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Lessons Learned: The First In-Situ Laboratory Fault Injection Test

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Abstract

The CSIRO In-Situ Laboratory has been a world first injection of CO_2 into a large faulted zone at depth. A total of 38 tonnes of CO_2 was injected into the F10 fault zone at approximately 330 m depth and the process monitored in detail. The site uses a well, Harvey-2, in SW Western Australia (the South West Hub CCS Project area). The top 400 m section of Harvey-2 was available for injection and instrumentation. An observation well, ISL OB-1 (400 m depth) was drilled 7 m to the north east of Harvey-2. ISL OB-1 well was cased with fibreglass to provide greater monitoring options. The CSIRO In-Situ Laboratory was designed to integrate existing facilities and infrastructure from the South West Hub CCS Project managed by the West Australian Department of Mines, Industry Regulation and Safety. While new equipment was deployed for this specific project, the site facilities were complemented by a range of mobile deployable equipment from the National Geosequestration Laboratory (NGL).

The geology of the area investigated poses interesting challenges: a large fault (F10) is estimated to have up to 1000 m throw overall, the presence of packages of paleosols rather than a contiguous mudstone seal, and a 1500 m vertical thickness of Triassic sandstone as the potential commercial storage interval. This unique site provides abundant opportunities for testing more challenging geological environments for carbon storage than at other sites.

While details of this first project are described elsewhere, lessons were learned during the development and execution of the project. A rigorous risk register was developed to manage project risk, but not all events encountered were foreseen. This paper describes some of the challenges encountered and the team's response.

Relocation of the project site due to changes in landholder ownership) and other sensitivities resulted in the need for rapid replanning of activities at short notice resulting in the development of the site at Harvey-2. The relocation allowed other research questions to be addressed through new activities, such as the ability to consider a shallow/controlled release experiment in an extensive fault zone, but this replanning did cause some timing stress. The first test at the In-Situ Laboratory was reconfigured to address some of those knowledge gaps that shallow/controlled release experiments had yet to address. Novel approaches to drilling and completing the monitoring well also threw up unanticipated difficulties. Loss of containment from the wellbore also posed significant challenges, and the team's response to this unintended release of gas and water from the monitoring well at the

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conclusion of the field experiment will be discussed. Other challenges that we encountered, their impacts, and our response are also catalogued here (Table 1 and below) to enable broad knowledge exchange.

Keywords: shallow release, controlled release, fault zone, DAS, DTS, leakage, South West Hub, fault injection, CCS

1. Introduction

The CSIRO In-Situ Laboratory has been established within the area of interest of the South West Hub CCS Project (SWH), in southwest Western Australia. The SWH proponent has been the Western Australian Department of Mines, Industry Regulation and Safety (DMIRS) since the earliest data gathering commenced in the mid-2000s. The investigation of a greenfield area in the Southern Perth Basin for potential commercial scale storage for emitters in the Perth and southwest region resulted in drilling of four wells, Harvey-1, -2, -3 and -4 [1] & [2] (Figure 1). The wells were located after a series of seismic surveys were conducted to understand the geology and structure in the area of interest. The geology of the area investigated poses interesting challenges: a large fault (F10) is estimated to have up to 1000 m throw overall [3], the presence of packages of paleosols rather than a contiguous mudstone seal, and a 1500 m vertical thickness of Triassic sandstone as the potential commercial storage interval provide abundant opportunities for testing more challenging geological environments for carbon storage than at other sites.

The absence of the regional drinking water aquifer (the Jurassic age Yaragadee Formation) was seen as beneficial to managing basin resource conflicts [4] and reduces community concerns for the South West Hub site as a potential commercial-scale storage site. Extensive research and data acquisition have occurred within the area which has indicated that there were a number of fault zones not previously identified through lack of seismic data in the region, summarized in [5]. The conclusion of the studies to date and related peer review and peer assist activities suggest that as a base case this site could be able to store up to 800,000 tonnes CO_2/per annum over 30 years via predominantly residual and dissolution trapping processes [6].

Modelling activities have shown that the base case (Figure 2) allows plume development and migration to remain well below the top of the Wonnerup Member, such that the need for a thick, laterally continuous seal is not deemed essential, although preferred. The paleosol unit in the Yalgorup, or possibly the Eneabba Formation further up the section is not equivalent to the oil and gas industry standard of a laterally thick, continuous seal. Thus, one of the underlying uncertainties relates to the behavior of the faults in the region, especially given the degree of uncertainty surrounding the sealing potential of the Yalgorup Member.

