Evaluating technology options to mitigate greenhouse gas emissions

wellbore integrity network summary report

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 28 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. IEAGHG is one of these Implementing Agreements.

The report should be cited in literature as follows:

'IEAGHG, "Wellbore Integrity Network Summary Report, 2012/01, January, 2012'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Orchard Business Centre, Stoke Orchard, Cheltenham, GLOS., GL52 7RZ, UK

Tel: +44(0) 1242 680753 Fax: +44 (0)1242 680758

E-mail: mail@ieaghg.org

Internet: www.ieaghg.org

Date Published: January 2012, Review compiled by Samantha Neades, design and layout by Toby Aiken and Becky Kemp.

Front & back cover images: Hoover Dam - example of good cement work, , Princeton University Campus - Venue for 2006, , Santa Fe - Venue for 2007, Paris - Venue for 2008, Pumpjack near Weyburn

Contents

Introduction 2

Technical Background and Network History 3

Summary of Key Findings and Future Research Directions 4

Network Findings 6

Summary: Current State of Knowledge 9

Conclusions and Recommendations 9

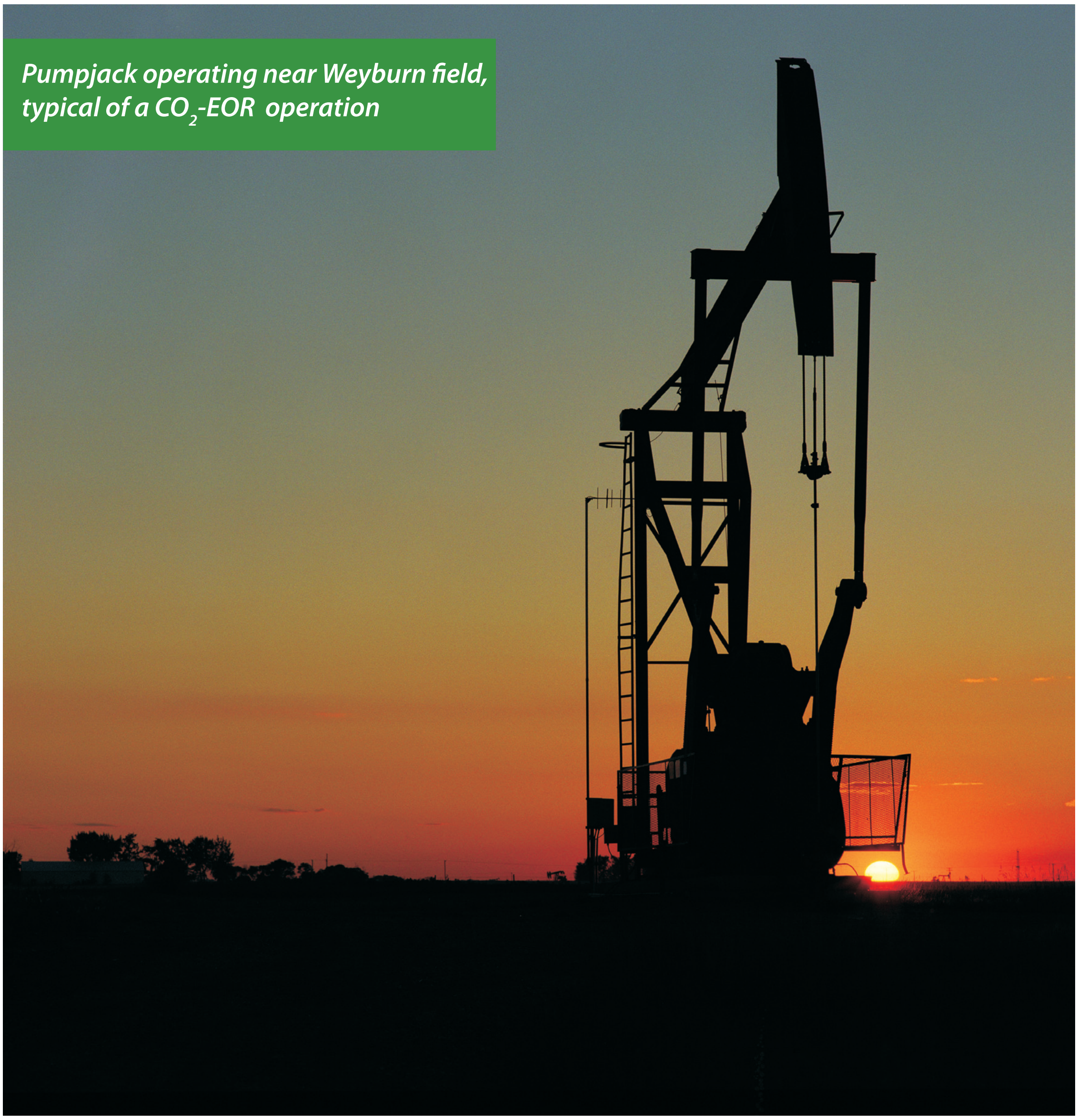
References and Acknowledgements 10

Non-corroded pipes - Christopher and Crow Presentation / Bad Cement Work on a Bridge - NThaulow Presentation

Introduction

