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The Modular Borehole Monitoring Program: a research program to optimize well-based monitoring for geologic carbon sequestration

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Abstract

Understanding the impacts caused by injection of large volumes of CO_2 in the deep subsurface necessitates a comprehensive monitoring strategy. While surface-based and other remote geophysical methods can provide information on the general morphology of a CO_2 plume, verification of the geochemical conditions and validation of the remote sensing data requires measurements from boreholes that penetrate the storage formation. Unfortunately, the high cost of drilling deep wellbores and deploying instrumentation systems constrains the number of dedicated monitoring borings as well as limits the technologies that can be incorporated in a borehole completion. The objective of the Modular Borehole Monitoring (MBM) Program was to develop a robust suite of well-based tools optimized for subsurface monitoring of CO_2 that could meet the needs of a comprehensive well-based monitoring program. It should have enough flexibility to be easily reconfigured for various reservoir geometries and geologies. The MBM Program sought to provide storage operators with a turn-key fully engineered design that incorporated key technologies, function over the decades long time-span necessary for post-closure reservoir monitoring, and meet industry acceptable risk profiles for deep-well installations.

While still within the conceptual design phase of the MBM program, the SECARB Anthropogenic Test in Citronelle, Alabama, USA was identified as a deployment site for our engineered monitoring systems. The initial step in designing the Citronelle MBM system was to down-select from the various monitoring tools available to include technologies that we considered essential to any program. Monitoring methods selected included U-tube geochemical sampling, discrete quartz pressure and temperature gauges, an integrated fibre-optic bundle consisting of distributed temperature and heat-pulse sensing, and a sparse string of conventional 3C-geophones. While not originally planned within the initial MBM work scope, the fibre-optic cable was able to also be used for the emergent technology of distributed acoustic sensing. The MBM monitoring string was installed in March, 2012. To date, the Citronelle MBM instruments continue to operate reliably. Results and lessons learned from the Citronelle MBM deployment are addressed along with examples of data being collected.

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1. Introduction

The overarching objective of monitoring geologically sequestered CO_2 is to demonstrate the safe and effective long-term storage and integrity of the target reservoir and ensure the protection of the environment in accordance with a regulatory framework. This is accomplished through a multi-faceted monitoring program by which data is acquired that (1) assures the public and regulators that the reservoir is behaving as intended, (2) validates conceptual models developed for reservoir engineering and storage management, and (3) demonstrates protection of drinking water and the greater environment. Well-based monitoring is a key component of a comprehensive monitoring program that can also include surface geophysics, atmospheric, and remote sensing monitoring technologies. The concept of "integrated" well-based monitoring is to engineer a single assembly consisting of an optimal suite of tools that reliably and cost-effectively meets monitoring objectives and eliminates the need to recomplete a well for disparate monitoring tasks.

There exist several examples of comprehensive integrated monitoring completions for CO_2 storage as part of storage demonstration projects. At the CO2SINK Project, Ketzin, Germany, the Ktzi 200 and 202 monitoring boreholes incorporated a permanent discrete pressure/temperature gauge, a behind casing electrical resistance tomography array (ERT), fibre-optic DTS, and a gas membrane sampling system, which continuously monitored the arrival of CO_2 and tracers [1, 2]. The Australian CO2CRC Otway Project Naylor-1 well, completed within the Waarree C depleted gas reservoir, consisted of an array of geophones and hydrophones, two permanent discrete pressure/temperature sensors, and a three-level U-tube geochemical sampling system [3, 4]. The SECARB Cranfield CFU31-F1 and F2 monitoring wells, completed to a depth of 3.1 km incorporated an ERT array, permanent pressure/temperature gauges both within the reservoir zone and behind casing for monitoring above the sealing formation [5]. A fiber-optic DTS system with separate heat-pulse cable was also installed but early failure of the heat-pulse system precluded its use. A system for performing continuous active source seismic monitoring (CASSM) modeled after the system installed as part of the Frio Brine Pilot operated for one month acquiring well test monitoring data but the sensor array failed just prior to initiation of the CO_2 injection [6].

2. Methodology

Our initial engineering of the MBM system focused on two lines of research: (1) robust methodologies for completing smart wells, and (2) technologies for incorporation into a comprehensive well-based monitoring solution. We paid particular attention to the root causes of failures and operational issues during earlier projects to see if there were common problems. Lessons that we took away from our own experience and through discussions with others were (1) to pay particular attention to the methodology by which electrical connections were performed, (2) careful selection of wetted materials, and (3) installation procedure. In addition, we noted several projects had experienced difficulty with pressure isolation. Following the experience and recommendations of the field operator at Citronelle Dome, we deployed a dual mandrel hydraulic set packer. Similar hydraulic set packers have been successfully installed in three additional instrumented monitoring wells since the initial MBM deployment and we have adopted it as the preferred method for intelligent tubing deployments.

