



4TH WELLBORE INTEGRITY WORKSHOP

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ACKNOWLEDGEMENTS AND CITATIONS

The IEA Greenhouse Gas R&D Programme supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by the IEA Greenhouse Gas R&D Programme as a record of the events of that workshop.

The fourth international research network on Wellbore Integrity was organised by IEA Greenhouse Gas R&D Programme in co-operation with Schlumberger. The organisers acknowledge the financial support provided by Oxand, Suez, Total and BRGM for this meeting and the hospitality provided by the hosts Hotel Concorde Montparnasse, Paris.

A steering committee has been formed to guide the direction of this network. The steering committee members for this network are:

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John Gale, IEA Greenhouse Gas R&D Programme (Co-chair)
Veronique Barlet-Gouedard, Schlumberger
Idar Akervoll, SINTEF
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Summary Report of 4th Wellbore Integrity Network Meeting

Date: 18 – 19 March 2008

Hotel Concorde Montparnasse,
Paris, France.

Organised by IEA GHG and Schlumberger,
with the support of Oxand, Suez, Total and BRGM



Schlumberger



SUEZ



FOURTH WORKSHOP OF THE INTERNATIONAL RESEARCH NETWORK ON WELLBORE INTEGRITY

Executive Summary

The fourth meeting of the Wellbore Integrity Research Network was held in Paris, France in March 2008. As with the previous meetings, there was a good attendance, covering research, academia, and regulators and the meeting included presentation of some new results, some of which generated in depth discussion and interesting points that were discussed in greater detail in the facilitated discussion sessions.

The presentations were held over 2 days, and were split into four topics. These were: Field investigations of wellbore integrity, Experimental studies of wellbore integrity, numerical modelling, and Monitoring, risk and development of best practices. Each session was followed by a facilitated discussion session on the topics covered by the presentations, as this format has been tried and proven over the previous meetings. The debates spurred by these discussion were often carried over into the coffee breaks, such was the interest and variation in opinion generated.

The level of involvement and discussion highlights that the issue of wellbore integrity is still of very high importance and that there is still much relevance and benefit in holding the network meetings. The insightfulness of some of the discussions showed the depth of knowledge and understanding involved with the participants is industry leading, and indeed the affiliations of the participants further illustrated this.

Discussions were equally weighted across the topics, with a wide range of inputs from most all the participants, demonstrating the value of the meetings and the level of interest felt by all who attend. There was some intense debate over several contentious issues, and this illustrated the work still to be done which the network can contribute to; there is a variety of opinions of some issues, and the CCS community needs to work through these conflicts to achieve a consensus if it is to present a unified front when addressing concerns of both the general public and regulatory bodies alike. The approval of these 2 groups will be vital in achieving acceptance of the technologies used for CCS, and the material presented by groups working on complex dynamic modelling show that real progress is being made towards demonstrating a good level of certainty of long-term, safe and secure storage.

Discrepancies highlighted at previous meetings between laboratory and field experiences are still present, but the gap between them is narrowing, and there was a feeling of an increased understanding as to what generates these gaps. With constructive criticism, some of the techniques used to extrapolate long-term data from short-term accelerated laboratory based procedures were questioned and defended, illustrating that, despite progress being made, there is still a long way to go.

The need for the continued existence of the meeting was discussed, and agreed as there is still new and innovative research being presented at the meetings, showing that there are still developments and breakthroughs to be made in the journey to the long term goals of providing assurance to stakeholders that the mechanisms operating within the wellbore are understood, risks can be identified and minimised in advance, and should leaks occur, monitoring methods will allow rapid detection and mitigation, therefore minimising or avoiding risks to health.

Contents

Executive Summary	3
1. Introduction	5
2. Aims & Objectives of the 4 th Workshop.....	6
3. Workshop Attendees.....	6
4. Workshop Programme.....	6
5. Technical Presentations	11
5.1 Field Investigations of Wellbore Integrity	7
5.2 Experimental Studies of Wellbore Integrity	10
5.3 Numerical Modelling.....	14
5.4 Monitoring, Risk and Development of Best Practice	18
6. Discussion Sessions	22
6.1 Field Investigations of Wellbore Integrity	22
6.2 Experimental Studies of Wellbore Integrity	23
6.3 Numerical Modelling.....	25
6.4 Monitoring, Risk and Development of Best Practices.....	26
7. Summary.....	27
8. Conclusions	29

1. Introduction

This fourth meeting of the wellbore integrity network was held in Paris, and hosted by Schlumberger. The president of Schlumberger Carbon Services, David White, gave an introduction to the meeting, introducing and giving a brief background to Schlumberger and their areas of expertise, encompassing their background of CCS activities.

At the end of the 3rd meeting of the network, it was hoped that the network meetings would continue to provide a valuable insight into the activities and state of art on wellbore integrity issues, and David Whites presentation mirrored that hope. David's presentation went on to state that the issues associated with wellbore integrity were a global problem, and on that basis, they need a global solution which has lead to an ever expanding global research and development budget.

He feels that although there is definitely a convergence of opinions taking place regarding CO₂ and climate change, there still exists a healthy scientific debate regarding some aspects of the science. This was born out in the discussion sessions, with numerous variations on views expressed, and this scientific debate is necessary in order to progress towards the ultimate goal of demonstrating safety and security of CCS, and in particular to this network, the ability to accurately model a '1000 year well'¹. The transition from the 1000 year well concept to that of accurate modelling to demonstrate safety over geologic periods has lead to an increased focus on the modelling community, and this was also borne out by the focus on the modelling session being much more detailed than in previous meetings.

David went on to say that even if the global population takes into account the uncertainties to CO₂ and climate change, there are definable benefits to curbing CO₂ emissions and improving efficiency of power generation. In terms of CCS viability, it is therefore important for the scientific community to be well prepared to answer any and all questions likely to be raised by the general public, regulators and legislative bodies alike.

David discussed the viability of different mitigation options, and the potential difference each option can make, and also provided a good summary of the issues which will need to be solved in order to obtain public acceptance of the technology, with particular attention to risks and regulations. He also commented that it was important to put risks and activities into perspective, and that one view was that currently, we have an effective leakage rate of 100%. Now, this is obviously an unjustifiable view, as emissions to atmosphere from power stations cannot be considered as leaks as they are not intended to do anything else, but it does add reason to the argument that any CO₂ that is stored and prevented from entering the atmosphere is a bonus over the current situation. Obviously, in terms of a scientific argument, this holds no water, but it can be used as an interesting discussion, and highlights that doing something is better than doing nothing. David concluded with the quote that there is 'No such thing as a bad experiment, just an unexpected result.'

¹ The concept of a 1000 year well was one conceived before the start of the inaugural Wellbore Integrity Network meeting, and the network set out to determine the feasibility of such a well. Since then, the concept has adapted, and is now looked at as accurately predicting the behaviour of injected gasses and wellbore materials for a length of time equal to that in which the CO₂ would become permanently trapped and immobilised.

2. Aims & Objectives of the 4th Workshop

The network was, at the start of this meeting, entering into its fourth year of operation, and the network was originally established with 5-year tenure. Therefore, the results and conclusions of this meeting will form part of the discussion at the 5th meeting in 2009 as to the validity of continuing the network past the original 5 years as planned.

The broad aims of the network remain unchanged, and they are:

- To provide confidence to all stakeholders that the mechanisms involved with maintaining wellbores is understood.
- That the safety of storage, specifically in relation to wellbores, can be ensured because the risks can be identified and minimised.
- That wellbores can be monitored for early signs of leakage, and remediated as necessary.

The meeting also had some specific aims identified in the conclusions from the 3rd meeting, and these included:

- Investigating the contrast between field and lab results.
- Updating the advances in technologies and understanding, as was seen between the 2nd and 3rd meetings.
- Continued investigation of the advancements made in the modelling of wellbores and the reactions between CO₂ and wellbore materials.