IEAGHG currently runs five international research networks on CO_2 geological storage, namely Risk Assessment, Wellbore Integrity, Monitoring, Modelling and Social Research. These networks meet on an annual basis, bringing together experts from industry, research institutions and regulatory agencies to discuss technical issues in the context of Carbon Dioxide Capture and Storage (CCS) deployment. Membership of the networks is open to those with a professional or academic interest in the particular network theme, and allows access to past network reports and presentations through the IEAGHG website, www.ieaghg.org.

The purpose of this report is to describe the Wellbore Integrity Network, summarise past meetings, outline key findings and identify current state of knowledge.



Pumpjack operating near Weyburn field, typical of a CO_2-EOR operation

Technical Background and Network History

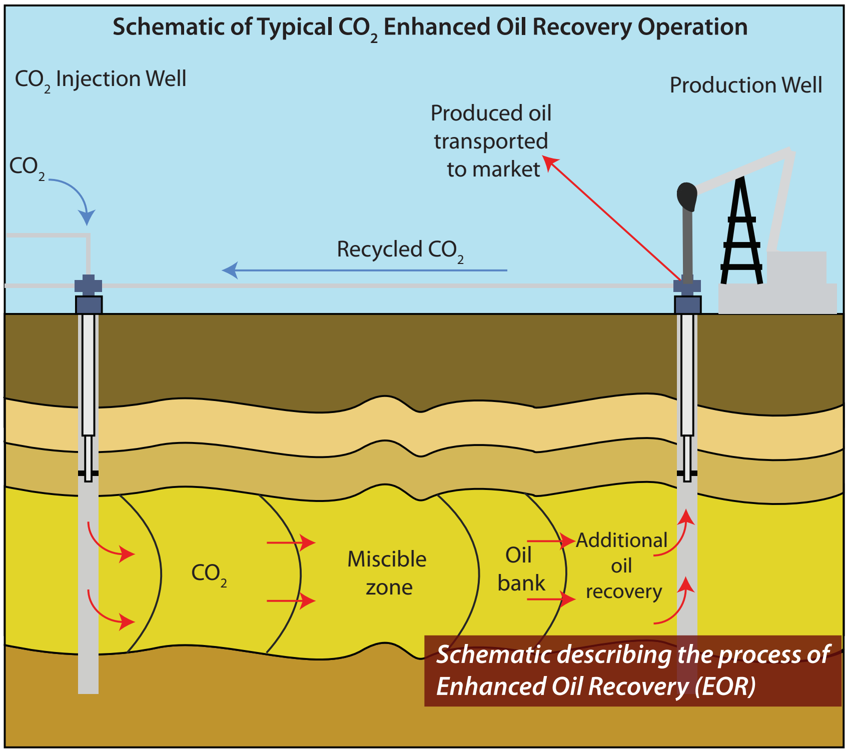
Wellbore integrity can be defined as the condition in wellbores that maintains isolation of geological formations, preventing vertical migration of fluids (Crow et al, 2010). Maintaining the integrity of wellbores is widely accepted as a vital issue for CO_2 geological storage, due to the requirements for sites to securely store CO_2 over long timescales. In cases where storage sites are located in sedimentary basins with a history of oil and gas exploration/production, existing wellbores could represent the most likely leakage pathway from storage reservoirs to subsurface resources, environmental receptors or the atmosphere.