2.1. Lessons learned – prior experience

Electrical connections proved to be a significant problem during several installations. At the Frio Brine Pilot in Dayton TX, an in-well electrical connector used for seismic monitoring and exposed to both brine and CO_2 was retrieved with significant corrosion and evidence of fluid leakage past elastomeric seals (Figure 1a) [6]. At the SECARB Cranfield Site a metal-on-metal compression seal that was used to protect electrical splices used for a heat-pulse monitoring system also failed and diagnostics indicated brine leakage into the cable. We have reached conclusions similar to others within the oil and gas industry: splices and seals are a critical weak point that needs to be engineered for reliability. Al-Omair et al., 2009 used welded junctions to deploy four quartz pressure gauges off a single TEC, to address this problem and minimize possible leakage points for a multi-zone completion in a Saudi Aramco field [7].

Figure 1. Examples of failures in (a) and electrical quick mate connector and (b) a polyurethane molded hydrophone during a CO2 sequestration pilot test.

Rubbers and plastics are known to be subject to enhanced deterioration upon exposure to wet CO_2. While plastic jacketed seismic cables are still frequently used within the seismic industry in the context of temporary deployments, polyurethane jacketed cables deployed at the Frio Brine Pilot and Australian CO2CRC Otway Project depleted gas storage demonstration experienced failures (Figure 1b). In the case of the seismic cable at the Otway Project, the cable was a migration pathway for reservoir gas, and represented a safety hazard that had to be mitigated by cutting and terminating the cable at the wellhead. For the MBM program we decided that the downhole completion would have no exposed rubbers or plastics, and instead would rely upon welded connections where possible. If it is not feasible to pre-weld a splice then a double barrier mechanical system using metal seals would be used to protect any splices.

Pressure control and isolation using packers are an important component in a monitoring completion. The MBM program considered different options for robust and reliable pressure control for long-term monitoring given its importance in ensuring well integrity. The primary benefit in pneumatic packers is the greater expansion they are capable of as compared to mechanical-set or hydraulic packers. However, several problems were noted with pneumatic packers which included a slow bleed-off of pressure leading to pressure communication across the packer elements. Pneumatic packers have often been cited for poor reliability, particularly for extended deployments [8]. Cement inflations can improve the reliability of pneumatic packers, but at the expense of retrievability [9]. While mechanical set packers have good reliability, the mechanical operation mechanism precludes incorporation of control lines. Hydraulic set packers have reliability that approaches that of the mechanical set packer, but with an operation mechanism that is conducive to incorporating feed throughs in the packer design.

Multifunctional completions are assembled from a collection of different purposed control lines. The CO2CRC Otway Project installation required the use of 11 lines, resulting in a challenging rig floor environment by which to safely run-in-hole and install the instrumented bottomhole assembly. Other projects such as the SECARB Cranfield project had similar control line counts. To reduce the number of lines a tube-in-tube concept was adopted for U-tube fluid sampling with the MBM package. Instead of the use of two distinct control lines, a 3/8” control line was fabricated over a ¼” line reducing the number of control lines and wellhead penetrations by one. The tube-in-tube was also adopted during the MBM project for operating hydraulic clamps, which were used to overcome a problem that was noted on prior projects when using bow spring clamps: poor coupling of seismic sensors to the formation. The MBM used hydraulically operated locking clamps to positively couple geophones to the borehole wall.

In summary, key findings that we focused on from prior projects to improve the reliability of our installation included:

(1) Elimination of polymer jacketed cables and elastomeric seals that could be weak links in system reliability

(2) Integrating both fibre-optic and copper elements into a single multifunction fibre-optic cable to improve data quality and minimize the number of control lines

(3) Using dual tube-in-tube control lines to simplify U-tube sampler deployment by reducing the number of spooling units and control lines required

(4) Deploying positive locking geophone clamps with tube-in-tube hydraulic lines, thus avoiding bow spring style clamps

(5) Elimination of subsurface fibre-optic field splices and electrical splices to the greatest extent possible and

(6) Use of a hydraulic-set packer as opposed to pneumatic packer for long-term zonal isolation and incorporation of an overshot tool to avoid rotation of the bottomhole assembly during installation.

2.2. Completion methodology

We will first examine the two methods that are frequently used for completing intelligent wells, tubing completion and behind casing, and then examine the different sensor technologies that have been used for reservoir surveillance during CO_2 sequestration demonstrations.

2.2.1. Tubing completion

Most commonly instruments are installed on tubing that is run into a cased well. The technology for installing instruments on tubing is commercially available consisting of specialized instrument mandrels, protective clamps, and services needed for spooling coiled control lines. While the exact details of each installation varies, the general approach is to (1) install instruments within protective mandrels that are incorporated in the tubing string, (2) utilize control lines between the instruments and the surface to both move fluids and data signals, and (3) pass the control lines through a modified tubing hanger in the wellhead that provides for pressure control. Stainless steel banding, centralizers, and protective clamps are used as required to ensure that the instruments and control lines are all secure and protected during the installation process. Other tools are available to incorporate in the tubing string that can be facilitate multizonal completions. Sliding sleeve valves when used with multiple packers permit independent access from a series of zones through the tubing string.

Careful attention to the sequence of events is required to ensure a successful installation. A CWOP (complete-the-well-on-paper) meeting allows all of the service provides to review the procedure and determine if there are any gaps in the program. Typical services that may be needed to supplement the basic workover rig services include tubing torque turning, fluid pumping and handling, swabbing or gas lifting, slick-line, wireline logging, spooling and wellhead completion. Normally it is desirable to use a workstring with a casing scraper and swivel head to clean and circulate fluid until the fluid returns are clean. When “landing” the completion, meaning installing it at the proper depth, a combined casing collar locator and gamma ray wireline tool can be used inside tubing to ensure proper depth control by referencing the installation to the open-hole gamma log and/or casing collars. Pup joints are then used to space out the installation, referencing the tubing installation to the earlier baseline gamma log.