3. Workshop Attendees

The meeting was attended by 73 delegates from 12 countries (Appendix 1). The delegates represented regulators, international industrial operators and geological researchers from Australia, Europe, North America and Asia.

4. Workshop Programme

The programme and agenda for the meeting are presented in appendix 2. The Wellbore Integrity Network meeting was divided into a series of sessions, which focussed on specific topics within the scope of the network, with discussion sessions held after each technical session.

5. Technical Presentations

5.1 Field Investigations of Wellbore Integrity

The presentations were held in 4 sessions, each covering a different broad topic, and with a related facilitated discussion. The results from the presentations are below, and details of the facilitated discussion sessions can be found in section 6.

5.1.1 SINTEF Assessment of Sustained Well Integrity on the Norwegian Continental Shelf, Preben Randhol and Inge M Carlsen, SINTEF Petroleum Research

Preben gave a detailed, geographically specific presentation about the activities of SINTEF on the Norwegian Continental Shelf, and the presentation was well received. Regional reporting is becoming more important and relevant as variations in practices around the world must be understood to determine best practices in different situations.

Operations within the Scandinavian region are moving more towards sub-sea injection programmes and injection in arctic regions. This type of operations encounter specific problems, including those associated with access when working in the sea, and more precisely difficulties with arctic conditions and accessing sites that may become ice bound.

The development trend of projects in this area is to re-use the existing well infrastructure, and this leads to the need for thoroughly documented field integrity. All wells used in these operations, both oil and gas producers and injectors, and gas lift wells have to be designed with two barriers to prevent hydrocarbons reaching the surface.

The presentation then went on to the more focused area of wellbore integrity, and revealed that of all the wells in the scope of operations on the Norwegian Continental shelf, between 20-30% of wells have suffered at least one leak. This highlights the importance of wellbore integrity, and indeed the presentation goes on to list 5 considerations as to why wellbore integrity is of such importance, and these are: safety, environment, production, reputation and asset value. These considerations are representative of the aims of the activities on wellbore integrity around the world, as they cover confidence, security, monitoring and environmental protection, the areas which will be influential in deeming a project publicly acceptable or not.

The SINTEF studies on wellbore integrity mapped leakage history from 1998 to the first quarter of 2007, and there is a notable rise in the percentage of wells that have suffered leaks, from 1.69% in 1998 to 25.5% in quarter 1 of 2007. On the surface, this looks like a worrying trend, but there may be mitigating factors in this, which are listed in the presentation to include the increasing age of the wells surveyed; as wells age, the degradation will increase, and this will increase the likelihood of a failure and leak. Another factor may be the processes involved in reporting and awareness of the issues and processes involved; the data doesn't appear to be strictly age related, in so far as some older fields have lower leakage rates than some newer fields. There is also an interesting correlation between an apparent increase in well failure and the date that the company employed an individual to manage and investigate leaks. This further backs up the theory that the leaks are not a new phenomenon, but rather they were not understood and reported correctly before this point.

At this point, the presentation was opened to questions, and Ron Sweatman asked what the main causes of leaks identified were. Idar Akervoll answered that they were mainly internal failures, but with some seal and steel issues as well. At no point in the investigation was a

cement failure noted, and Idar confirmed that if such a failure were present, it would have been identified. Although determining the leakage pathway is tricky in this case study, it is thought that monitoring should be able to determine it.

5.1.2 Charles Christopher, BP; A Comprehensive Wellbore Integrity Programme,

Charles Christopher gave a brief summary of the requirements of a CO₂ Wellbore Integrity Programme which included field data and references to an ongoing project, although no results or conclusions were presented from this project as it is incomplete, the preliminary results therefore still require careful evaluation and confirmation before being disseminated.

Despite this, there were three main points presented as possible areas for future development and research:

- The kinetics tests carried out within the laboratory environment did not reciprocate and match the results gleaned from the field experiments. This suggests that more extensive field and laboratory work is required to determine the consequences and repercussions of this if the results are replicated in subsequent experiments.
- A cement core taken from the well covering a depth to include both the cap rock and cemented section shows signs of very good bonding between the sections. It was also noted that the cement section appeared to be porous and is being analysed in more detail to determine this.
- It can be concluded that a comprehensive wellbore integrity programme must include the regulators involved in a storage project, as well as the surrounding community and the project operators. As much information as is possible should be assimilated and disseminated at an early stage to minimise the need for repeated requests for information.

Charles finished by saying that there were some very interesting and promising results coming from the project, but until full evaluation of results have been carried out no figures and data will be published yet.

5.1.3 Theresa Watson, TL Watson & Associates, Review of Failures in Wells used for CO₂ and Acid Gas Injection

Theresa presented work undertaken by TL Watson and Stefan Bachu of the Energy Resources Conservation Board reviewing failures in wells used for CO₂ injection and acid gas disposal in the Alberta region of Canada. The data is newly acquired, and the report is yet to be completed, but the initial results are discussed by this presentation.

The work described how the acid gas / CO₂ wells in Alberta were assessed, along with the regulations that applied when the wells were drilled, and this in itself provided a good overview of the regulatory changes and procedures throughout the region. The report highlighted the fact that according to the regulations, there is no requirement to inspect the casing used in the wellbore to determine the presence of carbonation and its action on the materials present in the wellbore. The regulations were noted to have no effect on the occurrences of H₂S leakage, although this is thought to be due to the stringent practices

followed by acid gas disposal operators as H₂S leaks are likely to be fatal due to the toxicity of the gas involved.

Unsurprisingly, the review shows that the failure rate is lowest in wells that were built for purpose over those that have been converted from previous operations; this was more pronounced in acid gas injectors over CO₂ injectors.

Theresa went on to analyse the causes of failures observed, and it was clear that the primary cause for injection failure was tubing and packer failure. These types of failures are easy to detect, and annual testing requirements are designed to ensure continued integrity of these elements, with failures needing immediate repair. When the report looked at failures not linked with injection, the spread of causes was not dissimilar to that of the general well population in the region.

Members of the meeting queried the impact of the use of specialised cements on the failure rates, and it was confirmed that experience shows that failures still occur; even when the well concerned was completed using specialised, CO₂ resistant cement.

5.1.4 Matteo Loizzo, Schlumberger Carbon Services, Advances in Cement Interpretation: Results from MOVECBM (Poland), COSMOS-2 (France/Germany) and Otway Project (Australia).

This presentation dealt with advances in interpretation of the results from cement experiments, and as a starting point, worked from the conclusions drawn from the EPA CO₂ Geosequestration workshop in 2007. From this point, analysis from the CO₂SINK and MOVECBM projects, amongst others, were taken and from this, the key advancements in the state of knowledge were highlighted.

It was explained that leaching relies on fluid flow transport, as the absence of this transport mechanism precludes the action of leaching through the cement. The presentation went on to provide a good explanation of the various pathways that can be present, and the mechanisms that can facilitate and assist leaching. Much discussion centres on the quality of cements used, but the presenter explained that the best possible cements will only be successful in resisting corrosion in the best circumstances and conditions. Even the strongest cement will crack if hit hard enough or subjected to sufficient stresses and forces, so the creation of pathways is always theoretically possible. To this end, the best designs should be used to minimise risks, and this should be coupled with effective monitoring to detect pathway formation as soon as possible.

The testing of cements was explained, and both sonic and ultra-sonic methods were described along with the combination of these methods with wire-line tools to maximise the ability to detect pathway formation and transport. The presentation went on to explain that these methods do still have limitations, and there are limits to what can be detected; an example being that when there is a fluid filled annulus, the testing is much less sensitive, and the attenuation of the tools becomes greatly reduced.