Despite the complexity of the topic, particular concerns regarding wellbore integrity and CO_2 geological storage can be simply summarised as follows:

- That injection of CO_2 (and any associated impurities) into geological formations will create a corrosive environment in which wellbore materials (steel and Portland cement) may be degraded, leading to loss of integrity and leakage of CO_2 and/or brine from the storage reservoir;
- That the presence in storage reservoir/caprock sequences of existing wells, which may have been constructed and/or abandoned to uncertain or poor standards, increases the uncertainty surrounding potential CO_2 and brine leakage. Poor standards of construction and abandonment increase the probability of cement-free zones, mud channels in cement, and mechanical defects, such as poor bonding between well materials, which can compromise zonal isolation of fluids;
- That wellbore materials (steel and Portland cement) may not survive indefinitely (regardless of the fluids) and could pose a long-term risk of leakage (e.g., over the 100-1000 year time frame).

Research directed towards wellbore integrity and CO_2 geological storage has involved laboratory testing of cement and to a lesser extent steel samples in the presence of CO_2 and brine, theoretical modelling, analysis of data from industrial analogues such as the CO_2-EOR and acid gas (CO_2 and H_2S) disposal industries, analysis of data contained in databases maintained by regulatory agencies, and field studies of wellbore samples. There are continued efforts to obtain samples of cement and steel from wells that have been exposed to CO_2 within wellbores, for example in Phase II of the IEAGHG Weyburn-Midale Monitoring Project in Canada.

Given the importance of wellbore integrity to CO_2 storage, IEAGHG organised a network dedicated to this topic in 2005, with an initial vision for meetings to be held over a 5 year period. Table 1 below summarises subsequent network meetings which have, in total, attracted over 450 delegates from more than 20 countries.



Schematic describing the process of Enhanced Oil Recovery (EOR)

Date	Host	Location	Number of Delgates
April 2005	EPRI	Houston, TX, USA	50
March 2006	Princeton University	Princeton, NJ, USA	57
March 2007	Los Alamos National Laboratory	Santa Fe, NM, USA	63
March 2008	Schlumberger	Paris, France	73
May 2009	Alberta Research Council, TL Watson & Associates	Calgary, Canada	77
April 2010	Shell	Noordwijk Aan Zee, Netherlands	59
April 2011*	University of Western Australia and Curtin University	Perth, Australia	75*

**Combined meeting with the Modelling Network*

Summary of Key Findings and Future Research Directions

When the network was initiated, the community was faced with the stark question of whether wellbore integrity was possible given the known chemical reactivity of steel and Portland cement with CO_2-saturated brine. Beginning with the first meeting, a great variety and number of experiments on cement and steel, field studies of wellbore systems, theoretical modelling, and operational/regulatory information have been presented at the Network meetings. As a result, the field has evolved significantly as captured in the proceedings of the network meetings with some of the key findings as follows:

- Durability of cement: field work and some experiments demonstrate that while Portland cement is reactive with CO_2, the rate of penetration is slow and the consequences to isolation may be of limited significance;
- Importance of interfaces: Initial concerns focused on the materials themselves, but research has demonstrated that the risk of leakage is associated with existence of interfaces between cement-steel and cement-caprock that exist either due to poor completions or to mechanical degradation;
- Corrosion of steel: steel reactivity is more rapid than cement and had been neglected in earlier research;
- Geochemistry: Rather than a prime-factor in wellbore integrity, geochemical reactions are now viewed as either aggravating or ameliorating existing leaks through dissolution or precipitation;
- Self-healing in wellbore systems: Experimental studies have shown that precipitation of calcium carbonate in cement and iron carbonate in corrosion reactions can reduce permeability of interfaces and could limit wellbore leakage;
- Origin of wellbore problems: The most significant processes in the loss or lack of zonal isolation are failure to place cement adequately at the time of completion and subsequent geomechanical stresses induced by pressure changes, thermal fluctuations, and wellbore operations including mechanical integrity tests;
- Cement formulations: CO_2 resistant cements have been developed; expansive cements (for sealing microannuli) have been described; non-Portland cement systems have been considered; and differences between neat Portland cement compared with pozzolan (flyash)-bearing cements have been demonstrated;
- Wellbore permeability: This remains a key research need, but substantial progress has been made with field measurements of effective wellbore permeability and experimental studies of cements with defects, both of which suggest effective permeabilities of the order of 1 mD;