Obtaining an uncontaminated geochemical sample requires that workover fluids are removed prior to sampling. While there are wireline tools that are available for use under openhole conditions which produce fluid through the well mudcake, the quality of the samples are often insufficient for supporting geochemical modeling of baseline aqueous conditions. Cleaning of workover fluids can be performed after installing the completion in the well by swabbing or gas lifting the well. Fluid returns should be monitored for electrical conductivity or other geochemical parameters that will indicate when the returns represent formation fluid. The introduction of an easy to detect tracer, such as fluorescein, to workover fluids will simplify quantifying the amount of contamination that persists after cleanup, as it is often impractical to clean up the well until there is no sign of residual workover fluids.

2.2.2. Behind casing completion

A second method of installing instrumentation is behind the casing with cementing of the instrumentation into place. There are several benefits to this method. Since the entire inside of the large diameter casing is empty it is available for temporary installations and wireline tools. This can include large diameter instruments such as seismic sources or multi-level clamping geophone arrays which cannot go inside of smaller diameter production tubing. If the casing remains unperforated then pressure control is simplified and instruments can be installed without additional pressure control tools at the surface. A second benefit is that for tools that require close coupling to the formation, such as electrodes for performing electrical measurements or fibre-optic acoustic sensors, the instruments have only a thin cement sheath separating them from the formation allowing good coupling to the formation. Since the well is instrumented at the same time the casing is installed, this method can reduce the total number of days on location when compared to a program where drilling and well completion are separate. However, to support the behind casing completion the results of openhole logging may need to be quickly interpreted for determining optimal placement of the different instruments. As the well is in an open and potentially risky state following drilling there are significant demands on the project team to make rapid decisions so that the casing and instruments can quickly be run-in-hole.

There are also several drawbacks to a behind casing completion. Because the instruments are on the outside of the casing they need to be protected using mandrels and centralizers when the assembly is run-in-hole. A larger drill bit size may be required, thus driving up well costs and drilling time. Cementing operations also need to be designed more carefully as the casing string with control lines attached cannot be rotated but instead must only be reciprocated. Closely spaced control lines can form a gap contributing to bridging of the cement, and the formation of a vertical pathway for migration of fluids, so the layout and clamping of the control lines must be carefully considered. Another drawback in behind casing completion is that it is challenging to repurpose the well from a monitoring well to an injection well. If there is a future need to perforate the well, the method of instrument installation must be amenable to an oriented perforation method used to avoid damaging or destroying the behind casing equipment. Perforating a control line could end up creating a conduit up to the surface.

2.3. Reservoir monitoring technologies

While monitoring geologically sequestered CO_2 is in many ways similar to oil and gas reservoir surveillance, the drivers for the types of data collected, the frequency and duration is driven by distinct regulatory and operational goals and objectives. The need to demonstrate storage permanence, plume spatial extents, reservoir integrity, and well integrity are all drivers for a robust multi-parameter monitoring program. Supercritical CO_2 has properties that differentiate it from formation brines or gas and thus methods that target those distinguishing properties are candidates for integrated monitoring completions. As an example, the seismic velocity of CO_2 is considerably slower than a similar brine saturated rock, and the thermal conductivity is lower, thus methods that target those properties can be used to identify the presence of and possibly phase saturation of CO_2 in a brine reservoir [6, 10, 11].

2.3.1. Pressure and temperature sensors

Pressure and temperature are perhaps the most fundamental of all reservoir parameters to monitor. For deep well applications discrete pressure sensors are normally fabricated with accompanying temperature sensors that are used to reduce temperature dependent sensor drift. Limiting the overall rise in reservoir pressure during CO_2 injection is needed to mitigate failure of sealing formations and prevent out of zone migration of the CO_2. Analysis of pressure transients can also be used to infer reservoir capacity through estimation of permeability and storativity. A further use two vertically separated pressure measurements within a monitoring borehole is to gauge the thickness of a plume of CO_2. Vertically stacked pressure sensors were used during the Australian CO2CRC Otway Stage 2 Residual Saturation Test to identify the thickness of a column of CO_2 within the brine saturated Paarratte Formation

[12]. Other uses for pressure monitoring include using a pressure sensor above or within a sealing formation to monitor the performance of the cement to isolate the reservoir.

The most common technologies used to monitor deep subsurface pressure are piezoresistive- and quartz- based measurements. Quartz crystal based sensors typically exhibit the lowest drift and highest sensitivities, and hence are normally the choice for long-term CO_2 monitoring. Accuracy can be as high as 0.02% of full scale range and resolution better than 1 PPM. There also exist fiber-optic based pressure sensors, with less accuracy than quartz and piezoresistive based sensors, but the ability to operate at temperatures greater than 150 °C lifespans can limit the lifespan of the electronic gauges.