Analysis of the channel porosity in the projects used as examples illustrates the effectiveness of the well design, and indeed the time log results from the Ketzin project clearly show when the cement turned from a slurry to a solid-set material. It was highlighted at this point that a good, solid cement can have certain drawbacks, in so far as if the well requires remediation in the future; repair by cement squeeze is much more difficult and less likely to be successful in a

stronger, harder cement than a weaker cement that was made with a higher water content. However, cements with higher water contents are more prone to higher porosity which is undesirable in CO₂ storage situations. For a detailed explanation of the differences in cement / water ratios, see the 2007 Wellbore Integrity Workshop report.

The presentation went on to highlight the types of cracks that can form and the problems associated with them. Specifically, it was explained that horizontal cracks on their own do not represent a great risk to storage integrity, but they can allow separate vertical cracks and defects to join up and potentially create pathways to subsurface areas above the caprock, thus causing integrity issues.

5.2 Experimental Studies of Wellbore Integrity

5.2.1 Brian Strazisar, NETL, Kinetics of Well Cement / CO₂ Reactions.

Brian drew from the presentation given at the previous meeting of the network, and gave an update on new results and completed aspects of the experiments. The focus of the experiments was on existing wells rather than new wells, and the potential impact of cement degradation in such wells on the integrity of CO₂ storage.

The experiments were able to simulate both hydrodynamic and solubility trapping of CO₂, and observed that the degradation rate commences high and drops off as the reaction continues. The penetration of the carbonation reaction on the cement sample was found to be in the region of a fraction of a millimetre, so on a well scale, very little.

The experimental procedure went on to project exposure into the future, over a scale of 20, 30, and 50 years, and these projections showed the carbonation penetration reaching depths of up to 1mm (the deepest penetration reached just over 1.15mm) depending on the critical state. The experiment looked at different cement blends as well, and the worst example was a 35:65 pozmix sample which, after a period of 9 days, had degraded right through, although the outside of the resultant calcite ring proved to be harder than the original cement. An opposite sample of 65:35 ratio also degraded right through over the 9 day timeframe, and also showed increased hardness of the calcite ring over the original cement. The porosity of this sample went from 1 to 19 microdarcy in the 9 day period.

- Q. If the porosity is measured, which zone is measured?
- A. The porosity stated is an average of the 3 identified zones.
- Q. How was the CO₂ pressure maintained as a constant over the 1 year period?
- A. A syringe pump was permanently attached to the apparatus, and although leakage did occur, the syringe pump maintained the pressure as a constant.

The key findings to date do show progress from the results presented at the 2007 meeting, and it is now understood that the fractures seen under the scanning electron microscope (SEM) are actually caused by the vacuum of the SEM.

There are no plans for future experiments to utilise higher temperatures, and it was clarified that the experimental procedure is using a 1% NaCl to maintain conformity with previous experiments. No other fluids have been used, but it is accepted that there will be differences in

the results if different fluids were used. There are no current plans to use 'typical values', but there could be some benefit of this for the future.

5.2.2 Bogdan Orlic, TNO, Some Geomechanical Aspects of Well Integrity

This presentation covered the work of TNO staff, and follows from the work presented by Franz Mulders at the previous meeting of the network. Franz discussed the De Lier project, which has subsequently been cancelled due to high associated risks and excessive remediation costs predicted in the event of a leak. Although this site has been disregarded, a new feasibility study is being undertaken on an alternative site. Both projects, when dealing with best practice for abandonment of wells, recommend the 'Pancake Plug' method, a diagram of which can be seen in the presentation slides. The presentation went on to discuss the implications and requirements for practical research projects and CCS activities in the Netherlands, and the stringent conditions imposed by Dutch Mining Law. These conditions lead to extended laboratory modelling to demonstrate the minimisation of risks, and to this end, the projects involved look at all the stresses that are imposed on wellbore materials, and the effects of combining different stresses to create multiple stresses of wellbore cements and casings.

There was an explanation of why wellbores in areas of high rock salt abundance are considered to be risky due to the inability of salts to withstand changes in stresses. This was countered by Cal Cooper of ConocoPhillips by saying that the slides used in the presentation illustrate that a high presence of salts promote flow, and that the salts can 'self seal', effectively remediating any stress fractures as they occur, making areas of high salt abundance potentially secure sited for CCS. It was conceded that this may be a point worthy of investigation, however, the intention of the report was to identify the leakage pathways rather than suggesting ways round the problems or storage options.

5.2.3 Veronique Barlet-Gouedard, Schlumberger Well Services, Cementitious Material Behaviour under CO₂ Environment – A Laboratory Comparison

This presentation dealt with the issues surrounding the effects of cement being immersed in CO₂ saturated fluids. The experiments described used a Portland + Fly ash Type F cement under typical pressures and temperatures encountered in a CO₂ storage situation. The equipment used has the potential to operate and test at much higher pressures and temperatures, but for the purpose of this experiment, both parameters were kept at levels analogous of a storage reservoir scenario.

The slides shown went through the basic set up of the experiments, and explained how previous research had determined the toxic levels of CO₂ for humans are at approximately 10% atmospheric concentrations, although effects are felt at anything over approximately 2-3%. This was explained as the background to the importance of wellbore integrity and its relevance to health and safety issues.

The experiments looked at the effects of wet supercritical CO₂ and CO₂ dissolved in water on cement samples over 3 weeks, 3 months and 6 months exposure. It was noted that after the 6 month period, all samples had been degraded, although the experimental conditions were regarded as more severe than conditions experienced in the field, in order to accelerate the results and allow extrapolation of the same effects under more average conditions. The slides show a clearly visible dissolution front in the samples, and it was also noted that after 3 weeks

exposure, there was an increase in sample strength due to carbonation and the sealing effects of this plugging the pores.

Veronique concluded with a series of graphs illustrating the change in pore size and related changes in porosity, and a good explanation of the criteria for durability of samples and an analysis of the performance of different cement types.

Charles Christopher commented that some samples obtained from the field appear more similar to the 3 month samples than the 6 month samples, suggesting that time may not be the correct variable to plot, and advised caution over use of the experimental data. It was also pointed out that the extent of degradation after 6 months can make extrapolation of results a complicated procedure.

5.2.4 B. Lecampion, Schlumberger Carbon Services, Evolution of Cement Mechanical Properties During Carbonation.

Brice Lecampion gave an informative presentation further covering the effects of carbonation and mechanical degradation of cements in the wellbore environment. The presentation described in detail the experimental procedure and the conditions under which the carbonation was measured.

The methodology used repeated scratch testing to expose the carbonation front by determining the strength of the cement at varying depths, and the depth of carbonation is extrapolated using the hypothesis that the carbonated area will have a higher strength than the un-reacted zone. The results from this can then be up-scaled to determine the long term processes and mechanical effects of the carbonation.

The results so far are promising, but as yet are incomplete, and further testing is required to conclude the experiment. With the preliminary results obtained so far, it should be possible to correlate the porosity of each zone and determine from this the mechanical properties of each zone. It is noted at this stage of the results, that the inner zones of all the samples retain similar properties to those of the initial sample material, suggesting that an un-reacted zone exists at the centre of the sample, but this is an unconfirmed speculation at the present time.

In the concluding remarks made regarding the early stages of carbonation that have been observed, it is stated that the mechanical performance of the cement sheath will be associated with the thickness of the dissolution zone in the early stage of CO₂ – cement interaction, also that up-scaling allows the operator to estimate the elastic properties of different zones found within the samples.

5.2.5 A. Schubnel, ENS/CNRS Paris, Hydro-Mechanical Properties of Carbonated Cements

This presentation described some work on a new experimental procedure designed to determine the hydro-mechanical properties of carbonation at in situ reservoir conditions for temperature and pressure. The methodology involved gluing sensors to the samples in order to obtain accurate measurements for V_p and V_s.

The results show that a high crack density equates to high conductivity at effectively zero pressure, and that the permeability reduces with increased carbonation, but the additional shear

stress induced by this drastically increases the formation of cracks throughout the samples. It is possible that this damage could be due to the re-pressurisation process, and there are plans to repeat the experiments under in situ conditions to rule out the possibility of influence from the de-pressurisation / re-pressurisation process.