- Factors governing wellbore performance: Databases were developed that allow correlation of wellbore attributes with likely wellbore performance as measured by sustained casing pressure (aka surface casing vent flow), gas migration and casing failure, and provide a key risk assessment tool;
- Co-contaminants: Reaction of co-contaminants (H_2S) with cement have been initiated and thus far have not been found to be significantly more deleterious to cement;
- Record of CO_2 operations: The network meetings have not revealed any significant accidents or environmental impacts associated with CO_2-EOR operations lending greater confidence in the ability to manage well integrity;
- Materials in wellbores: Research suggests that proper use of carbon steel and Portland cement may be adequate and that stainless steel and special cement formulations may be less critical to achieving well integrity.

Significant challenges as well as untapped research potential remains in the wellbore integrity field. The following research areas represent potential topics or themes for future network meetings:

- Long-term integrity: Almost no work has been done to consider the very long-term (100-1000 years) durability of cement and steel and the implications for long-term storage security;
- Multiphase flow processes in wells: Current leakage models in wells are based on Darcy flow and do not adequately represent multiphase flow in fractures/ interfaces characteristic of wellbore defects;
- Permeability: Effective permeability of wellbore systems are still poorly known and needed in risk assessment;
- Frequency: What features of wells (age, materials, completion details) represent increased potential for wellbore failure and how frequently do wells fail?
- Leak detection: The ability to detect, locate and quantify wellbore leakage is not yet sufficient;
- Geomechanics: Models of the impact of stress due to injection/production activities on wellbore integrity including formation of microannuli, fracturing of cement or caprock, and deformation of steel;
- Coupled geomechanics with flow and reaction: Analysis of the potential role of stress in creating fluid flow pathways in the wellbore coupled with determination of CO_2/brine flow rates and the consequences of geochemical reactions on modifying the effective permeability of the mechanical defect;
- Coupled experiments: Experiments that couple stress with flow of CO_2-brine through synthetic wellbore systems (steel-cement-rock) designed to illuminate flow mechanisms, permeability, and self-healing;
- Self-healing: Under what conditions do geochemical (precipitation) and geomechanical (deformation) processes seal wellbore defects?
- Fate of leaking fluids: Are (near) surface or subsurface aquifers the most likely destination of leaking CO_2 and brine and what factors control this behavior?
- Shale gas analogue: Analysis of the experience of methane leakage in the shale gas industry may be very instructive with respect to frequency and mechanisms of wellbore failure (that are certainly the most significant cause of problems) as well as the migration and geochemical impact of gas through the wellbore;
- CO_2-EOR: Relatively little information has so far been obtained from the vast experience available in the CO_2-EOR industry with particular reference to the frequency and cost associated with remediating old wells during initiation of CO_2 floods;
- Regulatory data: Significant opportunities exist in regulatory databases on wellbore performance including mechanical integrity test data, accident frequency, and remediation activities;

The problem of wellbore integrity is nowhere so acute as when considering CO_2-EOR as sequestration or storage in depleted oil and gas fields (Carbon Capture Utilization and Storage, CCUS). While not applicable in many regions, CO_2-EOR offers tremendous potential as a technology bridge to saline aquifer sequestration because of the potential financial offsets gained from oil production. However, this will not be possible without an effective strategy for well integrity.

Network Findings

2005 Meeting

The first network meeting in Houston set out some of the key issues for wellbore integrity and storage, as follows:

- Ensuring wellbore integrity over long timescales presents a novel challenge for the oil and gas industry. Whilst application of 'state of the art' technologies can reduce risks associated with leakage, it is impractical to absolutely guarantee a 'leak-free' well;
- Standard Portland cements will react with CO_2 – portlandite and calcium silicate hydrates convert to carbonate minerals such as aragonite and calcite, with potential impacts on wellbore integrity. Laboratory experiments can simulate these reactions but extrapolation to field reaction rates is problematic due to unrealistic laboratory conditions;
- Alternative cements resist carbonation reactions by reduction/elimination of portlandite, or use of inhibitors – however the use of such alternative materials may significantly increase costs and have not been widely tested in field settings;
- Studies of wellbore issues from the CO_2-EOR industry represent the most appropriate industrial analogue to provide data on likely failure rates and associated processes and to inform storage risk assessments and risk management strategies.