2.3.2. Fluid sampling

Monitoring wells can be strategically situated such that they intersect the injection CO_2 plume and monitor its growth over time. High quality uncontaminated fluid samples permit accurate assessment of the geochemical impacts of the CO_2 and can facilitate modeling of its long-term fate. Wellhead sampling, which is often used to sample a production fluid stream is not appropriate for CO_2 monitoring wells as the samples do not accurately portray the subsurface gas composition and multiphase fluids lead to highly disturbed wellhead conditions due to rapid expansion of the rising gas phase which can result in slug flow. Wireline samplers are one method to retrieve accurate fluid samples from the subsurface and preserve multiphase fluid composition. Obtaining a wireline sample requires the mobilization of a wireline unit to the field, and if the well is under pressure requires pressure control equipment such as a lubricator and grease head.

Additional methods for analyzing subsurface fluid composition have been developed specifically for monitoring CO_2 sequestration projects. As part of the CO2SINK project in Ketzin, Germany, a membrane gas sampling method has been developed that allows a continuous stream of dissolved gas to be analyzed at the surface [2]. The method, referred to as Gas Membrane Sampling (GMS), uses two small capillaries from the surface that form a loop in the subsurface through a silicone membrane connection that is exposed to formation fluid. An argon carrier gas flows through the loop and is continuously analyzed at the surface using a portable quadrupole mass spectrometer. The CO2SINK project successfully used this method to identify when CO_2 arrived at the monitoring wells and the arrival of co-injected tracers.

While the GMS method has the benefit of providing a continuous stream of gas for analysis, it cannot be used for recovery of aqueous fluids. The U-tube methodology and GMS are similar in that two capillaries are used to both supply gas and recover fluids, but the U-tube uses a check valve in the subsurface to admit both gas and liquid to the loop of tubing, and then a charge of high pressure N_2 to recover the fluid at the surface. The U-tube sampler was first used for fluid sampling as part of the Frio Brine Pilot in 2004, and subsequently has been used at more than a dozen other projects including the SECARB Cranfield Test, Cranfield, Mississippi, the CO2CRC Otway Project, Victoria, Australia and most recently installed at the Hontomín TDP, Hontomin, Spain and MUSTANG Heletz field site in Israel [13,14].

Both the GMS and U-tube methods are well suited for continuous monitoring. The GMS has the strengths of being able to operate continuously in an autonomous fashion with the limitation that it only recovers gas and accurate quantitation requires careful calibration. The U-tube method samples both gas and liquid or a multiphase combination at discrete intervals in time, but the sampling method requires a user be present and the infrastructure for operation is more complex than that for the GMS system. While an automated U-tube system was operated as part of the Frio Brine Pilot, the operation proved cumbersome for liquid sampling [14]. Once the U-tube fluids became gas dominated and were self-lifting, then it was simple to perform real-time analysis of the produced continuous gas stream [15].

2.3.3. Fiber-optic monitoring

Fibre-optic monitoring spans a large range of technologies that can either be discrete point-based or distributed in nature. Discrete point based fibre-optic sensors often rely upon fiber-bragg gratings (FBGs) to “reflect” back to a detector a signal that when processed reflects a parameter such as temperature or strain. The complexity of installing FBGs exactly where a measurement is to be made housed within a pressure tight assembly has limited the adoption of the technology for subsurface measurements. More commonly technology based on distributed technology, in which the entire length of the fibre is the measurement sensor, has been adopted for subsurface monitoring. To date, parameters that can be monitored using fully distributed fibre-optics include temperature, acoustic energy and strain.

Distributed temperature sensor (DTS) systems were initially developed in the 1980s and were quickly recognized as a useful tool for borehole monitoring, finding application in both geothermal and petroleum exploration and production [16]. Today's commercial DTS units use Brillouin scattering to work with single-mode fibre, or Raman scattering can be used with multi-mode fibre. Spatial resolution is typically 1 m with some units working at resolutions up to 13 cm. Measurement times can be as short as a few seconds, but to obtain accuracies of ±0.1 °C or better the optical signals need to be averaged for several minutes. The CO2SINK project used DTS cemented behind casing in two monitoring boreholes [6].

Distributed acoustic sensing (DAS) is a younger technology than DTS, but has seen tremendous growth since its commercial introduction six years ago. Based upon Rayleigh scattering, light transmitted down the cable will continuously backscatter or 'echo' energy which can be sensed. Since each 10 nanoseconds of time in the optical echo-response can be associated with reflections coming from a 1-meter portion of the fiber (two-way time of 10 ns), a single optical fibre can act as a multitude of sensors providing "seismic" traces along the entire length of the fibre. Initial testing of the technology as part of the CO2CRC Otway Project and testing at Ketzin showed the promise of the technology, but the low signal-to-noise ratio was considered limiting [17]. More recent testing conducted just this year showed significant improvements in sensitivity, and there exists strong potential for future well-based seismic monitoring to use fibre-optic technology as its foundation [18].

