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# Large rock mass experimentation @ Mont Terri underground research laboratory – $CO_2$ containment assurance experiments

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**Abstract**

The Mont Terri Underground Research Laboratory (MT-URL) and Consortia affords member organizations the opportunity to bridge the gap between bench and large field scale experiments. At this underground test site, CCP4 ($CO_2$ Capture Project Phase 4) partners, a four company collaboration that includes BP, Chevron, Petrobras and Suncor, along with the Swiss Topographic Survey (swisstopo) who operates the laboratory, are conducting 1) an experiment that focuses on the mitigation of pressure leakages associated with $CO_2$ containment in near wellbore injection well systems using novel sealants and, if resources are available, 2) a fractured caprock breach sealing experiment.

The mock well system experiment for $CO_2$ breach mitigation is of immediate interest. This experiment, designated CS-A, is operational with equipment installation accomplished late 2nd quarter 2015 and experimental protocols that commenced late December 2015 scheduled to run through the summer of 2017. Sealant testing is scheduled to begin in late 2016. The objective is to assess the ability to characterize and seal induced leaks at micro annular interfaces (casing, cement and country rock) using novel sealants with determination of the long term sealing integrity. The 2nd experiment is in an earlier stage of development, having been scoped in 2014 for costing and resource alignment. This second project requires additional participants to spread costs before the final design is set.


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## 1. Introduction

Mont Terri Underground Research Laboratory (MT-URL) is located near St. Ursanne, Switzerland (Figure 1). Laboratory investigations are carried out in the Opalinus Clay, which is a proposed host rock for future deep geological disposal of radioactive waste. This underground laboratory offers an intermediate field scale that provides experimentalists the means to control boundary conditions directly; to observe large scale rock mass driven reactions that mimic full field scale conditions. The rock laboratory is solely for research purposes - no deep geological disposal is permitted at the site. Located 300 m underground, access is via the security gallery of the A16 Mont Terri motorway tunnel. Federal Office of Topography (swisstopo) operates and maintains the rock laboratory.

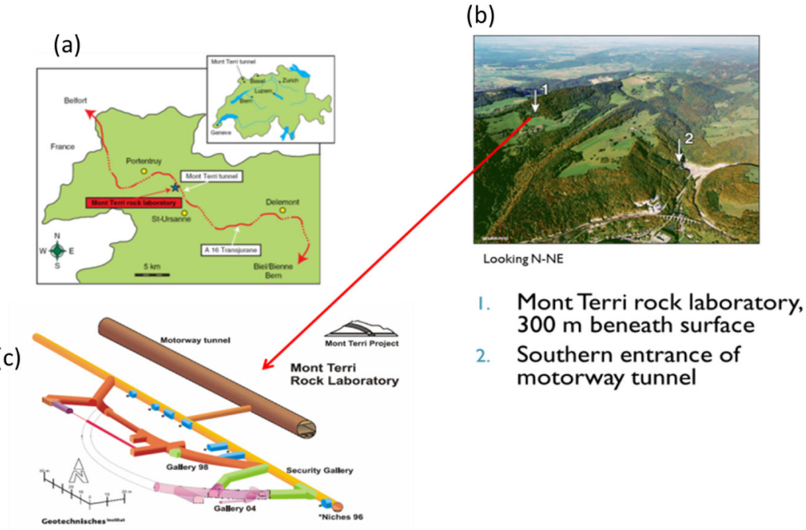


Figure 1: Mont Terri underground research laboratory location.

Containment risk associated with $CO_2$ storage is impacted by injection well system performance. According to a special report on $CO_2$ storage submitted to the IPCC [1], active injection wells, along with inactive wells that have been abandoned, are identified as one of the most probable sources of leakage pathways for $CO_2$ escape to the surface.

Origins of pressure leakage common to injection well and completions architecture are shown in Figure 2. . Casing and cement interface pressure leakage due to temperature cycling from differential casing to cement sheath movement are shown. For the Mont Terri based well leakage study considered by this paper, particular focus was made to investigate micro-annuli development associated with heat-cooling cycles.

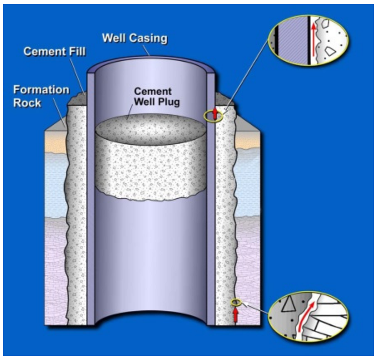


Figure 2: Well system leakage mechanisms at casing / cement and cement / rock formation boundaries (modified after IPCC 2005 report [1]).