A question was asked at this point as to whether samples should be created under in situ conditions as this could involve different stresses than creating samples under ex-situ conditions and then subjecting them to in situ conditions. The answer to this was that currently it is not possible to create samples in the suggested manner, however new equipment that is under development at the present may make this a possibility and will be investigated in more detail when the equipment is ready for use. An additional comment suggested that dry samples are representative of the conditions near the wellbore perforations as the injected gasses would force any free fluid from the area, thereby drying the cement.

5.2.6 G. Rimmel, Schlumberger Well Services, How to Accelerate Cement Ageing in CO₂ Fluids: LIFTCO₂ and COSMOS-I

This next presentation dealt with experiments into accelerated ageing of experiments to extrapolate results of long term wellbore integrity and immersion in CO₂ fluids. The acceleration factor was used to illustrate the time frames anticipated to be involved in a CCS project, rather than a laboratory based experimental procedure.

Although there have been, and still are, many experiments being carried out on the subject and effects of mechanical properties of carbonation, this procedure differs in that it uses an electrical current flowing through the cement sample, and bubbling of CO₂ through an electrolyte to simulate the ageing of the materials and samples over the life of a CCS project.

The methodology called for core samples to be taken and the carbonation and degradation extent measured. The mineralogical analysis shows marked differences between the experiments using 0 volts and those using 10 volts; the alteration front is slightly thicker at the cathode in the 10 volt simulation. The alteration fronts varied from 0.3mm with a 0 volt current, 0.6mm at 10 volts, and 1mm at 30 volts.

Questions were asked as to the effects of higher still voltages, and it was explained that this was investigated, but there were increased enhancements, and indeed it can induce radial cracks in the cement samples. The main discussion from this presentation ran into the prolonged discussion session, and focussed on the theory that in a cement ageing test, it is extremely undesirable to alter the physics involved with the processes, and by inducing an electrical current, this is exactly what was being done to the situation. This was countered by stating that the results show the same reactions at different rates, so the experiment was judged to be accurate. This seemed to be a divisive issue, with some involved with the discussion agreeing that the changes made to the physics rendered the experiment unstable, and others siding with the theory that as the results show the same reactions at increased rates, it is a valid methodology.

5.3 Numerical Modelling

5.3.1 Rajesh Pawar, LANL, Numerical Modelling of Wellbore Leakage in Large-Scale CO₂ Injection Simulations Incorporating Wellbore Details and Complexities of Phase-Change

Following on from his presentations covering the CO₂PENS model from the 2007 meeting, this set of slides covered the motivation behind the research, and outlined the studies previously completed on the subject, before explaining the complex mechanisms involved in a wellbore release scenario. Briefly, the mechanisms include: flow in the wellbore and / or annulus, the presence of multi-phase fluid flow which in turn can induce phase change, and these effects are coupled with the possibility of heat and mass transfer reactions, stresses imposed, both geological and mechanical, and geochemical reactions that can be present as well. The interactions between these are vast and varied, and Rajesh referred to the study carried out by Lynch et al in July 1987, whereby it was stated that:

'To characterise CO₂ leak through wellbores and to develop effective mitigation strategies it is important to accurately capture wellbore flow physics and couple wellbore flow with reservoir flow.'

The presentation then moved on to the ever-increasing number of models purporting to cover large scale fields, but describes the associated problems with the models as well, and also the context of some models; some models describe the area modelled as the wellbore area, and some as the near-wellbore. In the context of modelling, the wellbore area is considered to extend a matter of inches from the wellbore, and the near wellbore environment is considered to surround the wellbore to a distance of up to 10's of metres.

The example used as a large scale injection operation was that of a large field, with known leaky wells, and modelled migration of injected CO₂ over a prolonged period of 400 years. Interestingly, in this scenario with wells known to be prone to leakage, the graphical interpretations show a maximum leakage of 10% of the total injected volume; in reality it is likely to be far reduced from this as the model does not incorporate mitigation and remediation of wells and leaks when they occur. This shows a much smaller quantity of leakage than some previous predictions have allowed for.

The model then moves on to cover and incorporate multiple layers and multiple wells in a much larger field, illustrating that the model is capable of large scale field predictions, and that significant advancements have been made in recent years in the ability of modellers to predict more accurately the long-term fate of CO₂ injected into geological storage reservoirs.

Q. Based on the example of a leak/flow rate of 3.5 kg/s, what is the distance travelled by this amount of CO₂ in a second?

A. It wasn't calculated, but would vary depending on the permeability of the geologic formation.

Q. Can preferential annular (micro) pathways be added to the model?

A. It can be specified, and the model allows for fluidity.

Q. How does the model handle phase changes?

A. there is a look-up table included in the model, and this allows for changes in thermodynamic properties.

5.3.2 Bruno Huet, Princeton University, Investigation with Dynaflow of the Effect of pH and CO₂ Content of the Brine on the Degradation Rate of Cement

The objective of the experiment described in this presentation was to better understand the mechanisms involved with the reactivity of cement and CO₂/brine water. The presentation also explained the various leakage pathways that could be present in a wellbore, and categorised them into 5 types:

1. Leakage between well cement and well casing,
2. Leakage between geologic formation and well cement,
3. Leakage through plug cement,
4. Leakage between well or plug cement and well casing,
5. Leakage through well cement.

The presentation included a short video clip demonstrating the concentration of mineral zoning which was very useful in describing the process that was discussed in the slides and the presentation. The images show the thickening of the calcite layer from 3 days to 29 days, and the zoning of altered and original cement is clear to see.

Although complex to describe, the graphs showing the analysis of the changes and progression of the calcite layer are quite demonstrative, and help to explain the experimental results. One of aims of the work was to compare the model to the results of Duguid et al, and it was found that in order to match the results of these experiments, it was necessary to increase the diffusivity by a factor of 4.

The presentation concluded by confirming that an equilibrium approach is sufficient to demonstrate transport in the wellbore, and that CO₂ uptake occurs during the formation of the CaCO₃ layer. Once the layer has formed, at a later stage, there is no CO₂ uptake, but rather a very slight release and only Ca leaks are present which demonstrates diffusion.

Following the conclusions, the research team laid out the challenges to be addressed in the future, and these included determining the pressure equation (density gradient), and the development of a model to illustrate multi-phase transport and the reactivity of cement exposed to wet or dry CO₂.

The presentation linked into the next, by Jean Prevost of Princeton.

5.3.3 Jean Prevost, Princeton University, Fully Coupled Geo-mechanics, Multi-Phase Flow, Thermal, and Equation of State Compositional Simulator

Jean Prevost introduced the model used by his team of researchers. He explained that the model is more complex than many models used, and that it takes into account all aspects of a CCS injection operation. This echoes the sentiment previously expressed by Stefan Bachu that a multi-element model is what will be needed in order to perform a complete simulation of a storage project, and this is what will be demanded by regulators to demonstrate a high level of certainty and confidence in a storage operation.

He went on to express that the Dynaflow model is currently the only model capable of showing the boiling of super-critical CO₂, however the results are still not perfect, and they are susceptible to errors, as shown on one of graphs by a large spike.

The model can demonstrate the interactions at the rock / wellbore interface, and the simulation can investigate the bending and shear stresses imposed on the caprock by the increase in pressure resulting from CO₂ injection and the deformation of the overburden as a result of this.

This is a particularly important factor as bending stresses can cause shear in the overburden which could potentially open new leakage pathways, threatening the structural integrity of the reservoir. As previously explained, there are still some areas susceptible to errors, and the future focus of work will look to correct these areas, and perfect the model.