3. Field demonstration

3.1. Citronelle field D9-8#2 monitoring well

The technologies chosen for the D9-8#2 MBM installation included U-tube fluid sampling, permanent quartz pressure/temperature gauges, a short string of 18 geophone pods with locking clamps and an integrated fiber-optic bundle to facilitate temperature, seismic, and heat-pulse monitoring. The geophone pods consisted of 15 single component vertical geophones and three 3-component geophones spaced at 50 ft. and installed at a depth of 6000 ft. The primary tubing is 2-7/8" 6.5 ppf L-80 RTS-8 with an internal coating of Tuboscope TK-805 to improve resistance to exposure to carbonic acid. The 2-7/8" tubing permits conducting periodic logging campaigns using wireline industry standard 1-11/16" slim-hole tools. A hydraulic set packer isolated the upper 9400 ft of the D9-8#2 well 7" casing from the 450 ft. of perforated casing open to reservoir sands. Figure 2 shows a schematic of the entire completion assembly which resulted from an extensive CWOP (complete the well on paper) process led by ARI International [19].

Experience from prior integrated monitoring completions showed that spooling and rig floor management of a multitude of control lines contributes significantly to the risks of damage and instrument failure during the well completion process. To reduce installation risks, the backbone of the MBM system is a flat-pack system, which consists of individual control lines combined into a single polypropylene plastic extrusion. Figure 2 shows the MBM flatpack, consisting of two tube-in-tube assemblies, a hybrid fiber-optic cable with singlemode and multimode fibers as well as six copper conductors, and a coaxial cable for operating quartz pressure/temperature gauges. Independent of the flat-pack was a control line used for transmitting signals from the 18-pod geophone array. When the flat-pack was initially extruded over the control lines, the bottom 450 ft was left unencapsulated so that the control lines could pass through the packer without the need to remove the plastic flatpack jacket. One of the lessons learned and most time consuming tasks of completing the wellhead was the removal of the polypropylene encapsulation from the up-hole (above wellhead) end of the flat-pack. It proved far more difficult to remove than originally anticipated, partly due to the chilly night air which significantly reduced the plastic's flexibility.

Based upon the experience from the local operator, Denbury Resources, the packer selected for zonal isolation was a hydraulic set dual string packer with asymmetric short and long string connections. The 2-7/8” long string connection was used for the production tubing while a smaller 1.900” facilitates pass-throughs for the fiber-optic, pressure/temperature gauge, and U-tube sampling lines. Figure 4 shows the dual-mandrel packer with an inset picture highlighting the pass-throughs that penetrate the short string coupling.

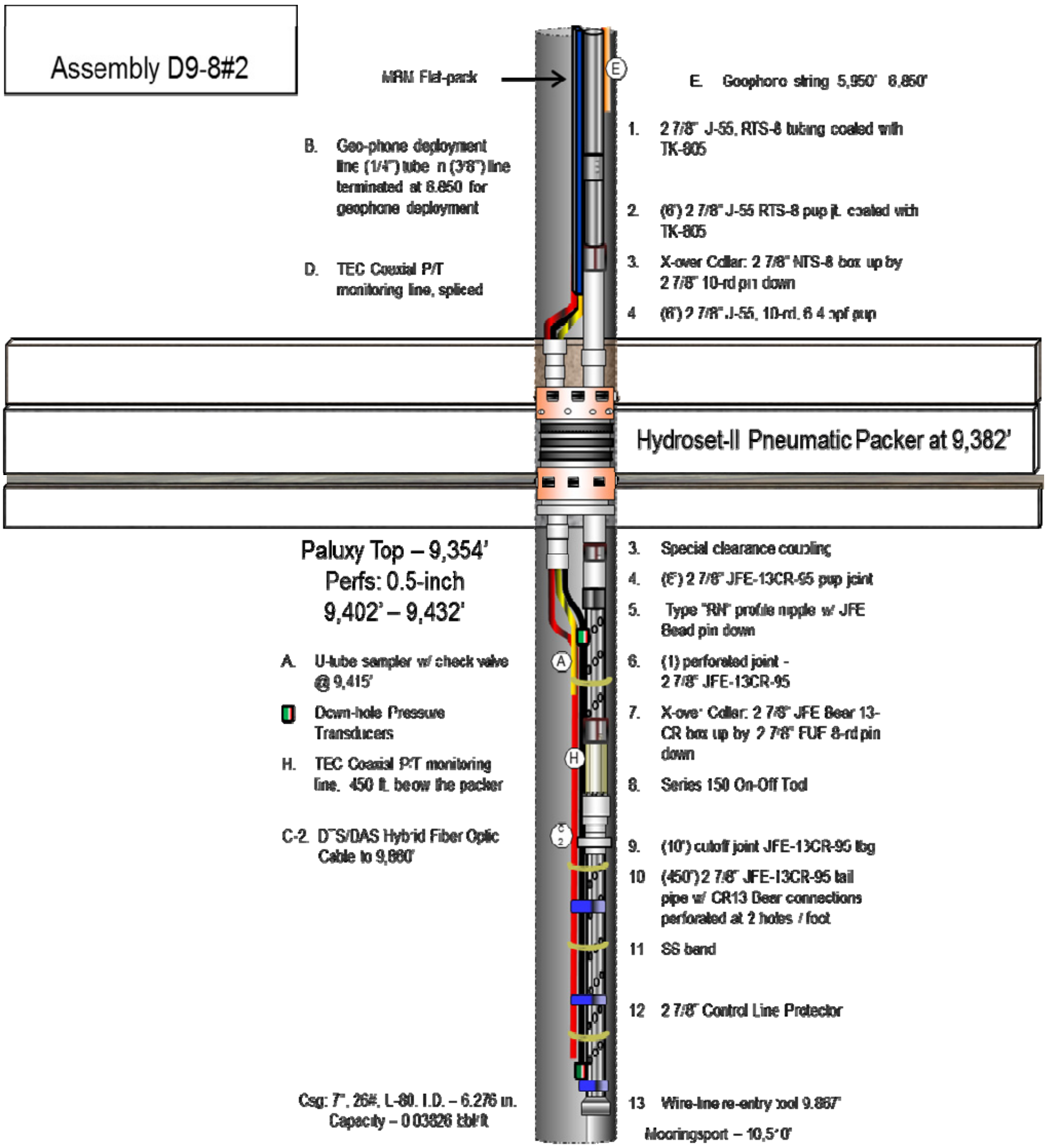
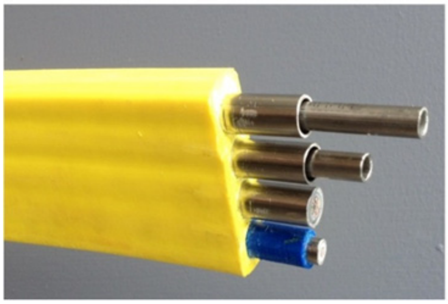