The meeting also identified key research needs at the time, including definitions for failure criteria, acquisition of detailed data from industrial analogues, further understanding of cement failure including by sampling of wells exposed to CO_2, and standardisation of testing procedures.

2006 Meeting

Princeton University, venue for the 2nd WBI Network meeting

The 2006 meeting highlighted wellbore integrity issues within the oil and gas industry. The meeting heard that up to 60% of wells offshore in the Gulf of Mexico experienced Sustained Casing Pressure (SCP) problems, compared, for example, with only 6% of the wells in Alberta that experienced Surface Casing Vent Flow (SCVF, equivalent to SCP), possibly indicative of compromised wellbore integrity. In the US Permian Basin, oil fields switched to CO_2 flooding typically required major remedial work on existing wells not previously exposed to CO_2 – involving pulling tubing and re-cementing activities. These various problems could be attributed to such factors as poor removal of drilling mud or poor cementing practices. Inadequate sealing could allow circulation of saline water, inducing corrosion of casing and deterioration of cement. The meeting heard that the American Petroleum Institute (API) had recognised these various problems and, in response, API was developing guidelines and standards for well completions and CO_2 floods.

The meeting also heard how cement samples taken from a well exposed to CO_2 in the Permian Basin showed limited alteration in comparison to some of the dramatic degradation of Portland cements caused by CO_2 in laboratory experiments. The design of new CO_2-resistant cements was welcomed by industry representatives but caution was also expressed on cost and performance aspects of such new cements.

2007 Meeting

Delegates at the 2007 meeting agreed on the continued significance of wellbore integrity, emphasised by presentations and discussions at the meeting concerning the issue of wellbore integrity in the context of developing wider CCS regulations.

An ongoing theme from previous meetings was the discrepancy, in terms of cement resistance to CO_2-induced degradation, between some laboratory experiments that showed rapid and deleterious CO_2-induced degradation of cement compared

Extracted Pipes used in CO_2 Injection – showing no serious degradation despite long exposure to CO_2

Santa Fe, venue for the 3rd WBI Network meeting

with field-based observations indicating decades-long persistence of cement in the presence of CO_2. Despite the advances in understanding of reactions and processes since the previous meeting, discussions highlighted the need for continued research on this topic.

Another significant aspect of the discussions addressed risks associated with old and abandoned wells in regions of intensive oil and gas industry activity. Two examples described were Alberta, where a large repository of information is available on historical wells, and in contrast Texas where records of up to 1 million old wellbores are highly variable. Delegates discussed the importance of the issue for storage site selection, and agreed the need for more research in the absence of defined standards for re-completing old wells.

2008 Meeting

The 2008 meeting included presentations describing wellbore experiences in two important oil and gas regions, the Norwegian North Sea and Alberta. In the former, between 20% and 30% of all wells had at least one leakage incident recorded, representing an apparent dramatic rise from the 1990's that could be due to increased awareness

Paris, venue for the 4th WBI Network Meeting

and reporting of problems. Cement failures were not known to be the cause of any problems, however. From a detailed study of 79 wells in Alberta used for CO_2 or acid gas injection, initial conclusions included that purpose-built injectors performed better than converted wells, and that a majority of wellbore integrity issues were caused by tubing and packer problems. Moreover, these failures could occur in wells that utilised CO_2-resistant cements.

The meeting included talks from various organisations concerning ongoing research programmes into cement carbonation and degradation. Discussions amongst delegates again highlighted discrepancies between laboratory test results and operational experience within industry, backed up by field data. An important knowledge gap identified was the mechanical behaviour of cements exposed to CO_2 over long timescales.

Presentations and discussions on the topic of predictive modelling highlighted the serious challenges faced by researchers in developing quantitative assessments of wellbore performance, especially over extended timescales. Regulators are likely to require quantitative models of long term storage site performance, as part of overall risk assessment and management plans, and wellbore integrity may have to be incorporated in such models for many sites. An example of the detail to be resolved is the understanding of processes that may affect the wellbore-formation interface, and the condition of the geological formations in the immediate vicinity of the wellbore.