## 2. Discussion

### *2.1. Experimental design*

The experimental concept is to develop and operate a full-scale $CO_2$ leakage and remediation test site to assess near well borehole sealing integrity. The aim of this work is the development of a $CO_2$ leakage remediation capability using novel sealant types that can be ultimately used in the field. At this stage of the experimental program, work has focused on the design and installation of a mock injection well completion consisting of a 6 m cased and cemented hole section that can be accessed roughly every meter for fluid injection / fluid extraction and pressure measurement. The equipment design provides the capability to test up to 3 sealants independently using cross-flow dipoles established between various Injection/Pressure (I/P) rings or modules. Figure 3 shows the equipment schematic along with a picture of one I/P module. The flow dipoles shown are for illustration only. During the flow sequencing performed to date, I/P injection and extraction pairings have been operated interchangeably, and will be summarized in the discussion section of this paper. Figure 4 shows the well test kit laid out at the design facility operated by SolExperts near Zurich.

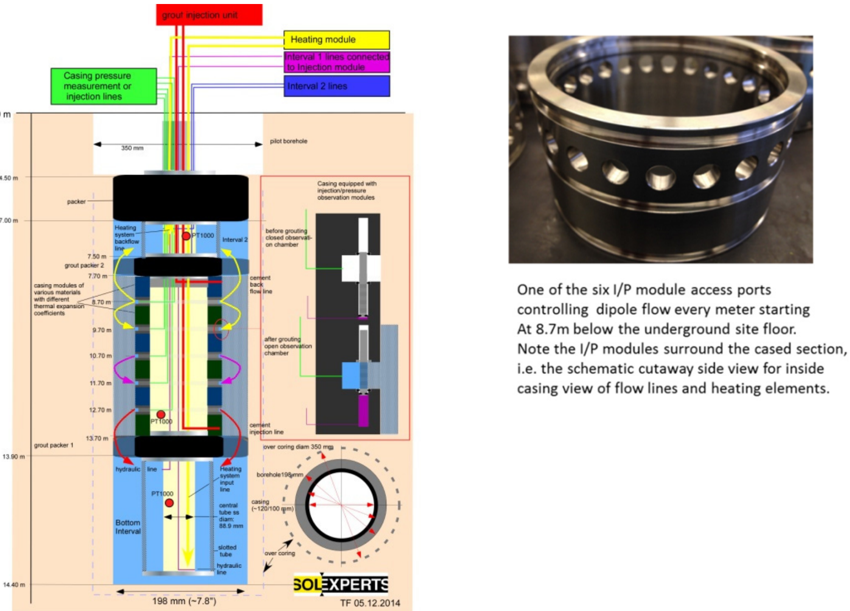


Figure 3: Well equipment design with I/P module detail.

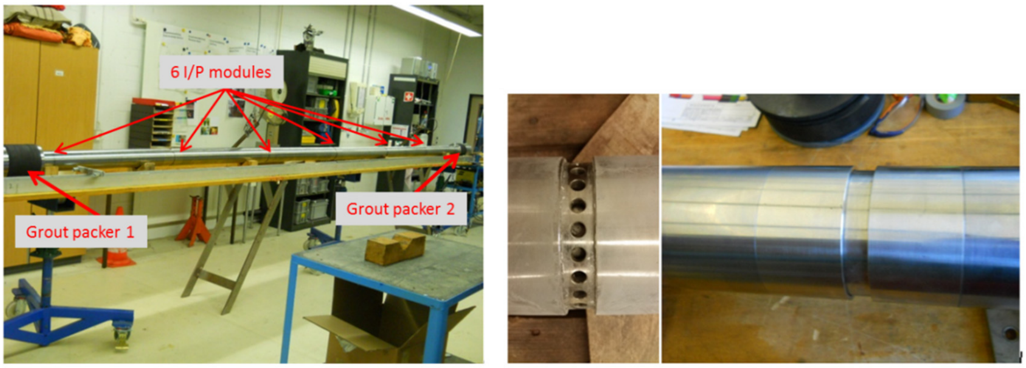


Figure 4. (a) Casing with 6 I/P modules and grout packers, (b) left: I/P module with open valve; right: I/P module valve closed.