The CSIRO In-Situ Laboratory has leveraged the extensive data collection and synthesis at the SWH. Initially to be located at either Harvey-3 or -4 [7] to test the top of the Wonnerup Member, the unconformity at the boundary with the overlying Yalgorup Member and the Yalgorup's sealing potential (Figure 1B), access became problematic (Issue #1) and the site moved to Harvey-2. The project was rapidly replanned (Issue #2), and new science questions developed to test the geological environment in the new location, which included the potential to test the F10 fault, intersected by Harvey-2 [3], at approximately 750 m at the top Yalgorup [8].

The first test at the CSIRO In-Situ Laboratory was reconfigured to address knowledge gaps that shallow/controlled release experiments had yet to address: many of the prior free phase CO_2 release experiments had been conducted at <25 m depth, with smaller volumes, often in unconsolidated sediments, where emissions to surface had been difficult to quantify [9] [10]. Relocating to Harvey-2 enabled a novel (not so) shallow/controlled release experiment be undertaken at an intermediate depth. The experimental design addressed some of the identified research gaps [9] [10] while also attempting to mimic a shallow accumulation resulting from possible leakage from the primary container. The role of fault zones in the migration of a CO_2 leak could also be evaluated. The drilling of the ISL OB-1 adjacent to the first well was challenging (Issue #3) for a range of reasons including the fact that it intersected the fault zone.

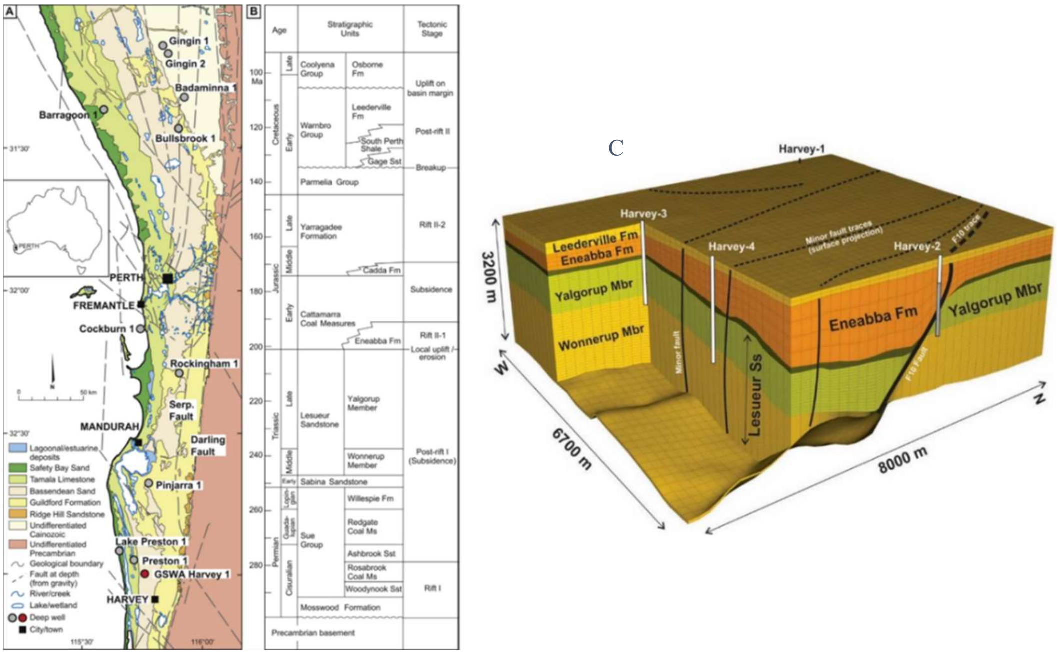

Figure 1 (A) Location map of South West Hub with well locations; (B) stratigraphy of the Southern Perth Basin; (C) model of the area of interest.

