.*
Recommended Best Practice for Well Abandonment

The recommended best practice for well abandonment with specific focus on long term well storage integrity involves 4 aspects:

- **Advanced materials:** improvements in the capacity of wellbore sealants to isolate stored CO₂ can be applied during drilling, completion, workover and abandonment operations,
- **Reduced cement permeability and reactivity:** either by reducing the water to cement ratio or the addition of specialist materials which also allows the slurry density to be adjusted over a range of values.
- **Use of non-Portland cements:** these are less reactive with wet CO₂, however they are not compatible with Portland cements, and cross-contamination must be avoided. They also entail higher costs than Portland based cements.
- **Self healing cements and swelling packers:** these contain specific additives that react with the fluids present to effectively block cracks and annuli to prevent flow. Swelling packers are used in case of cement failure – they are designed to swell upon contact with hydrocarbons, water or both.

Carlsen and Abdollahi (2007; In: Randhol et al., 2007) describe a methodology for abandonment that is shown in figure 2 below. The process involves removing the tuber and packer before placing a cement plug at the bottom of the well, and then injecting a specialised fluid into the reservoir to clog the near-well area and displace the CO₂ to minimise contact between CO₂ and wellbore materials. The casing is then milled at the level of the caprock and cement injected into this open section to prevent leakage along micro-annuli between casing and cement elements. The well is then filled with non corrosive completion fluid. If secondary seals are present, then an additional cement barrier should be placed at this point.

**Figure 2:** CO₂ storage well before (left) and after abandonment (right) according to the methodology described by Carlsen and Abdollahi (2007; In: Randhol et al., 2007).
Expert Review Comments

Comments were received from numerous expert reviewers, and the feedback was both constructive and supportive of the work that had been carried out. The initial feedback led to a further amendment of the report, which was well received by were met with positivity from the Further comments on the revised report were then incorporated into the final report.

The draft report was presented to the 5th Meeting of the IEA GHG International Research Network on Wellbore Integrity (as a work in progress) in order to provide a thorough review process, and to ensure that the report was critically assessed before being published. Many comments were made at this stage and discussions raised some points for clarification and amendment. Following these amendments, the report was well received, and represents an unbiased view of the problems faced by CO\textsubscript{2} storage CCS projects and reviews the options available to overcome such problems.

Conclusions

The study references work carried out by Watson & Bachu, 2007, that states that wells can be classified as either existing or future wells. Existing wells are further sub-categorised as abandoned or operational, effectively giving 3 well categories: abandoned, operational and future wells, and this classification is key to understanding and rationalising the risks posed to a field during the initial screening process.

The report demonstrates that there is much experience gained through previous pilot and demonstration operations, and that there is a great deal of knowledge on various abandonment techniques that have been proved suitable for CO\textsubscript{2} storage purposes. Recognition of this knowledge is not always evident, and in communicating with regulators and the general public, this level of understanding and confidence should be expressed. This assessment demonstrates this comprehensive range of techniques implicitly, and demonstrates the accepted limitations where relevant.

Due to this knowledge base, future wells can be designed, drilled and abandoned taking into account the CO\textsubscript{2} storage operation, using state-of-the-art technologies. What remains is for regulatory regimes to stipulate clear guidance on recommended best practices within their spheres of influence and operation, facilitating straight-forward start up and initialisation of projects.

One of the most valuable outcomes of the study is the analysis of the risk management methodologies, and this demonstrates that there are a range of methods available, depending on the aim of the assessment, to perform an in-depth analysis of the risks. Alongside this is the analysis of factors affecting well abandonment and the impact they have on the risk of leakage. This analysis will be very useful in the primary stage of a project, in allowing the site characterisation and screening process to be compared with this matrix to determine an overall risk to long term integrity of CO\textsubscript{2} storage.

Recommendations

The contractor recommends in the report that to facilitate international cooperation, all regulations should be provided with an official English language translation, and indeed further discussion should be entered into as to whether such regulations should be freely available for those who wish to read them.
With such a wide range of guidelines and standards, best practice should be clearly defined and stipulated within regulatory instruments to facilitate use of best practice by operators. The study showed that regulations from different regions incorporated many of the same basic elements, but to varying degrees. An example of this is the variation in recommended length of cement plug previously mentioned, stipulating from 15m to 100m in some regions, but the cement plug is a ubiquitous element of abandonment methodology.

It is suggested that all regions and regulatory bodies adhering to the same set of guidelines is unlikely to be realistically practicable, however, all regions with regulatory regimes should clearly stipulate the requirements in their regions, as well as any relevant recommendations for best practice procedures to follow.

If regulatory instruments include best practice recommendations, then it should be possible to make an early assessment of existing wellbores to determine economic feasibility of storage projects by comparing these practices to the initial site characterisation results.