### *2.1.1. General requirements of mock completion system*

The following test system operational requirements were sought.

a) Long enough cased and cemented borehole test section to allow 3 independent sealant tests

b) Possibility to create various types of leaks in a cased and cemented borehole section

c) Possibility to inject sealants and fluids or gases

d) Check the performance of the sealants in-situ and post mortem:
   i. In-situ: permeability tests of the cement annulus before creation of a leak, during presence of the leak and after sealing the leak
   ii. Post mortem: overcoring and laboratory analysis of the cemented test section after sealant injections

e) The experimental setup should be able to create the following types of leaks:
   i. Micro-annulus in the cemented annulus (created by casing contraction due to temperature decrease)
   ii. Tensile cracks in cemented annulus (caused by temperature cycles, expansion of casing due to temperature increase)
   iii. Flow channels

*2.1.2. Site preparation after equipment installation for CS-A experiment*

Subsequent to the mock completion equipment installation, re-saturation after air drilling was performed. Referring to Figure 5, injection sites for saturating the near well system with water compatible to the Opalinus Clay host rock chemistry are shown. Treated water was initially injected in to interval 1 and interval 8 and in the 6 I/P modules. Along the way, pressure was monitored at the pressure lines of the 6 individual I/P modules located in the cased and cemented section and of intervals 1 and 8. Figure 6 depicts the pressure profile measured from 27 April 2015 through 6 December 2015 during the saturation phase of the experiment. The vertical axis is scaled from 0 – 800 KPa. The saturation response was more complex than expected, with the lower open hole chamber interval 1 (BCS_A1_INTP01 - blue line) and upper open hole chamber interval 8 (BCS_A1_INTP08 - black) pressures depicted along with I/P module 1 (BCS_A1_INTP02 - red), I/P module 2 (BCS_A1_INTP03 - green) and I/P module 3 (BCS_A1_INTP04 - orange). The plot indicates open hole chambers interval 1 and interval 8 pressure responses to be acting in unison, while the displayed intervals along the cased and cemented section appear somewhat isolated to flow. The temperature profile during this re-saturation period was near ambient, ranging from 14.8 ºC to 15.5 ºC after the equipment installation was completed in April 2015. Temperatures were measured in interval 1, the cased and cemented section and interval 8 (see Figure 7).

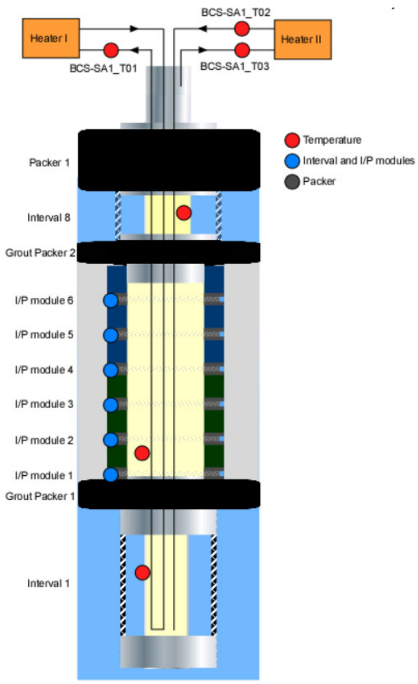


Figure 5. Mock completion injection / extraction access design for the CS-A experiment.

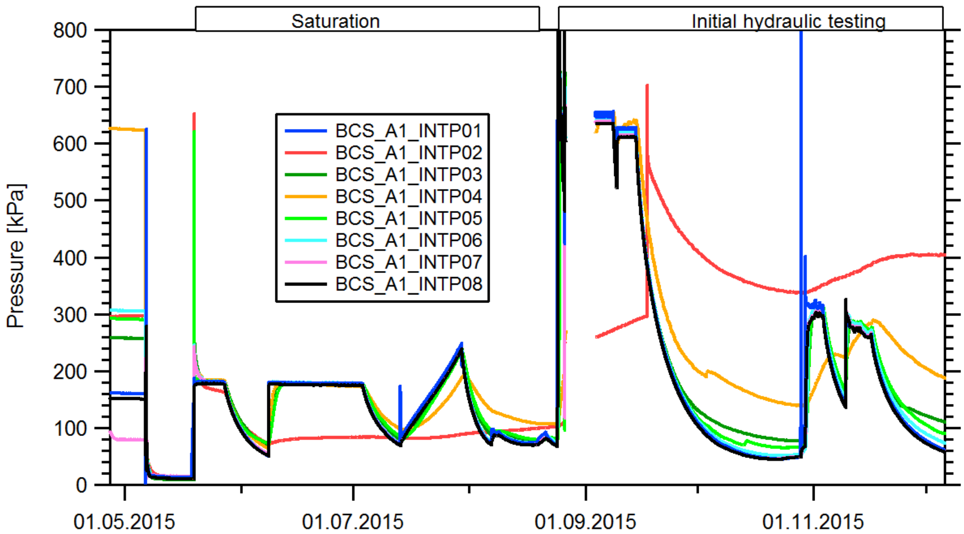


Figure 6. Re-saturation of CS-A experiment mock completion installation after air drilling.