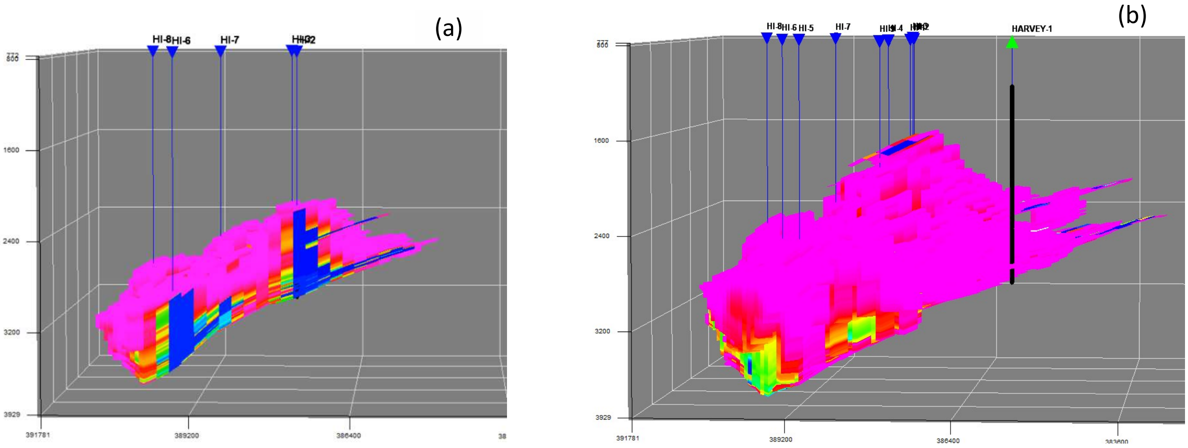

Figure 2 (a) Base Case: 800,000 TPA over 30 years/ 9 wells/ injection depth 3200m, gas saturation 0.19/ salinity 50,000 ppm/ open faults/ Wonnerup – Yalgorup in communication, results in the shallowest depth that the CO_2 is modelled to reach at 560 m below the top Wonnerup. (b) Base Case: 3 million TPA over 30 years/ 9 wells/ injection depth 3200m, gas saturation 0.10/ salinity 200,000 ppm/ open faults/ Wonnerup – Yalgorup in communication, results in the shallowest depth that the CO_2 is modelled to reach at 17 m below the top Wonnerup. Modified from [6].

Further details of the geology, the recompletion of Harvey-2, drilling of the monitoring well ISL OB-1 and the first test are discussed in detail in [8] and at this conference. The site set-up is shown in Figure 3.

In brief the test design was as follows:

- Injection into Harvey-2 at a perforated interval (336 – 342 m)
- Total volume planned 40 tonnes CO_2
- Injection into the Eneabba Formation (sandy interval)
- Injection rate planned 10 tonnes per day
- Monitoring well ISL OB-1 drilled 7 m away
- Completed with fiberglass casing
- Total Depth of ISL OB-1 378 m
- Wide range of monitoring methods including fibre optics, well bore logs, surface seismic, soil gas monitoring etc.

The first test was conducted in February 2019 where 38 tonnes CO_2 were injected and the arrival of CO_2 successfully monitored. A casing failure in ISL OB-1 (Issue #18) brought a premature end to the test and the injection ceased. The well was successfully brought under control, the CO_2 vented and well worked over. At surface, the release of formation water from the failure point was minor and the well pad (a crushed limestone pad) was removed and replaced. The event was reported to the regulator and related relevant government bodies under the guidelines of the environmental management plan, and the site is now prepared for future experiments.

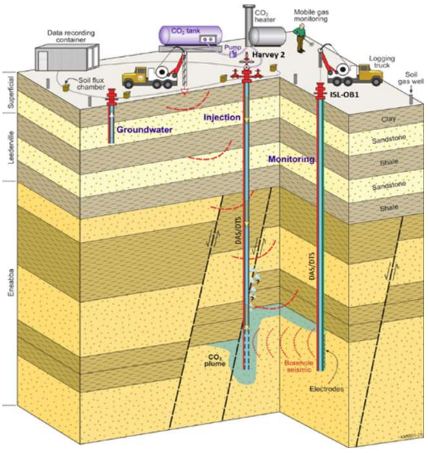

Figure 3 Schematic diagram of the well and test configuration. The injection interval is at approx. 330 m for reference but scales have been exaggerated for clarity. From [8].

2. Lessons Learned

Table 1 summarizes some of the risks encountered during the execution of the first CSIRO In-Situ Lab experiment. While a risk register was developed and maintained during the lifetime of the project, several risks were not foreseen. Some risks triggered a series of events beginning with the changes to land access around the original wells planned for use (Issue #1). Response to this and other issues were often exceedingly time-constrained and generated new challenges (Issue #2). The issues have been categorized as community-based, geological-based or technical/operational issues. The list in Table 1 is not exclusive, but details of some of those issues encountered, what happened, resultant impacts, our responses and some of our new learnings are explored below.

2.1. Community

There are a number of benefits to conducting demonstration/field laboratory-scale activities for new and contentious geoscience projects. Modelling and conventional laboratory-based activities provide much background information and significantly aid design for the transition to commercial-scale activities as has been observed in a number of field experiments. But the ability to see (albeit in miniature) the scale and nature of a geological carbon storage project, particularly adjacent to a potential commercial-scale site such as the SWH can give stakeholders and community groups more detail of the impact and footprint of a site. Visualisation of these activities are important to gaining trust in bringing about new activities such as CCS. Reinar (2015) [11] states "…it is difficult to engage in a serious public debate over risks or to develop an effective risk communications strategy if there is no actual project on which to present information." Thus, the role of pilot or demonstration sites is of particular importance to gaining community trust [12].