Figure 2. Schematic of the D9-8#2 well completion resulting from an extensive CWOP planning process. This was supplemented by a detailed tubing sheet with callouts to every tubular component and device in the well [19].

(a) (b)



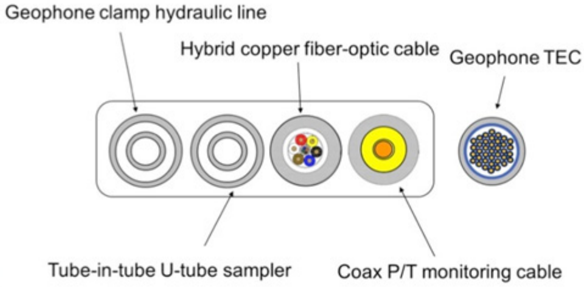


Figure 3. (a) The MBM 'flatpack' and schematics for the individual control lines (b). The overall dimensions of the flatpack profile is 12 mm x 50 mm.

Figure 4. An asymmetric dual-string hydraulic set packer used for zonal isolation of the D9-8#2 well. The inset picture reveals the small string set up with compression fitting for feeding through the control lines.

To eliminate the need for splices, an overshot was used to couple the 450 ft long tailpiece to the bottom of the packer. The overshot joined perforated tubing below the packer with the packer assembly, which eliminated the need for rotating threaded joints together, which would be impossible with continuous control lines strapped onto the bottomhole assembly. This eliminated the need to splice the fibre-optic cable, which would have created a weak point. Fibre splices often lead to later failures and require lengthy pauses in the completion procedure, as splicing on a rig floor is demanding difficult work even under favorable weather conditions. Extreme conditions such as high humidity, wind and rain necessitate performing fibre splice work in a protected enclosure and increase the risk of poor outcomes of splicing efforts.

The MBM installation in the D9-8#2 well did not use gauge carriers, but rather the pressure gauges and U-tube inlets were strapped to the tubing using stainless steel bands and protected with cross coupling protectors. While that method worked for our installation, a preferred deployment method is to use gauge carriers that recess the instruments away from the casing wall and can protect the instruments even if the well contains a pronounce dogleg. Figure 5a shows a typical gauge carrier used for collocated deployment of a U-tube sampler and pressure temperature gauge as deployed at the MUSTANG Heletz Field Site in the H18b well. Figure 5b shows a crosscoupling protector used to prevent damage to the control lines during the run-in-hole procedure at Citronelle field site.

Figure 5. (a) Installation of collocated U-tube and pressure temperature gauge in a custom gauge carrier design to protect the instruments during installation. This was at the MUSTANG Heletz Project installation. (b) Protection of control lines using cast cross-coupling protectors at the Citronelle Site.

The D9-8#2 geophone pods were deployed using novel hydraulic clamps designed to overcome the poor results we had experienced with bow spring clamps. The design objective for the clamp mechanism was to decouple the geophone pods from the tubing to minimize the coupling to tubing vibrations, while effectively attaching the geophones to the casing wall with a high-enough clamping force to provide good coupling to the formation. Figure 6(a) shows the specialized clamp with a single geophone pod. Figure 6(b) shows the tube-in-tube hydraulic line broken out from the flatpack which was used serially operate all 18 of the clamps. A separate ¼” hydraulic line ran the 900’ length of the 18 pods (about 900 ft) to form a fluid loop.

The basic installation procedure was as follows: (1) clean-up of the well, (2) assemble and lower the bottom-hole assembly, (3) run-in-hole, and (4) set the wellhead. The D9-8#2 was already perforated prior to commencement of the workover operation. The clean-up followed standard procedures with a scraper run and circulation of fluid until the well produced clean fluid. While it is common to hang the control line sheaves off the workover rig’s monkey board (a work platform above the rig floor), given the stiffness of the flat-pack a sheave was suspended near the top of the mast and the flat-pack guided straight down the length of the derrick mast to the slips. The packer was mounted on a joint of tubing and raised into the pipe rack prior to run-in-hole. The fibre-optic control line was installed through the packer passthrough and a rig hand on the monkey board helped guide the lines in the well. After installing the initial 450 ft. of tubing an overshot was used to couple the packer assembly with the tailpiece.