2009 Meeting

The 2009 meeting in Calgary attracted significant interest from industry, reflected in the composition of the delegates list and by a number of presentations. Delegates viewed data which showed reductions in oil and gas industry well blowouts between 1991 and 2005, attributed to improvements in engineering design and management practices. The meeting also heard examples of successful re-plugging of old/abandoned wells from North American CO_2-EOR projects, and on the development of alternative plugging materials to conventional cement that have been successfully applied to well completion and remediation problems. The potential importance of old/abandoned wells to CCS projects was highlighted by discussion of the De Lier gas field in the Netherlands, which was not pursued as a CO_2 storage site because of the technical challenges and associated costs of re-plugging old wellbores – some being present in an urban environment.

Another key topic of discussion was around definitions – leakage is a critical concern for CCS projects, but some industrial analogue data may include small scale, near-surface integrity issues which would not necessarily affect storage integrity. The meeting also allowed continued debate on the challenges of extrapolating long term cement performance predictions from accelerated laboratory experiments; recent research by the DOE/NETL in the USA had produced encouraging results during attempts to calibrate experiments with field data. Nevertheless, the meeting heard how risk assessments of wellbore integrity for CO_2 storage remained essentially qualitative or semi-quantitative, relying heavily on expert judgement supported through analogue data. Also agreed by delegates was the importance of effective monitoring of wellbores for leakage as a risk management tool.

Summing up the meeting discussions, an apparent dichotomy was evident between the confidence of industry representatives who emphasised the practical experience of successful CO_2-EOR projects dealing with wellbore integrity issues, and the caution of storage researchers who stressed the novel aspects of industrial scale CO_2 storage – including long timescales, regulatory/public perceptions of risks associated with leakage, and reservoir pressurisation.

2010 Meeting

Whilst the 2010 meeting was well attended, albeit with fewer delegates than the previous meeting, setting an agenda for the full 2 days proved challenging for the steering committee; ultimately there was a heavy reliance on hosts Shell, and Schlumberger, to contribute presentations. However, the meeting began just as the Macondo Well blowout occurred in the Gulf of Mexico, providing a dramatic highlight to discussions of wellbore integrity.

A study undertaken by TNO on behalf of IEAGHG, commissioned as a result of previous network meeting discussions, was reported to the delegates. The study looked at wellbore abandonment practices from a geographical and historical perspective. A central conclusion of the report was that old wellbores will present a major risk consideration for many sites, whereas newly constructed wells should be associated with minimal risk. Other talks at the meeting also underlined that recent advances in wellbore technology should minimise risks associated with new wells. For example, API reported that of 15,000 operational CO_2-EOR wells in the USA, only 0.009% experienced serious operational problems due to a 'loss of control'; these statistics do not include minor leakage incidents that can be readily repaired. Picking up on this theme, the meeting heard arguments that leakage needs to be assessed in terms of risk (i.e. taking into account potential impacts) so that possibilities of minor leaks do not assume exaggerated importance to CCS projects.

The assessment of risks associated with old wells would continue to be a focus of future research but is site-specific in nature. Delegates agreed that most storage reservoirs can be assessed and risk managed using available data and well records, with re-plugging undertaken as necessary but subject to cost factors.

Latest developments in corrosion studies of wellbore materials reported to delegates tended to focus on the importance of micro-annuli and material interfaces, providing potential pathways for CO_2 migration and enhanced corrosion. The meeting heard how many processes could promote 'self-healing' of pathways through factors such as mineral precipitation. Similarly, shale creep could be utilised as a 'self-healing' process to augment zonal isolation measures for abandonment.

2011 Meeting

Following the problems encountered by the steering committee in setting an agenda in 2010, the 2011 meeting was held as a combined meeting with the modelling network; wellbore integrity issues were discussed in a dedicated session.

The meeting heard from two initiatives to publish guidance on wellbore integrity issues for CO_2 storage. The US Regional Carbon Sequestration Partnerships (US RCSP) programme had compiled best practice guidelines for drilling, well installation, operations and closure. A Joint Industry Project on guidelines for wells, led by DNV, was also reported to the meeting; delegates heard that monitoring will be emphasised as a critical element in the guidelines, and that predictive modelling will be recognised as essential component in the risk management process.