A recent workshop hosted by The Geological Society of London and UK Geo-Energy Observatories (UKGEOS) in February 2021 [13], explored in detail the challenges that relate to demonstrating and re-engaging with the public and regulators around carbon storage, geothermal and other geo-engineering activities. Transparent demonstration of the considerations required to embark on such activities requires significant amounts of information to meet regulatory requirements. The ability to demonstrate geo-engineering activities such as geological carbon storage allows stakeholders and publics to come on site and observe the footprint of these activities and leave with a sense of the detailed effort involved in conducting underground activities. Visits to commercial-scale operations are challenging due to the need for significant induction programs and other industry standards to reduce risk and harm to visitors and infrastructure. For example, in Western Australia, access to Barrow Island (site of the Chevron Gorgon gas processing and CO_2 storage infrastructure) is strictly limited due to the State Act that designates it as a Class A nature reserve and protected habitat.

2.1.1. Issue #1 Land Access Rescinded

Specific to the CSIRO In-Situ Laboratory the loss of access to the Harvey-4 well (Issue #1) approximately one week before going on site to complete that well posed a significant challenge that had knock-on effects impacting the entire project. Discussions with the landholder were via DMIRS, who had negotiated and held a lease with the landowner for several years as part of the SWH. By mutual agreement, DMIRS and CSIRO decided that no further activity would occur at Havey-4 as a sign of good faith to the community. This well has subsequently been plugged and abandoned.

DMIRS also had a lease on the site of Harvey-3 well. A change to ownership of the land on which that well sat meant that the new landholder had little previous knowledge or experience of the activities in the region related to the broader CCS project activities. Again, being respectful of their situation, it was agreed that no CO_2 injection would occur on that well site. It has however been instrumented for long term monitoring and other experiments have taken place. This site is managed by Curtin University.

2.1.2. Issue #2 Time-line compression

In spite of the changes detailed above, the agreement to conduct a research experiment was still active. The team were able to identify the potential to utilize the Harvey-2 well and develop an alternative hypothesis and field experiment. The decision to conduct a shallow/controlled release in the Harvey-2 well resulted from three considerations: prior knowledge of the shallow/controlled release landscape through a review by [9], the configuration of the well, and the geological location of the well.

Roberts and Stalker (2017) [9] had conducted a review of shallow/controlled release experiments and concluded that (a) there were knowledge gaps around intermediate depth releases, (b) no releases into highly faulted areas had occurred and (c) previous projects had difficulties in quantifying systematically any releases at/surface. These and other outcomes of the review were used to develop a question around the evolution of leaks from primary storage containers, and what they may look like at intermediate depths if they were to accumulate near baffles or permeability barriers.

The Harvey-2 well is on the margin of the SWH area of interest. As such, its design was purely for acquiring some additional data to the east of the F10 fault and not regarded as a critical piece of infrastructure for the commercial investigation; hence the wellbore diameter was smaller than Harvey-3 or -4. When the well bore developed instability problems following continuous coring, it was cemented to approx. 400 m thus limiting subsequent activity to shallower depths.

The third key element was that the Harvey-2 well crossed the F10 fault. This was not planned during the drilling but was subsequently confirmed by seismic data. At the top of the Yalgorup Member throw is anticipated to be of the order of 750 m and reconstruction of the fault in the area tested suggests a 200-300 m fault zone [8]. Evidence is seen in the continuous core, though this is nuanced.

Having established the experimental test plan, much of the work completed in order to conduct activities at Harvey-4 were required to be replanned, new equipment procured, other equipment returned and a new environmental management plan developed and submitted to the regulator. As significant changes had taken place, the additional work and timeline was severely compressed and an aggressive timeline was developed.

Additional constraints included the requirement to wait until winter rains had ceased in order to allow for heavy vehicles to access the site, as the site is very flat and prone to flooding in the winter (Issue #14). As a result, the drilling of the monitoring well ISL OB-1 commenced in mid-November 2018 (late spring in the southern hemisphere), injection took place in February, monitoring until end of March and decommissioning and site clean-up and closure had to occur by end of April 2019. The hard stop was the end of the funding and just before the rainy season commenced, restricting heavy vehicles and topsoil damage to the local farmer's land.

The aggressive timeline did mean that there were few moments to reflect and consider potential new risks and this issue may have been responsible for other unforeseen challenges.