5.3.4 Jeremy Saint-Marc, Total, An Innovative Approach to be Proactive when Designing Cement Sheath for Gas Storage

Total's presentation is not available on the IEA GHG website as permission was not received to us it as part of the report. The presentation described the Total well design, including cements and casings. The purpose of the design is to connect the surface to the subsurface in a model, and demonstrate the links between the two facilitating safe transit of fluids and suitable abandonment procedures to retain the fluids safely in the formation.

To ensure maximum security of storage, a minimum of 2 barriers are used, one of which is used as a backup of the primary barrier, and both barriers consist of cement and packer materials. The casing design is initially a geometric circular design, and then external conditions and stresses are introduced to determine the most suitable material to resist these external factors. Failure is defined as the point at which tolerances are exceeded resulting in a breach of confinement. A similar process is used to determine the most suitable cement, however as it is assumed that even the best cement may leak in the future, best practice includes designing better wellheads to confine and CO₂ that leaks through the cement and would otherwise manifest as Surface Casing Vent Flow (SCVF).

The design of the primary barrier of casing and a cement sheath will be dependant on the environment surrounding the well, i.e. pressure, temperature, porosity etc. The model scenario involves a 6 month period for installation and testing of the wells, followed by a production phase, and abandonment some 30-50 years later. Continued cycles of processes promote fatigue and stress to the materials, which would probably lead to failure of the wellbore system. Understanding the impacts of certain external factors means that continued testing can confirm a well as being safe, by determining the stresses that must not be exceeded.

The chemical interactions were initially unknown, so the development of a chemical model was undertaken. Into this was incorporated the cement design and in situ conditions to make a thermo-chemo-hydro-poro-mechanical model of wellbore integrity. Total developed the software necessary to model and bring together the well history, well integrity, cementing procedures and rock mechanics into a comprehensive system for wellbore environment modelling.

5.3.5 Rick Chalaturnyk, University of Alberta, Numerical Simulations for the Design of In-Well Verification Testing of Well Integrity

Rick described an approach to wellbore integrity that started with the notion that determining that the ability to capture the exact state of all the wellbores in a given field is very difficult, and therefore the approach was taken to combine both real data gathered from the field, with analytical or numerical simulations to quantify the processes associated with hydraulic integrity of the wellbores.

The approach looked at a great range of background information, and used extensive data from the Weyburn project to build a database. The Weyburn project was the idea for the data gathering exercise as data was collected from 185 wells from day 1 of the project.

The model was used to determine various elements of the wellbore environment including degradation rates from sulphate attack and stress distributions inside the cement and the formation. The output of the model was a set of predictions for the long-term integrity of the wellbores, and the extent of degradation for 100 to 1000 years, but no-one believed the predictions that the model produced. The model also allowed adjustments to demonstrate the effect of variations in the number of perforations, and the effects this has on the pressure and the different reactions in the silt, sand and shales surrounding the wellbore.

5.3.6 Jonathan Ennis-King, CO2CRC, Reactive Transport Simulations of the Effect of Transport Parameters on the Breakthrough Time for Vertical Migration of CO₂ in a Micro-annulus of a Cement Ring

This presentation described a 2 part experiment, to simulate gas phase transportation, and a fracture-matrix theory to determine the vertical migration rate of CO₂ up a micro annulus in a cement plug in a conventionally completed, Portland cement well.

The geochemical model used encountered some challenges in relation to the C-S-H phase, and therefore the decision was made to follow the work by Carey and Lichtner (2007) representing CSH as a discrete set of solid phases spanning the composition range of the cement. Diffusive transport is recognised as a slow process when taken on its own, with movement of less than a metre over 1000 years, so the experiment references the SACROC study which suggested vertical transport through a high permeability 'shale fragment zone'.

Once these parameters had been established, the challenges facing the research team was to estimate the transport parameters, including fracture size, permeability, and capillary pressure thresholds, to determine if the transport path is continuous or broken. The parameters that were used are shown in detail on the slides of the presentation.

The next stage was to establish the reservoir conditions and input these into the model before using the model to calculate the predicted flow in scenarios with and without reactions. The similarities and differences observed in these simulations allowed determination of the thresholds, flow rates and the effects of the reactions on the transport mechanisms.

The elements of the experiment relating to Fracture-Matrix theory used the results of Sudicky and Frind (1982) and Tang, Frind and Sudicky (1981), with adaptation's to move from adsorption-diffusion to reaction-diffusion, from planar diffusion to cylindrical geometry (wellbore) and move from single-phase to two-phase.

These experiments concluded that a continual micro-annulus leak can be retarded due to consumption of CO₂ in the reactions with the cement, the cement element holds the key uncertainties and unknowns in the transport parameters, and that the fracture-matrix theory can predict the scale of retardation. The direction of future work in this area should concentrate on extended detailing of the geochemical model, increased characterisation of the transport parameters, and refining the fracture-matrix theory to make it quantitative.

5.4 Monitoring, Risk and Development of Best Practice

5.4.1 Ron Sweatman, Halliburton, CO₂ Resistant Cements and Chemical Sealants

Ron started his presentation by addressing the question of whether class I or II wells have ever leaked into sources of drinking water. The evidence and testing supplied by the US EPA, State Regulators and the UIC Programme all confirmed that there have been no recorded leaks from either class of wells into Underground Sources of Drinking Water (USDW). The testing completed shows that 2% of class I wells surveyed showed signs of poor external MIT, compared to 11% of class II wells – the classification used for CO₂ injection.

Ron then asked the delegates whether any of them had heard of a CO₂ leak from a class II well, and none of those present had, which lead to the question of what makes these wells so effective? The presentation went on to list the extensive repository of best practices and procedures for the design and installation of wells. Also, tests performed by researchers at Princeton University have shown that less than 1% of injected CO₂ converts to Carbonic Acid (H₂CO₃), and most of this is formed at some distance from the wellbore due to high initial flow rates.

Additionally, it has been noted that cement exposure to CO₂ can be reduced by a substantial amount by the interactions of various brine fluids with drilling fluids or cement filtrate near the wellbore. This interaction can form a barrier by reducing the permeability in the near wellbore formation. Ron went on to discuss the already-presented issues associated with the carbonation and degradation of Portland cements, but with the additional aspect of the possibility of the reaction acting as a self-sealing mechanism, and this was backed up to some degree by a series of chemical equations describing the reactions. Although this has been discussed before, the extent to which it occurs is not fully understood.

Ron then discussing alternative sealing methods, which is an area given comparatively little thought and discussion at previous network meetings, despite the fact that there are examples of where Pozanite has been used as a sealing mechanism, and has been operating as such for up to 36 years in situ conditions.

The presentation concluded by outlining some suggested next steps, which start by getting all the delegates and contributors to the wellbore integrity network on the same page, agreeing on the same preferred methods and practices, before then providing an informed, consensus opinion to regulatory and legal bodies, and using documented successful case studies develop new API/ISO standards and address the issues raised by regulators with hard facts and knowledge.

5.4.2 Theresa Watson & Stefan Bachu, TL Watson & Associates & Energy Resources Conservation Board, Field Scale Analysis of Risk Wellbore Leakage

Theresa presented a review of previous work and an update from the presentation at the 2007 meeting of the Wellbore Integrity Network. She discussed the price implications on wellbore construction (which developed from a subject covered on her poster presentation). The issue faced is one of speed Vs efficiency. The theory is that at times of high demand, wellbores are created and completed at as fast a rate as possible to maximise profits, but the possibility is that these wellbores will not be as high a standard of completion as those completed at times of low demand, when time is not as much of a critical value, and therefore completion standards are likely to be higher.

In conjunction with the ERCB, TL Watson have created a user query-able database which can predict which wells in a field are most likely to leak, and also compares this with environmental and demographic information to categorise the risks associated with those leakages. This tool is likely to be increasingly useful, as it is predicted that within the province of Alberta, there will be approximately 1 million wells by 2056, compared with 343,000 in 2006.