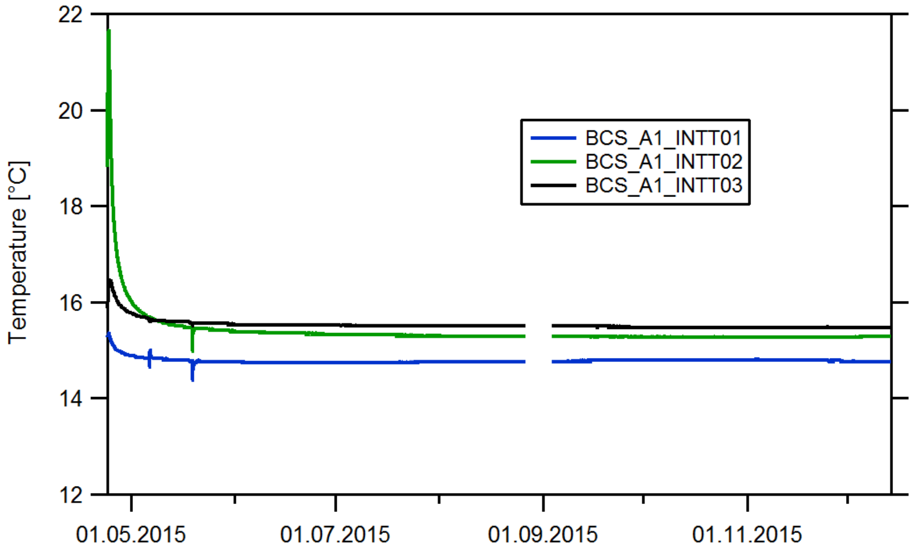


Figure 7. Temperature profile after CS-A equipment installation. Temperature sensors placed in lower open hole chamber interval 1 (BCS_A1_INTT01), in the cased and cemented section (BCS_A1_INTT02) and in the upper open hole chamber interval 8 (BCS_A1_INTT03).

### *2.1.3. Heat – cooling cycles for micro-annulus creation*

Referring to the experimental design requirement to create leakages along the cement-casing boundary by micro-annuli creation (*Section 2.1.1.e. i.*), cyclic heating followed by cooling to ambient laboratory conditions was performed. Three heat sensors installed in the mock completion are shown as red dots in Figure 5. Heat measurement data was acquired in interval 1, in the cased and cemented section between I/P modules 1 and 2 and interval 8. Figure 8 shows temperature from these 3 locations. The maximum temperature achieved 12 May 2016 within the cased and cemented section (BCS_A1_INTT02) was approximately $73^0$ C. The cool-off period began shortly thereafter, cooling rapidly to $30^0$ C by 13 May. The heating/cooling cycle impact on permeability creation for the CS-A experimental mock completion system is shown in Figures 9 and 10. Hydraulic connectivity between the various I/P modules and for the lower and upper open hole chambers have been increased. However, the flow patterns are complex, representing a considerable challenge in the quest to test 3 sealants that can restore pressure isolation to the system.

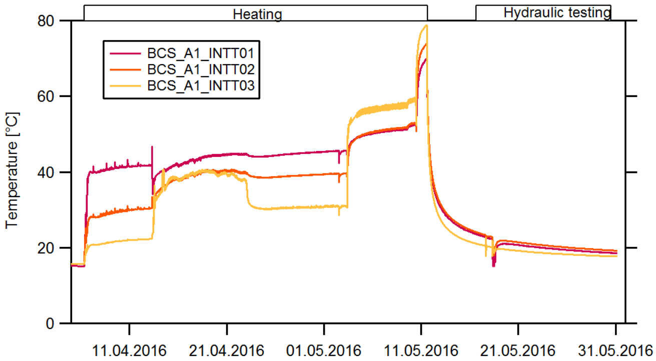


Figure 8. Mock completion heat/cool cycling 06 April 2016 to 01 June 2016 for micro-annuli creation.