2.1.3. Other community issues

Currently there are no formal State based regulations relating to the geological storage of CO_2 (Issue #10). Wells Harvey-1 to Harvey-4 were drilled under Section 115 of the Mining Act. We were able to drill ISL OB-1 under the same Act, liaising closely with DMIRS, having provided an Environmental Management Plan in association with both the original and subsequent plans for the drilling program. Various State government legislation and regulations had been discussed for the Harvey-4 project plan [7] and DMIRS indicated that up to 100,000 tonnes CO_2 could be injected for research or scientific purposes in the absence of formalized onshore CCS legislation. For the subsequent shallow/controlled release experiment at Harvey-2, this activity was not regarded as storage and so the Department of Water were consulted. They concluded that CO_2 was not considered a contaminant, and that the local groundwater too saline for use as potable water, therefore environmental risk was low. This approach was in keeping with the handling of the Ginninderra field site activities in ACT [14].

As mentioned above, seasonal variation (Issue #14) on the site meant that there was a limited window for on-the-ground activity. This indirectly caused significant challenges for surface and soil gas monitoring. In winter, the surface was water filled and very muddy, while in summer, the mud dried and developed deep > 1m desiccation cracks (Figure 4). This uneven surface made it difficult to seal round the Li-Cor chambers and made surveys with some equipment difficult to manage (Issue #6). Installing the enviroprobes for soil gas sampling was difficult in the baked hard clay, and risked disturbing local wildlife (i.e. venomous snakes!).

2.2. Geological Issues

There are always geological challenges in every project, and they are typically regarded as site specific. The geology of the Harvey-2 location, while lending itself to the opportunity to inject into a large fault at approx. 330 m was difficult because of said fault and challenges related to drilling in a difficult stress regime (note the larger Darling Fault to the east of the area on the margin of the entire Perth Basin (Figure 1).

2.2.1. Issue #3, #4, #5 and #6 Drilling the new observation well ISL OB-1

Drilling, while a standard procedure, tends to have surprises and these can be exaggerated during the drilling of a well for research purposes. Drilling so close to the original well (Harvey-2, 7 m away) may have contributed to those challenges which were predominantly geological but did impact on operational timelines due to delays. Table 1 again illustrates some of the challenges at a high level. In short, the opportunity to conduct more static and dynamic models prior to the execution of the test may have helped to understand the behaviours observed but may not have altered the outcomes of the actual drilling and completion itself.

All wells drilled during the SWH investigations to date have experienced difficulties in drilling and stability, particularly through the Yalgorup Member [14] and resulted in some poor logging data. It is particularly problematic where there are interlayering of sands and muddier intervals, and further impacted by the stress regime, causing significant wellbore instability, contributing to Issue #3 and #5.

While lessons learned from the drilling of Harvey-1, -2, -3 and -4 were employed to the best of our ability, often there was not the relevant information for the drilling of ISL OB-1 because of its different focus. The area of interest in this case was in the top 400 m of the geological cover. In all the previous wells in the area, this was not of interest, as during drilling to deeper intervals, the objective had been to get through that material as rapidly as possible and reach the Yalgorup and Wonnerup Members for reservoir and seal investigations. Usually during drilling operations this top section is the testing area for optimizing mud weights (Issue #6). In addition, shallower intervals tend to be more poorly consolidated and difficult to manage (Issue #3). This is an issue often cited during the review of shallow/controlled release experiments (< 25 m depth) and can cause significant disturbance of soil during the insertion of casing/tubing [15] [9] [10] and references therein.

Drilling in a fault zone presents a whole new range of challenges (Issue #5). Typically, this is avoided at all costs. Few deliberately drill into these zones, though over the last few years, there have been a number of emerging CCS related projects that have either considered or are executing activities in this space to describe and reduce risk predictions around faults and CO_2 containment (e.g. CAMI; Containment and Monitoring Institute, Canada [16]; Mont Terri Rock Laboratory, Switzerland [17]; CO2CRC Otway project [18]. Experience from the CSIRO In-Situ Lab site and others will aid improved drilling through sharing knowledge, particularly with the drilling contractors so that they understand that they will be entering difficult geological terrain and that it is actually a priority to do so for the research being conducted.

Other geological issues are more standard and manageable, such as having a good idea of the porosity and permeability behaviour of the formation entered (Issue #12). This is typically managed by having a good geological model and a well identified range of scenarios. However, this may not have been as rigorous as we would have liked due to challenges relating to Issues #1 and #2 The previous plan, to recomplete Harvey-4 with a 5 zone pump testing ability through the Wonnerup and Yalgorup Members (Michael et al, 2018) was extensively modelled at the first interval anticipated for CO_2 injection in the Wonnerup Member, and as such the work done was not relevant to a 330 m injection into a different formation with different physical and mineralogical properties.

Figure 4 Flat lying land, showing extreme desiccation cracks posing a challenge in the baked hard clay soil for various surface monitoring techniques.

2.3. Technological/Operational

Operationally this project was already time-constrained due to the funding agreement demands and its ambitious approach to the earlier project [7]. The limited on-the-ground time caused by Issue #14 further compressed activities. It must be noted here however, that the redeveloped operational timeline was able to be executed on time and budget and with minimal impact and no loss time injuries. Other challenges were inherited from using existing infrastructure and are discussed briefly below.