5.4.3 Rick Chalaturnyk, University of Alberta, Monitoring of Wellbore Performance at Penn West CO₂EOR

Rick gave an overview of the monitoring project underway at the Penn West CO₂EOR project, and outlined the instruments used in the observation well. The project is a collaborative project, running over a period of several years, and the aims of the project are to develop an increased understanding of the eventual fate of CO₂ injected into hydrocarbon reservoirs as well as further developing the understanding of the role of geological storage of CO₂ can play in mitigating the long-term effects of climate change.

While demonstrating the suitability of the reservoir and others like it for EOR and CCS, the aims are also to develop and demonstrate a comprehensive monitoring programme, demonstrating that it is possible to detect and quantify the long-term fate of injected CO₂. The project will also develop post-closure monitoring programmes, and evaluate the different tools available for monitoring.

The monitoring tools used cover the expected range of survey methods including 3-d seismic surveys to determine the extent of the CO₂ plume migration, downhole sensors for pressure and temperature, and the installation of geophones in the wellbore. The combined effect of the using these monitoring techniques allowed the formation of an accurate picture of activities and reactions of the formation to the injection process, and accurate logging of pressure and temperature within the well. These were plotted on a graph against time which was referenced to the activity of injection and cementing to demonstrate the effect surface activities have on the reservoir below.

It is hoped that this monitoring project will help develop understanding and break down gaps in knowledge which will then be transferable to other operations around the world. The costs involved with the array of monitoring equipment and technology lead to comments from the engineers that they were “sticking my house down this hole!” The results however show the effect of the CO₂ on the reservoir temperature as the front passes, and also highlights the pressure fluctuations resulting from opening the valves at the wellhead. The accurate

monitoring has greatly helped understanding of these processes, and will be hugely beneficial in demonstrating confidence and assurance of the eventual fate of CO₂ and its effect on the reservoir for the development of CCS into a commercial venture.

5.4.4 Jerome Le Gouevac, Oxand S.A., Well Integrity Performance Management: A Risk-Based Approach – Application to a Carbon Capture and Storage Project in Algeria

This presentation centred on a case study in Algeria, where an oil and gas company were interested in investigating the possibilities held by injecting supercritical CO₂ and the associated enhanced recovery of natural gas (EGR). The company had a specific field in mind which had 9 existing wells, 3 of which they wished to convert into injectors, and Oxand and Schlumberger worked in partnership to determine the suitability of these wells for the proposed purpose. They developed a trademark assessment called 'Performance and Risk Assessment' (P&RTM) which was used to assess well integrity over the injection phase.

There was a good amount of existing available data, and on the basis of this, the goals were set to include proposals for a risk mapping exercise for the 9 wells, prioritisation of mitigation options including a cost/benefit analysis, and determination and justification of the 5 most suitable wells for conversion to injectors. The data and goals were incorporated into a work flow involving static and dynamic modelling, probability and severity of leaks with a mapping exercise leading to a series of recommendations.

The static model was conceived by combining aspects of the surrounding geology and parameters of the wellbore itself; while the dynamic model integrated degradation mechanisms and fluid transport to determine risks and severity of leakage. Once these models were developed, certain scenarios were simulated using a programme called SIMEO-STORTM. Once the risks were identified and assessed, the recommended actions were developed to allow the operators to make informed selections and choices for the operation of the proposed project.

The activities performed allowed the use of a risk-based approach to act as the criterion for supporting the decisions made for well selection, proposals for 5 of the existing wells to be converted, and a risk management strategy was developed accordingly. The operators were satisfied with the assessments carried out, and the process allowed informed and more importantly justifiable decisions to be made regarding the operation of the site.

Questions were taken from the floor as follows:

Q. The approach to some of the work appears to be deterministic, how was this approach determined?

A. There was a model used for the entire project, and this dictated the approach used.

Q. How was the level of knowledge in the consequence grid normalised?

A. This was an issue faced in conjunction with the operator, it was discussed jointly, and the decision involved opinion from the operator, therefore it could be subjective to some degree, but it is difficult to avoid this.

Q. What degree of cement permeability was considered as a risk?

A. Risks were not necessarily associated with cement permeability; risks were defined by a range of information, not just single aspects of wellbore integrity and performance.

5.4.5 Craig Gardner and Bob Carpenter, Chevron, CO₂ Cementing – Where Are We Now?

Craig Gardner presented some review work carried out by Chevron, and the presentation stated that although there is some very good laboratory based work underway and completed, and also some excellent field results available, they must be looked at in conjunction with each other to for a worthy analysis of the current state of cementing technologies. He echoed Ron Sweatman's question of how many wells are known to have leaked, and suggested that a leakage event must be associated with a specific time frame within the life cycle of a project to bare relevance and hold value as reference information.

Many presentations look at methods of abandonment and their relative merits, and this presentation also touched on the concept that often zonal isolation will depend on the ability of the cement sheath to withstand externally imposed stresses, and Craig also pointed out that very little, if any, laboratory work has been done on the mechanical property evaluation of resistant and normal cements following long-term CO₂ exposure.

The presentation also looked at various limiting factors and leakage pathways before opening the talk up to questions from the group.

Q. As more CCS projects come on line, will there be a reduction in the costs associated with CO₂ resistant cements?

A. It is a possibility, but sources are limited as most of the resistant cements are only available from 1 country.

Q. Are new cements working towards solving stress cracking and mechanical integrity issues?

A. Not really, development is currently focussing on resisting CO₂ degradation rather than mechanical stresses.

At this point, a general query was made regarding the use of alternative materials other than cement, and Craig stated that they are not given a great deal of research as they have generally proven to be less effective as cement.

Q. What percentage purity is considered acceptable for CCS purposes – is there a need for new laboratory work to investigate the effect of different purities?

A. Craig opened this question up to the group as it wasn't something covered by the presentation or the work of Chevron.

There may be pressure to move towards the acceptance of dirtier streams of CO₂ which if likely to have impacts on many aspects of storage. It was suggested that acid gas injection can be considered as CO₂ injection with impurities, and more countries are taking up acid gas disposal options, as well as considering on-shore injection. The London Convention (dealing with off-shore injection) states that the CO₂ stream must be 'overwhelmingly CO₂', but doesn't give a definitive answer. Comments were made that we must consider 2 streams – that from coal power generation that will likely contain SO_x, NO_x, and particulates, and that from gas power generation that will contain H₂S.

6. Discussion Sessions

As in the previous meeting of the Wellbore Integrity Network, it was decided that open, facilitated discussions were of more worth than closed break-out groups. The meeting included 4 of these sessions, and the salient points from these are described below.

6.1 Field Investigations of Wellbore Integrity

The discussion began with some questions asked to those who conducted laboratory based experiments, and dealt with how porosity was determined and measured. It was stated that good laboratory procedures allow the researchers to create cement samples with consistent porosity values. The discussion moved to the potential effect of stimulation on cement quality as opposed to straight forward carbonation, this reflected some of the work presented by Bill Carey and Walter Crow and they confirmed that their work had not yet investigated this aspect, but history tracking has taken place stimulation experiments will hopefully be identified and carried out in the future.

The next topic discussed queried whether existing analytical techniques can identify changes occurring in the cement as it sets and segregate those effects from the changes that take place over periods of years in the field? In the examples described in the presentations, the cement was installed through a high water/CO₂ environment so distinguishing the changes can be difficult and there may be ambiguities in the measurements which are difficult to rationalise.

Bill Carey's presentation raised another question, that of whether it is possible to determine if the cement – shale interfaces are intact in the samples. Bill confirmed that in some instances they were intact, but generally they were separated. The experimental procedure did not look at changes in the geology of the shales.

Much discussion also debated what can be expected from future experiments and hypothesising from what has been found in other samples. It was noted that there is a trend developing towards uniformity of samples from each location, and a suggestion was made to make an effort to bring together the samples that are well-referenced by many publications and presentations to allow first hand comparison and analysis.