After installation of the packer, the run-in-hole procedure proceeded similar to other spooling operations, with the exception that each of the 18 geophone pods required approximately an hour to assemble. The initial design of the clamping mechanisms used a multitude of bolt fasteners, requiring caution to not drop small parts down the well, and reflecting the limited time for testing and development of this particular design. For a repeated deployment we would use a redesigned pod clamp ideally taking less than half the time to install. Once the completion assembly reached the intended depth the control lines were run through the tubing hanger and the wellhead was completed. For precise space out a gamma/CCL can be used, although that was not part of the D9-8#2 procedure as the targeted interval was quite thick.

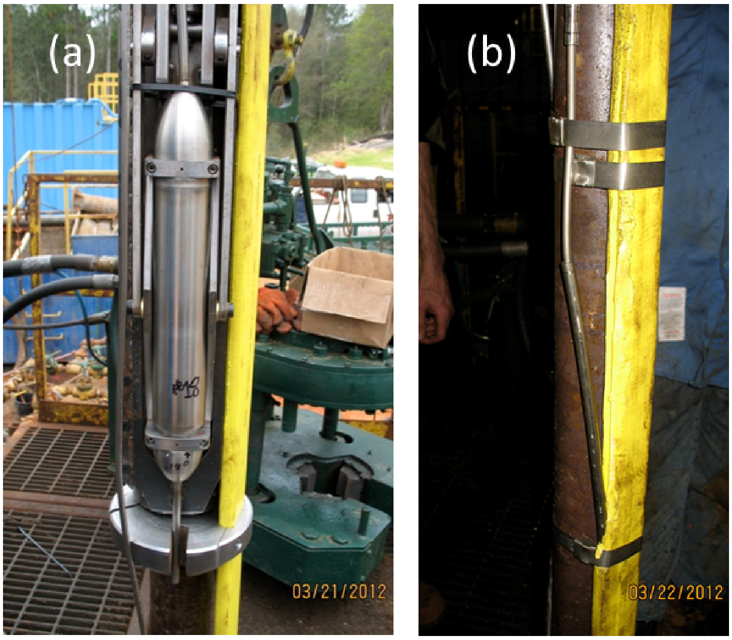


Figure 6. (a) MBM Geophone with hydraulic clamp, mounted on tubing with yellow flatpack. (b) Flatpack with hydraulic line, each attached to tubing with steel banding.

3.2. Baseline MBM data collection

All of the installed monitoring systems worked as intended after the completion operation had concluded. Figure 7(a) shows the D9-8#2 pressure response during the early commissioning of the CO_2 injection system with injection in the D9-7 well, approximately 300 m away. The periodic spikes in the temperature are caused by the operation of the heat-pulse system using the hybrid fibre-optic cable. Figure 7(b) shows the baseline thermal data after well completion and also a thermal profile after the heat-pulse system has been turned on. The spike at about 9440 ft depth is the thermal signature associated with the hydraulic set packer.

An opportunity to acquire distributed acoustic seismic (DAS) data with the Citronelle MBM system became available utilizing emergent DAS technology. Using single-mode fibres deployed in the MBM, we tested the distributed acoustic sensing (DAS) system currently under development by Silixa, Ltd (Silixa's iDAS) and compared iDAS to the clamped geophones deployed as part of the MBM system. DAS is a new technology with limited testing, but it holds good promise to simplify borehole seismic monitoring. Silixa, as a collaborator, processed the DAS data present herein.

While DAS testing was not part of the planning process for the Citronelle MBM installation, the installation of single mode fibres provided an opportunity to field a DAS test in June 2012. While initial results had limited data quality, the results demonstrated that DAS data could be acquired with the MBM fibres at Citronelle. The results from the 2012 test were reported in [12]. Following discussions with project team members, we proposed to work with the Citronelle sequestration project team (part of the Southeast Carbon Sequestration Partnership, SECARB) and Silixa to acquire new DAS data with the MBM system. A repeat survey was conducted in August 2013 which focused on testing a large source effort (up to 128 sweeps per source point rather than the standard 4) at a limited number of locations [13]. The acquisition was designed to leverage the planned vertical seismic profile (VSP) acquisition using the MBM geophones.

Figure 8 shows DAS VSP data from ~1450 channel segments, each ~2 m long from well head to reservoir. A primary attribute of DAS data acquisition, as compared to traditional geophones, is the large spatial sampling at small intervals. One advantage of the small interval sampling is the ability to average over larger intervals to improve signal-to-noise ratios (SNR). Figure 9 shows that while a short (~2 m) DAS channel may have poor SNR compared to a geophone, DAS data can be averaged over variable spacing allowing a trade-off between spatial sampling and source effort to achieve comparable signal-to-noise ratios as a co-located geophones. In this case, 16 vs 64 vibroseis sweeps are compared for 14 and 2 m iDAS channel length (cable length) versus a single co-located geophone with 4 vibroseis sweeps stacked as a reference.