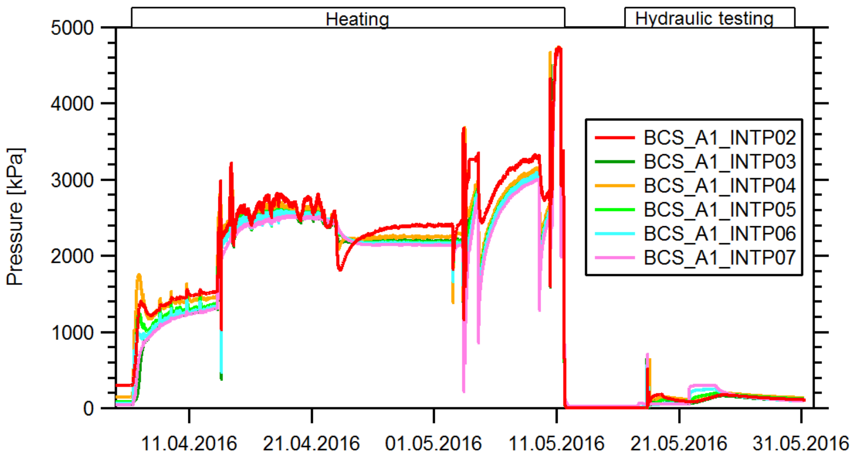


Figure 9. Mock completion pressure test response in the cased and cemented hole section during the heating-cooling cycle.

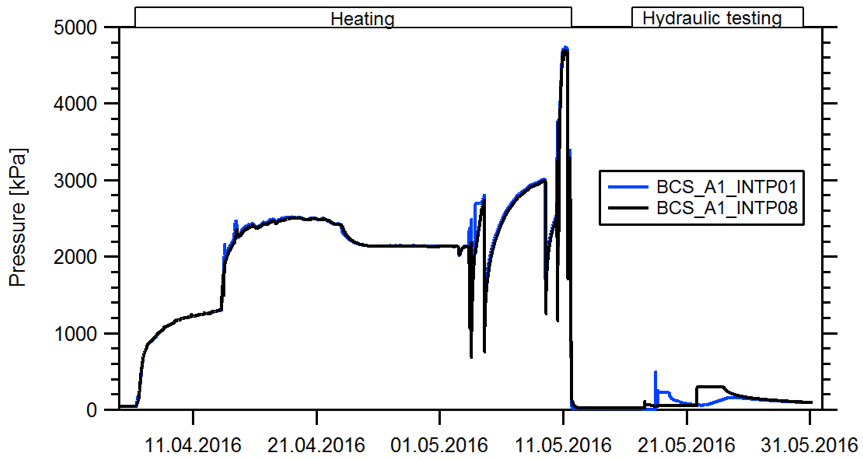


Figure 10. Mock completion pressure test response in the open hole chamber intervals 1 and 8 during the heating-cooling cycle.

## 3. CS-A experiment flow path diagnostics – current interpretation

At this point, flow paths created during the heating/cooling cycle phase of the experiment indicate relatively greater permeability development at the outer cement sheath/formation boundary compared to individual I/P modules in the cased and cement section. The current interpretation is shown in Figure 11. Close examination of pressure response and pump-in fluid quantities indicate high connectivity between intervals 1 and 8, along with considerable fluid storage behavior in these open hole chambers. The figure also shows treated water injection / extraction dipoles used to establish hydraulic connectivity at the casing/cement boundary.

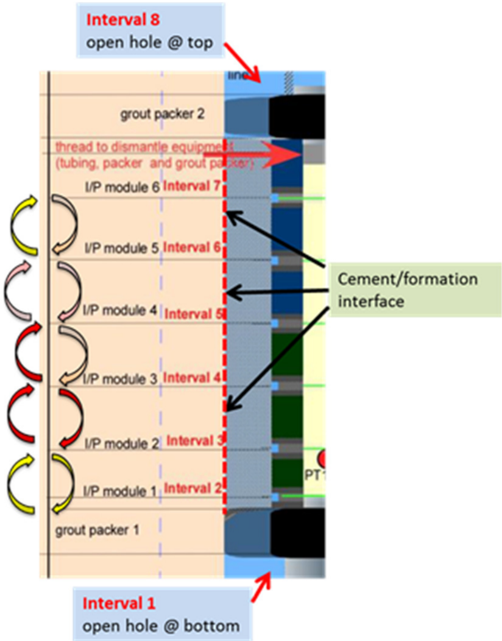


Figure 11. CS-A experiment flow interpretation along the outer cement sheath/formation boundary.