2.3.1. Issue #4 Completing ISL-OB1

There was unintended introduction of cement into the well bore during the setting of the fiberglass casing. This caused plugging of the wellbore from the base of the new casing to above the planned perforation interval for Harvey-2. Once recognized, the team evaluated the benefits and risks of attempting to remove some of that cement to reach the depth equivalent to the perforations. The procedure required drilling and reeming of the cement and did occasionally cause some of the fiberglass to be pealed away where contact was made. Efforts to stabilize the drill reduced impacts, and cuttings were carefully monitored to see if there was any damage evident – and a few pieces of fiberglass casing were observed and the cement removal stopped as close as possible to the required depth. It is likely that this process could have compromised the strength of the fiberglass casing when pressures increased during the duration of injection, contributing to Issue #18. It also prevented logging runs at the area of interest as the tools require several metres of additional depth to observe the formation.

2.3.2. Issue #7 Harvey-2 well preservation

The ability to reuse existing infrastructure has occurred before in research projects and field trials such as with the Frio Brine I Project [19] and at the CO2CRC Otway Project Stage 1 (Naylor production well, [20]). Both project proponents acknowledge a range of issues relating to the reuse of infrastructure not discussed further here. However, newer commercial-scale projects under consideration in the Netherlands and other North Sea proximal countries are investigating the potential to utilize not only depleted gas fields, but the associated infrastructure and pipelines.

In the case of the Harvey-2 well, having been drilled for other project purposes and not being geographically located in the likely fairway for a commercial-scale injection site with the SWH, the well underwent a period of inactivity in which it was shut in. However, there was no subsequent replacement of the well bore fluids with a non-saline water or inhibitor, or removal of suspended materials. Due to the variable mud weights and mud invasion (Issue #6) there was significant additional material in the well that may have impacted on injection performance. In addition, Harvey-2 was left uncased below 207 m for an extended period of time, and associated activities are listed in more detail in [8], but confirmed injectivity challenges that were observed during the operational phase of injection of CO_2. Cumulatively, these and related rock property behaviors contributed to greater damage and mud invasion than anticipated, resulting in the need for higher than anticipated injection pressures.

2.3.3. Issue #8 Contamination of the ISL OB-1 completion

Other challenges affected data acquisition and results. For example, during drilling and completion of ISL OB-1 (Issue #8), a metal-free completion was required for some monitoring methods (e.g. electrical resistivity imaging, induction logging and electromagnetic logs). During logging, a regular (every 9 m) response was measured consistent with the introduction of metal in the casing and corresponded to the casing joints. The conclusion was that metal was introduced into the fibreglass cased well via pipe dope or sealant that likely contained undisclosed particulate metal (possibly molybdenum disulphide). Although unintentional, the resulting response acted as a useful calibration point for the tool, but the response also overlapped with some zones of interest making interpretation difficult. This potential problem had been registered as a risk, resulting in the identification of sealant that had been previously used successfully at other sites and believed to be free of contamination. Based on the observations, it is assumed that the formulation of the sealant had been altered subsequently, and we caution future field experiments to not make the same assumption when simple chemical testing could have eliminated the risk.

2.3.4. Issues #11, #15 and #16 Equipment failures (Sensor failures, general equipment, surface monitoring)

It comes as no surprise that there would be equipment failures over the duration of a highly technical and complex field experiment. The following range of issues can be consolidated and discussed together. All these activities were technical/operational risks.

A decision was made to complete the well with sensors behind the casing (see [8] for details). The cementation of the well (Issue #4) may have impacted on the performance of some of those instruments and the curing process may have contributed (high levels of heat generated during curing) resulting in loss of all pressure and temperature gauges (Issue #11). Fortunately, there was a degree of redundancy with the monitoring system so this had minor impact but meant that we lost some real-time information on pressures at the monitoring well that may have aided mitigation of Issue #18.

One of the hoses connecting the CO_2 from tank to pump to well failed part way through the injection phase (Issue #15). There was a degree of urgency relating to replacing this hose as stopping injection posed risks for the experimental design and hypothesis i.e., the risk that the CO_2 at the current rate of injection at that time (see [8] for figures of rates) would have been so low, that the CO_2 may have dissolved before being resolved by any of the monitoring methods. Procuring a replacement was delayed due to logistics of working in a semi-remote, low population density area where services to supply replacements were limited. The delay also meant that the duration of injection was extended, and the manpower planning became impacted. The introduction of higher injection rates through exchanging pumps became more of a focus. Ultimately this may have contributed to Issue #18, where it is believed we may have breached our maximum pressure briefly, resulting in the casing failure at ISL OB-1 [8].