Other presentations included updates on recent efforts to predict cement performance from laboratory tests, with results that allowed for self-healing characteristics of processes such as precipitation of new phases in pores. Results therefore tend to better replicate operational experiences. The meeting was also updated on the field sampling exercises undertaken as part of the IEAGHG Weyburn-Midale project, with results due to be published in 2012.

Summary: Current State of Knowledge

Sidewall core illustrating interface of cement and caprock shale

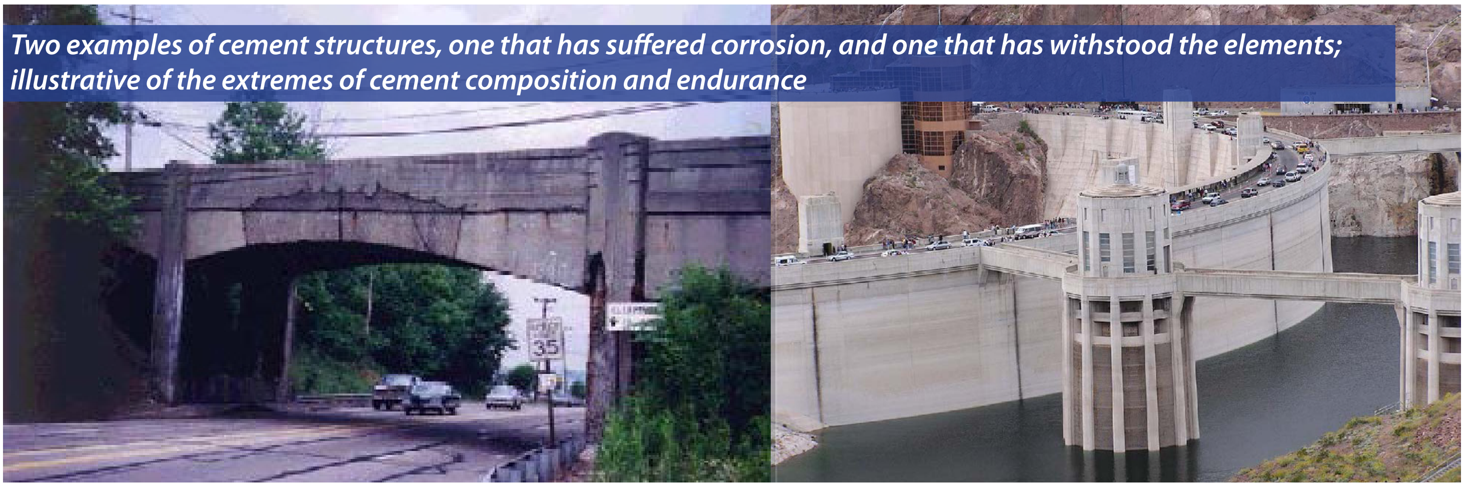
Given technological advances in drilling and improvements to management practices in the oil and gas industry, there is a strong argument that risks associated with new, purpose-built wells at storage sites can already be adequately managed and are likely to be actively monitored. Conversely, existing wells have been subject to variable standards of construction, operation and abandonment according to such factors as age, regulatory jurisdiction and geographical location and may be difficult or expensive to monitor. Poor practices are more likely to have resulted in defects that can allow vertical fluid migration in such wells. The presence at some storage sites of existing or abandoned wells remains a complex risk management issue that will require effective monitoring programmes and possibly remediation works, as have been applied at some CO_2-EOR sites.

Many of the presentations and discussions at network meetings have inevitably revolved around the potential effects of CO_2 injection on wellbore materials, and particularly on cements. Zhang and Bachu (2011) provide a review of both mechanical and chemical factors that can lead to wellbore integrity issues for existing wells, with a focus on the complexity and phasing of reactions that can affect cements as witnessed by both laboratory experiments and field samples. Initial reactions between CO_2 rich brines and conventional cements are likely to result in the precipitation of calcite, which is likely to reduce permeability by 'clogging' pore spaces and fractures. Laboratory experiments have shown that subsequent exposure to brine in a "high-flow" environment can lead to calcite dissolution and degradation of the cement; however, this may be mitigated by the presence of calcite in reservoir rocks, which would mean that brines were already in equilibrium with calcite and thus unlikely to result in dissolution. In the absence of flow that would wash/flush away the calcite, further cement degradation is likely to stop, as diffusion is a very slow mechanism for bringing CO_2-saturated brine in contact with original cement.