Work continues to define the flow characteristics between I/P modules. To that end, additional flow dipole testing is underway that will likely be followed by a comprehensive flow tracer test program. The results of this work will be presented at a later date along with the results of the sealant testing program. Figure 12 depicts pressure injection testing action plan to determine intervals 1 and 8 chamber isolation after grout packer re-set (12a). Subsequent injection and extraction port dipole flow tests (12b) depicts injection at 25 bars in to interval 2 while extracting fluid at interval 3. Intervals 4 – 7 show pressure monitoring during the interval 2 - 3 dipole test. This dipole test sequence is scheduled for completion in September 2016. The tracer testing program is designed to quantify fluid flow distribution along the experimental system. This further work is necessary for sealant test design, i.e. sealant ingredient concentrations and pumping schedules.

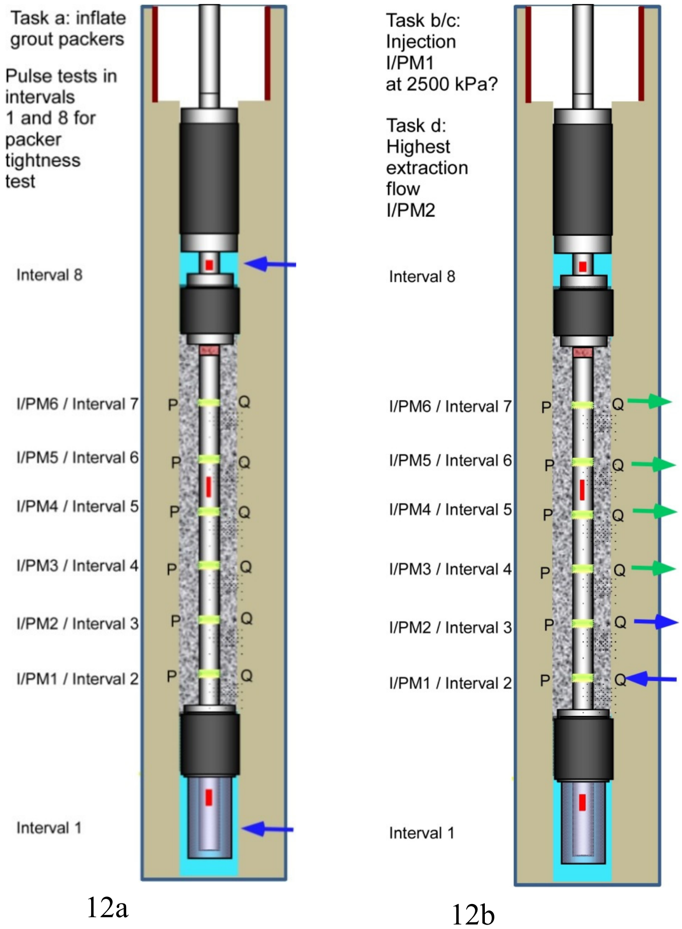


Figure 12. Mock completion injection / extraction access design.

## 4. CS-A experiment sealant testing program – the next steps

### *4.1. General*

The aim of this experimental program is to develop sealants that restore containment to well completions experiencing $CO_2$ leakage. Slow gas leaks associated with micro annuli interfaces that develop between casing, cement sheath and country rock are particularly problematic. Developing sealants specifically designed to operate in wells under conditions encountered during $CO_2$ injection will address the need to demonstrate the availability of intervention strategies that mitigate leakage through wells.

#### *4.1.1. Next phases of the project include*

a) Complete flow diagnostic using treated water injection; September 2016

b) Modify tracer testing program to accommodate treated water test results; October 2016

c) Finalize sealant injection program and implement; 4th Qtr16 - 2nd Qtr17

d) Overcore mock completion system; 3rd Qtr17

e) Assess results and report-out; 4th Qtr17

## References

[1] IPCC Special Report on Carbon dioxide Capture and Storage (September 2005), section 5.7.2 Processes and pathways for release of CO2 from geological storage sites, page 244.

[2] A Review of Sustained Casing Pressure Occurring on the Outer Continental Shelf by Bourgoyne, et al 1999 http:/www.boemre.gov/tarprojects/008/008DE.pdf .