Debate also covered definitions of strengths of cements as the term strength can be used in several different contexts. The general consensus was that the term strengths should refer to the compressive strength of a sample, although Rick Chalaturnyk suggested that measurements of tensile strengths may prove more interesting and beneficial. Additionally, Rick pointed out that measurements of cement stiffness can also be valuable information for developing knowledge and understanding of the behaviours of cements in the wellbore environment.

Going back to the presentation of Bill Carey and Walter Crow, it was noted that the perforations in the samples were largely isolated from each other, and the absence of extensive cracking prevented them forming channels which might be found in the field environment. It was accepted that this was a limitation of the experimental procedure, and the methodology attempted to eliminate the potential for statistical error wherever possible, but limitations still exist in the procedure.

Veronique Barlet-Gouedard stated that the field results collected by Schlumberger correlate with the their laboratory work, which is a great benefit, and that many people associate

porosity with carbonation, but the laboratory results show the deposition of calcite can be associated with changes of porosity, often reduced porosity as the pores can become blocked with the calcite deposits. This is the first time that the field and laboratory results have confirmed each other to such a strong degree. Bill Carey suggested that it was still too difficult to understand the interactions in cement and they depend greatly on the type and blend of cements used, sometimes showing uniform carbonation, but at others showing fairly disparate carbonation. The response observed in the cement cannot be solely due to carbonation, this is an important fact as it shows that carbonation is not the single impact-bearing factor on porosity of cement.

At this point the discussion was steered with a pair of questions; what is the best recommendation for cement at the current time, and what is the end state that we are most concerned about?

Representatives from Chevron stated that Chevron may choose a cement with low permeability cement that may not allow good measurements. Many delegates commented that some of these questions may be better answered by some of the presentations scheduled over the remainder of the meeting.

Theresa Watson commented that in many situations you don't have all the data you would like to determine quantity of water, densities and other properties, and that cement quality, good or bad, can be irrelevant if channels exist in the cement for transport, and that most issues are likely to occur from uncemented areas, rather than the cemented areas.

Stefan Bachu summarised many points by stating that so far, almost everything we can measure is qualitative, but when it comes down to regulation of CCS, the regulators will want quantitative figures, and at this stage this will pose a problem as we can't provide this information. This should be a research area highlighted for the future. Bill Carey stated that there is a lot of data on sustained casing pressure and surface casing vent flow (SCP & SCVF) that could be used to determine quantitative figures, but this doesn't allow for post abandonment situations.

Ron Sweatman stated that just because there exist reports of SCP, it doesn't automatically mean that it will be a problem, SCP can be caused by gas from the reservoir, not necessarily gas from the injection process. Correct abandonment procedures can overcome or work around problems as and when they occur.

Veronique Barlet-Gouedard commented that flexibility for cement depends on the injection scenario, and questioned whether flexibility is always required if the temperature can be changed – sometimes expansion properties can replace flexibility properties. This point was generally conceded, although this option is highly dependant on surveys to accurately determine individual requirements together with reservoir properties and conditions.

6.2 Experimental Studies of Wellbore Integrity

The second discussion session was initiated with the provocative question of why are we conducting experiments to simulate cement ageing when it seems that carbonation is not a major problem in existing wells in the field?

This sparked a large debate, and the main reason that was agreed by the majority of the delegates was that we are looking to attempt a demonstration of security of storage for 100-1000 years, and there is no historic data from wells in the field for a comparable scale. The experiments show that we have the ability to speed up reactions that occur naturally, but how can we justify the assertion that performing a test in an electrical field of 30 volts is equivalent to several hundred years of 'normal' wellbore activity in the field. The general opinion was that by maintaining a control sample in 'normal' conditions, we can measure the enhanced effects and extrapolate against the control sample to determine the acceleration rate according to the scale. There are plans to adapt the LIFTCO₂ protocol for high pressure high temperature (HPHT) conditions to generate more realistic conditions for CCS application.

If we can prove the physics are the same and that 3 weeks of accelerated experimental conditions is equal to 1 year of normal field conditions, then we have a very good model which is suitable to use now, but this is highly dependant on the ability to prove the physics used in the base calculations are correct. If we compare the 3 week 30 volts sample with the 6 month sample shown in some of the presentations from Schlumberger we can correlate them to demonstrate distinct similarities although they are not close enough to be classed as being subjected to the same effects. In order to utilise this experiment as a model, would require accurate measurements and adjustments to align the samples, nevertheless it is a good analogue and the method can be developed into something more beneficial and very interesting.

The next question that was asked was what type of experiment or testing procedure do we need to develop in order to generate the assistance required by modelling groups to model activity in the wellbore environment. It was agreed that the experiments presented at this meeting show that progress has been made, and that the network meetings are still providing a platform for knowledge dissemination, however it was again pointed out that discussions are still focussing heavily on cementitious and Portland materials, and not enough time was being given to the alternative sealants and sealing agents such as elastomers. It was suggested that if there is a move towards deviated or horizontal wells, we will need alternatives to current cement, however this was countered by representatives of Schlumberger who suggested that price is still a prime concern, even with cements that perform very well, and elastomers are comparably more expensive than the best performing cements and will therefore be considered as a less attractive option to a commercial application. Additionally, if the requirements for an operation include the re-use of existing wells (which is likely) then we will need to gain a comprehensive understanding of the cements that are likely to be present in the wellbore already.

At this point, the suggestion was echoed from before whereby the samples referred to are brought together to allow analysis and a move towards a definitive method for sampling. Walter Crow commented that some samples had been subjected to complete degradation, with no compressive strength remaining, and questioned whether this can be reconciled to field experiences of cements from much older wells still remaining intact. Bill Carey used this to reiterate the need to compare samples first hand.

Representatives of Chevron queried that given the scenario that everything at the injection well appears to be perfect in terms of permeability, porosity, and resistant cement, what does the supercritical CO₂ look like at a distance of 500 yards from the well where it may interact with an existing 'bad' well? Brian Strazisar postulated that it would initially form a supercritical plume, and that long term it would dissolve into the reservoir fluids, but this depends on the flow rate and duration of injection etc.

6.3 Numerical Modelling

In this third session discussion, there was a great deal of talk regarding permeability modelling, and the relative merits of establishing an experimental procedure that would return to a similar permeability as the initial condition, and it was decided that in order to facilitate the measurement of migration, it would be necessary to simulate the reservoir's return to its initial permeability, or as close as possible. A note of caution was sounded however, that an incorrect permeability can give a distorted figure for the velocity of the CO₂ plume front, so steps must be taken to ensure that the initial data is accurate to maintain validity to the model.

There is also a strong relationship between permeability and resistance, so there is a high level of benefit to be gained from working with multiple parameters to maximise the accuracy of the results. Assessment of the permeability can assist in determining a picture of the reservoir properties, although if measuring the permeability of the cement sheath, it is only possible to measure the average permeability. It was stressed at this point that permeability may not account for the total flow present as other variables can have an impact on flow as well, so a thorough range of measurements are required to measure flow as well as permeability.

There are also issues regarding the interpretation of data gathered, for example if the first data log isn't perfect, it will push the following results out of line and result in inaccurate readings.

Stefan Bachu informed the group that the previous week the Federal Government of Canada said that all new power plants must be CCS ready, and this fact combined with the trend of many oil companies that have started looking for suitable storage sites leads to the important question that government, opposition to CCS and ENGO's will all ask, which is:

How much, when and where will leaks happen?

Stefan suggested that this approach would lead to the decision to play on the safe side and not conduct CCS operations, so what is needed is to bound the problem by explaining that we have the ability and technology to detect and quantify leaks, as well as having the means to mitigate leaks if they occur.

Another key question that needs answering is what happens 50+ years after injection ceases? Does liability still lie with the operator, or does it transfer to the state? Regulators do not have answers to these questions, and oil companies in the Alberta region are targeting the deepest possible reservoirs in the least penetrated areas in order to minimise the risks associated with storage.