Priority areas for further research identified in network meetings include:

- Standard definitions for wellbore integrity issues that can be applied to CO_2 geological storage;
- Mechanical properties of carbonated or degraded cements;
- Further field sampling of wellbore materials that have been exposed to CO_2 at reservoir conditions, allowing improved understanding of processes and calibration of laboratory experiments/theoretical modelling;
- Development of quantitative modelling and integration into storage site risk assessments;
- Effective monitoring strategies for wellbores and potential leakage.

Two examples of cement structures, one that has suffered corrosion, and one that has withstood the elements; illustrative of the extremes of cement composition and endurance



Conclusions

The network has provided a valuable international forum for discussion of wellbore integrity issues pertinent to CO_2 geological storage since its inception in 2005. The network meetings have presented detailed information from industrial analogues to storage, especially from the oil and gas industry including North American CO2-EOR and acid gas disposal projects. Statistics on wellbore leakage and failure rates have been presented and discussed, whilst best practice guidelines have been debated.

Research over the last 6 years has greatly improved our understanding of processes linked to potential alteration and degradation of wellbore materials, especially cements. Much of the relevant research is included within presentations made at network meetings.

Presentations and discussions at network meetings have indicated that wellbore integrity issues for new, purpose-built CO_2 injection and monitoring wells should be manageable with appropriate use of best practice guidance, backed by experience from the oil and gas industry. The presence at some storage sites of existing or abandoned wells remains a more complex risk management issue that will require effective monitoring programmes and possibly remediation works, as have been applied at some CO_2-EOR sites.

Quantitative prediction of wellbore integrity over longer timescales, and integration into risk modelling for storage sites, remains challenging and will require continued research effort as the number of large scale storage projects associated with CCS deployment increases over the coming decade.

Although recent network meetings have continued to attract significant numbers of delegates, the steering committee has found increasing difficulty in setting agendas that incorporate new research. This was particularly problematic in 2010, and led to the decision to hold the 2011 meeting in combination with the more recently instigated Modelling Network, which has attracted greater numbers of delegates and volunteers for presentations. On the other hand, there is continued recognition that there remain important research questions in wellbore integrity that create uncertainty in the long-term storage of CO_2.

Recommendations

Whilst wellbore integrity remains an important topic for storage, IEAGHG should consider whether current levels of new research warrant a dedicated network. The topic could alternatively be incorporated in other network meetings (Risk Assessment, Monitoring, Modelling), or the network could be revived at an appropriate point in the future when warranted by information from new research and increased numbers of storage sites. Another possible alternative is to held meetings every two years rather than annually.

Collectively, the presentations made at network meetings since 2005 constitute a useful body of knowledge. IEAGHG should consider an indexing or database system to allow network members to make full use of the information.

References and Acknowledgements

References

Crow, W., Carey, J.W., Gasda, S., Williams, D.B., Celia, M., 2010. Wellbore integrity analysis of a natural CO_2 producer. International Journal of Greenhouse Gas Control 4 (2), 186-197.

IEAGHG Report 2009/08. Long term integrity of CO_2 storage – well abandonment.

Zhang, M., Bachu, S., 2011. Review of integrity of existing wells in relation to CO_2 geological storage: What do we know? International Journal of Greenhouse Gas Control 5 (2011), 826 – 840.

Acknowledgements

IEAGHG is indebted to present and past members of the Wellbore Integrity Network steering committee for their efforts in setting previous agendas and participation in meetings. The following steering committee members contributed to the preparation of this summary report:

- Stefan Bachu, Alberta Innovates Technology Futures
- Bill Carey, Los Alamos National Laboratory
- Mike Celia, Princeton University

IEAGHG also acknowledges the support of the various network meeting hosts and sponsors since 2005.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Orchard Business Centre, Stoke Orchard,
Cheltenham, Glos. GL52 7RZ, UK

Tel: +44 1242 680753
Fax: +44 1242 680758

mail@ieaghg.org
www.ieaghg.org