A further challenge resulted from the late change to the surface monitoring plan. The original deep, but small injection at Harvey-4 [7] was now a shallow/controlled release at Harvey-2, meaning that there could be significant movement of the CO_2 and monitoring groundwater and soil gas was essential (Issue #16). A range of monitoring activities were quickly identified, and expertise obtained for those additional activities, which included more groundwater and soil gas monitoring, but the program was not optimized, and the on-the-ground conditions had not been anticipated until the site had significantly dried out in mid-December (the desiccation cracks Issue #14). The difficulties of working on the hardened ground was also a challenge for the microseismic monitoring equipment deployment.

2.3.5. Issue #18 Wellbore leakage

Only 38 of the 40 tonnes CO_2 planned were injected at this first test. Injection operations ceased when it was recognized that there was wellbore leakage taking place in ISL OB-1. Evidence of leakage began with the upward flow of water prior to a scheduled logging run. The well remained un-capped for observation and resulted in the release of water and CO_2 in periodic bursts (geysering). The cyclicity of the periodicity was monitored, and a timing window was established to conduct safe re-capping. After securing everything, regulators were immediately notified and the evaluation of contamination by water and CO_2 conducted. The site and well underwent minor remediations and made safe. The bottom hole pressure data was reviewed and found to have exceeded 6200 kPa prior to the release, which was significantly higher than the pressures used in the modelling scenarios. The limited number of modelling scenarios for the new location meant that we did not capture the influence of phase changes to CO_2 during the injection pressure alongside the higher than anticipated pressures required to overcome the lower permeability encountered. This meant that the upper pressure for the overall project was reached during the latter stages of injection.

The contribution of Issue #4, the subsequent remediation and evidence of some degree of damage to the fiberglass casing may have generated a weak spot that facilitated the failure of the wellbore. The higher than anticipated pressures may have contributed to the failure rather than been the sole cause. Consolidating this information and the overall risks was not ideal and likely a victim of Issue #2 timeline compression.

3. What went right?

In Section 2 we cover a lot of activities that went “not right” or were unanticipated. Clearly the change in location and compressed timeline for delivery of the project did contribute to several of the challenges listed in Table 1 but did not compromise the outcomes of the test. Results of the overall experiment showed the successful identification of CO_2 both from well bore (DAS and DTS) and repeat surface seismic collection, among other methods. These are all shown in [8] and subsequent papers by this team of co-authors.

But it has to be recognised that the data from the well failure have provided a huge amount of insight into what a CO_2 leak might look like at an intermediate depth via monitoring, and what the impact of such an event might be. An ability to monitor, remediate, visualize and manage this event contributes to our understanding of potential wellbore leakage risks and their consequences. This information can and has been shared with regulators, industry and the community to demystify the consequences surrounding the most likely way in which CO_2 may escape to surface – through a well bore – not via a fault.

4. Conclusions

The activities conducted under the first CSIRO In-Situ Laboratory are described in detail in [8] and at this conference. The purpose of this test was to mimic leakage from a deeper reservoir into an intermediate zone or minor baffle and evaluate the potential leakage path to surface. The role of a major fault on that journey was also to be explored.

However, the advent of a well bore leak and the monitoring program surrounding this first test was able to provide information on how the CO_2 and related rocks and fluids behaved during that process. The experiment supports the observation that one of the main issues identified in [9] [10] is that of leakage along wellbores and pipelines during controlled/shallow release experiments but noted more broadly for commercial-scale CCS projects as a major risk. The experiment also significantly contributed towards understanding and identifying the expression of an unintended wellbore leak. The patterns seen in data through a range of monitoring methods can be used to develop both future project monitoring at commercial scale and what the early warning markers might be. During field trials, pilots or demonstration projects the risks and consequences can still be small enough to manage but allow for new insights when things do “go different” and can demonstrate, in this case, a fast-fail within the boundary of our regulatory obligations and provide a significant body of lessons learned.

Table 1 List of some of the risks encountered, their impact on the project and how the project team mitigated those risks. C = Community; G = Geological; T = Technical/operational issues.