Cal Cooper of ConocoPhillips asked whether the wellbore is the greatest risk, as the chance of a blow out is more likely than a wellbore failure when dealing with deeper wells as the pressure will build more quickly if things go wrong. Stefan answered this by stating that the operational aspect is relatively less important as the activities are understood and regulated – these issues affect other analogous operations, and there is a proven method for dealing with them. Problems will arise when unexpected leaks occur and are unexplained.

Matteo Loizzo from Schlumberger questioned whether Stefan was suggesting requirements for the safest possible option, or for a limited leak scenario. Stefan qualified his comments by stating that no regulator will specify an allowed amount of leakage as it is too publicly unacceptable – there is enough opposition to CCS already, without effectively endorsing leaks

from storage reservoirs, which leaves the solution as a risk based limitation approach to ensuring safety of CCS operations.

Cal Cooper agreed with Charles Christopher who reiterated the need for bounds to be placed on criteria, as it's close to impossible to generate a leak capable of posing a risk to human health – risks and leaks must therefore be quantified and explained. Jean Prevost then suggested that there has been evidence of reactions within the cement plugging leakage pathways, so maybe we should work towards developing a testing procedure to discover the possibilities of using these reactions to our advantage.

The next point raised was that erosion of the well casing is more likely to pose a risk to wellbore integrity than micro-annulus in the cement, and erosion of the cement will happen to some degree due to the corrosive environment of the near-wellbore. Researchers must generate a quantifiable identification of risks, and an analogy was given that planes shouldn't fall out of the sky, but sometimes they do, well shouldn't leak CO₂, but sometimes they will – the question is how much will they leak, not if they will leak.

Public acceptance is a key factor in any CCS operation, and talking to the public about limited acceptable levels of leakage will not be accepted, and could result in project cancellation. It must be explained that leaks can be detected at an early stage, and mitigation procedures realised to minimise or prevent risks and exposure. Bill Carey suggested we could compare CCS to EOR operations as the process is similar, but Stefan Bachu reasoned that the increased injection quantities involved in CCS would not allow direct comparison. Theresa Watson concluded by saying that of all known leaking wells, none leak at a rate of greater than $\frac{1}{10}$ th of a cubic metre a day, and in comparison with David White's comment in the introduction, currently we have "100% leakage". Regulators may approve doing CCS, but the regulator responsible for the site may have a different view – the research community need to talk to both types of regulators, address the issues and forge a way forward.

6.4 Monitoring, Risk and Development of Best Practices

The fourth and final discussion session focussed around the result of a questionnaire that was circulated by Jorg Aarnes of DNV, the results of which are summarised below.

Based on the information and knowledge gathered, it is concluded that, in terms of well integrity for CO₂ storage operations, the main risk is leakage through abandoned wells. The risk of leakage through abandoned wells is of course site dependent, but guidelines for managing this risk will nevertheless be needed at many storage sites. Indeed, the survey revealed that there is almost a consensus that the integrity of every abandoned well in the associated storage region needs to be assessed based on the well-specific data in order to evaluate storage feasibility of a particular storage formation. The main concern is related to material degradation of the cement and steel casing, but lack of adequate abandonment practices is also a general concern.

Apart from concerns about the long term integrity of abandoned wells, there is awareness that current well construction standards and operating practices should be revisited and modified to serve as guidance for safe operation of CO₂ injection wells. This includes requirements to well materials and linings, as well as mechanical integrity and leak detection testing.

The conducted survey also gives grounds to conclude that well integrity related knowledge gaps still exist. In particular, we lack sufficient knowledge about long term material properties,

and we do not yet have adequate predictive modelling tools, i.e., computer simulation software capable of predicting long term material degradation, while accounting for the main chemical, mechanical, thermal, and possibly hydrological conditions that a well will be exposed to over its life time. This implies that at sites where the risk of leakage through abandoned wells is relevant, operators will have to address and manage this risk by implementing proper monitoring programs and devising mitigation and remediation plans to handle potential leakage events.

Individual well assessments are not realistically possible, and the example used to illustrate this point is that the North Sea, an area likely to be subjected to CCS, has approximately 17,000 wells, whereas Alberta are drilling 60,000 new wells every year, and Texas has approximately 1.5 million existing wells. The more viable approach is to look at the scale of pilot and demonstration projects, which is likely to be a good deal smaller than commercial operations, and therefore there are likely to be only a few wells coming into contact with the CO₂ plume. These wells can be subjected to individual assessments, and from this we can learn and extrapolate to a larger scale, such as might be involved with a commercial scale operation, with fewer well assessments.

It was suggested at this point that wells drilled before c. 1940 were often installed without any casing material, and therefore the wellbores will be very different to current ones, and indeed many may not exist anymore. This was contradicted by Theresa Watson who said that in over 50 wells entered, each over 50 years of age, everyone of them was still present. It was suggested that there may be influencing factors in terms of differing geology having different impacts on old wells.

The discussion then moved to provision of direction for regulators. Should regulators look to consider all wells as potentially involved in CCS operations or not? They will require some input from the network in order to avoid huge financial penalties on industry that render CCS unfeasible.

The final issue addressed was that of reservoir pressures. The question was asked as to whether injection should be scheduled to cease when the original reservoir pressure was reached. The consensus was that formation fracture must be avoided, so injection would need to stop when the reservoir pressure is reached, but then should this pressure be set as the original pressure before extraction of oil or gas? It was suggested that the most likely limit to be imposed is a percentage of the fracture pressure, not higher than the original pressure of the reservoir. The additional benefit of not exceeding the reservoir pressure is the removal of a driving force for leakage. The issue with setting a percentage of fracture pressure was pointed out that the fracture pressure of a reservoir can be subject to change, highlighting this as an area for future consideration.

7. Summary

Bill Carey affirmed that it was still intended to continue the meetings of the Wellbore Integrity Network as they were still generating interesting and in some places contentious debate, and that there is still a tangible benefit, with new material being presented. There is a frustration that knowledge isn't developing faster, but there is a general move towards a consensus, with the challenge for the group to move towards a mentality and consensus of perspective for the next meeting.

There was a notable input from geomechanical experts, which will hopefully grow in the future, possibly addressing the question of what scale of micro-annulus, if any, can be sustained by the wellbore. Wellbore imaging is also of great importance, and there is anticipation of what to expect in the future in this area, it is looking very interesting, but also more problematic than first thought.

The ultimate measurement to strive for is an in situ test; models cannot fulfil the requirements on their own and our knowledge base comes from collaborative field and laboratory work, which puts us in a very fortunate position. EOR activities can be viewed as an analogue in terms of reservoir pressures, which could be a beneficial argument used to convince the public into acceptance of the technology and operations.

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8. Conclusions

The key conclusions that can be drawn from the meeting are:

1. The contrast between field and laboratory based experiments noted at last years meeting is still present, but results are moving together, demonstrating a greater understanding of the interactions and reactions in the wellbore and near-wellbore environments. Laboratory experiments designed to simulate long-term exposure to CO₂ are showing results more in-line with experience gained in the field. There is however still some question of the methods used to accelerate the ageing process, and this is an area for further consideration and development.
2. The models that have been developed to simulate long-term, large-scale CCS operations have improved greatly, and will be required to play a major role in addressing the concerns of both public and regulatory bodies alike. The models have been developed to allow feedback from real-life experience to improve and streamline the simulations, meaning that each subsequent simulation will be more accurate and reliable than the previous.
3. There remain a great variety of sampling techniques, and there would be a great benefit in rationalising these into a consensus methodology. This will also prove beneficial in presenting a unified approach when justifying actions and proposals to the general public and regulators.
4. The network organisers will attempt to facilitate at the next meeting the opportunity to bring samples together to allow comparison and contrast activities. It is envisaged that this may run alongside the poster presentation at the next meeting, but it is also accepted that transport of samples may not be possible.