Risk encountered		What happened?	Response	C	G	T
1	Land access rescinded	Access to Harvey-4 well rescinded, scope limited at Harvey-3	New project plan developed and executed at Harvey-2 to allow CO_2 injection	■		
2	Time-line compression	Project re-planned for Harvey-2 as shallow/controlled release experiment, new equipment required	Rapid redevelopment of project timeline, processes and procedures to execute project on revised time and budget. Identify new long-lead items to accelerate.			■
3	Drilling ISL OB-1	Difficult drilling environment due to poorly consolidated materials at shallow depths resulting in borehole stability problems.	Closely interact with drillers to evaluate progress and discuss challenges. Keep communication and dialogue going, be clear on the purpose of the activity. Slow down, change out bits. Review information on Harvey-2 to optimize. Proximity to Harvey-2 could have caused localized damage.		■	
4	Completing ISL OB-1	Unintended cementing up of well at the planned perforation interval (unseated plug)	On discovery, liaised with drillers to adopt a staged approach: the well was re-entered and some of the cement drilled out. Stabilisers used to keep straight, cuttings monitored for evidence of reeming of casing, camera surveys. Close observation to enable quick stop. No space to send logging tools to monitor reservoir interval.			■
5	Drilling in a fault zone	Poor consolidation, limited experience because people do not typically choose to drill into large faults	Closely interact with drillers to evaluate progress and discuss challenges. Keep communication and dialogue going, be clear on the purpose of the activity. Keep well vertical to minimize risk initially. Future experiments could introduce deviated well configuration to maximise fault interaction. Review risks identified in other wells in area.		■	
6	Mud balance and caking	Extensive mud invasion in Harvey-2	Made injection challenging. Mud balance is usually worked through in the shallow intervals (i.e. can be highly variable at start of drilling, especially if initial target is deeper). Using the Harvey-2 well log data meant that we risked overbalancing and mud invasion/blocking			■
7	Harvey-2 preservation	Industry standard suspension not undertaken, causing sedimentation and plugging issues.	Difficult to remediate at short notice, tried range of pumps and pressures to manage injectivity. May have contributed to Issue #18			■
8	Well drilling and completion	Metal contamination from pipe dope/sealant in the fibreglass casing of ISL OB-1	No post installation remediation options identified, used signal for calibration. Some uncertainties at points of interest were unfortunate. Don't make assumptions			■
9	Fault zone accuracy	During injection, pressure buildup was observed. Geometry, juxtaposition, zonation etc were poorly described and understood	Were we in the fault zone? Increase the modelling scenarios to understand range of permeabilities that could be anticipated (not done due to Issue #1). Experimental results helped illuminate, but more data acquisition would help. Issue #6 contributed to uncertainty as to whether were we in a compartment resulting in Issue #18		■	
10	Regulatory environment	No regulation in place in State of WA for CCS	Worked closely with state regulators to develop an appropriate Environmental Management Plan. Open dialogue, site visits and weekly meetings	■		
11	Sensor failures	Failure of several sensors that were placed behind casing. Other sensors were not able to be fully deployed	Contingency planning through use of different types of sensors reduced exposure to loss of sensor types. Sought to understand the information that could be gained despite not having all sensors fully deployed			■
12	Uncertain permeability	Predictably, permeability was unpredictable!	Potential for a broad range of geological models. Various injection pumps were available and used to manage injectivity. Increasing modelling scenarios may have reduced uncertainty. Would not have predicted caking #6.		■	

13	Noise	Some sensors were impacted by noise generated by CO_2 injection	Provision of quiescent periods; future plans to make sure that there are scheduled quiet periods for longer tests		▨
14	Seasonal variation	Extreme seasonal differences in environment conditions limited the field window and affected suitability of monitoring tools.	Compression of timeline to be on-the-ground for the dry season only (i.e. the hot season); management of fire risks. Wet season limited movement of vehicles and well drilling deployment, deployment of monitoring equipment.	▨	
15	Equipment failures	Hose leakage and pump upgrades	A hose failure delayed injection due to logistics of replacement. Due to Issue #, #12 the initial pump unit was delivering CO_2 too slowly. Progressively upgraded pumps over the duration of injection		▨
16	Surface monitoring	The monitoring program was initially not developed to consider the fault zone given that injection was planned for Harvey-4. Some of the flux chambers near the well were flooded due to the incident and drilling operations.	Surface monitoring program was updated and the resource allocation was increased. Partnering with external expertise to accelerate deployment. Flux chamber locations not optimised relative to drilling/well plugging operations affected by #17		▨
17	Data retrieval and review	Not all data could be observed live off site, or observed live on site. Regular data downloading was problematic.	Some data had to be acquired manually from gauge readings limiting review and interpretation time to react to changes. Delayed alert to breach of injection pressure. Likely contributed to the unintended leakage from the observation well. Plan better for all data acquisition, logging, backing up, reviewing and reporting workflow. Escalate importance in operational planning. Identify clear lines of communication and responsibilities		▨
18	Well leakage	Wellbore leakage to surface at ISL OB-1. Formation water and CO_2 ejected.	Observe well behavior. Removed non-essential staff from site for safety reasons. Capped well, when identified safe to do so. Regulator notified and plans executed to remediate as per industry standard. Review monitoring data for future early warning identifiers	▨	▨

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