4. Conclusions

CO2 storage is expected to require dedicated monitoring wells for ground truth and improved remote sensing. Previous work demonstrated the difficulties in deploying multiple monitoring technologies in a single well. An overarching goal of the MBM project was development of a robust borehole monitoring package with a suite of instruments. The fact that all of the instruments installed in Citronelle D9-8#2 are still functioning as intended after 2+ years is a testimony to the robustness of the Citronelle deployment package. The pressure-temperature gauges are providing high quality data. The fiber-optic cable has been used for passive DTS, active DAS and active heat-pulse monitoring. The short geophone string is also working and providing conventional VSP data, although some of the 3C pod channels had wiring failure at installation and are are not providing good data. To date, four WVSP surveys have been acquired for monitoring with the MBM geophones. The geophone string itself has since been redesigned by the manufacturer to eliminate the problem that led to the loss of channels. Finally, the U-tube is providing samples as intended from the reservoir that can be used to positively confirm the arrival of CO_2 and tracers. We expect that future deployments will certainly benefit from our efforts, particularly through the use of a highly engineered instrumentation flat-pack that can replace a large number of independent control lines. We consider the Citronelle MBM system a successful prototype and 'blueprint' for borehole monitoring of CO_2 storage monitoring.

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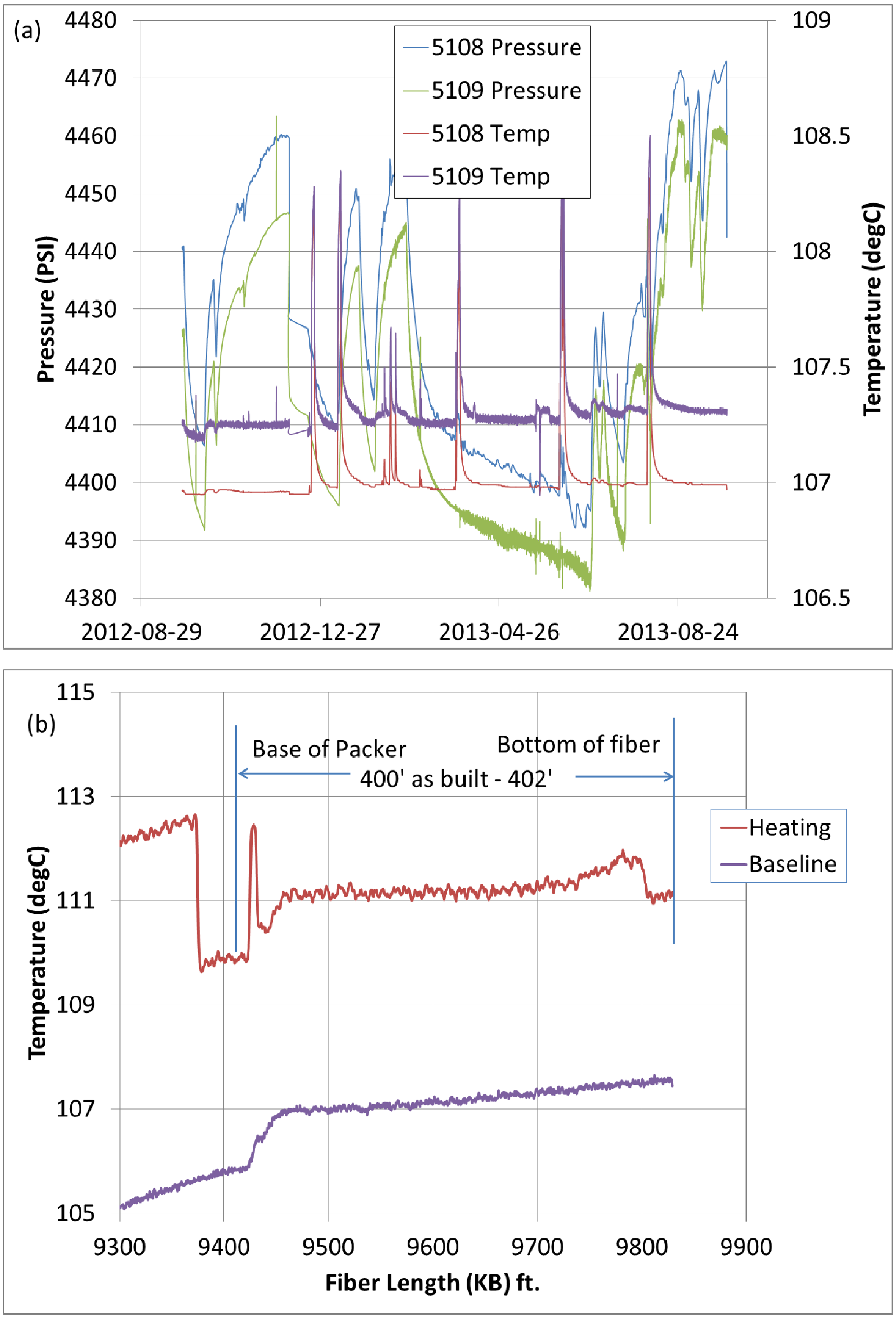

Figure 7. (a) Pressure response at the D9-8#2 well caused by commissioning of the CO_2 capture and injection into the D9-8 well, approximately 300 m away. (b) Thermal baseline and heat-pulse thermal response.

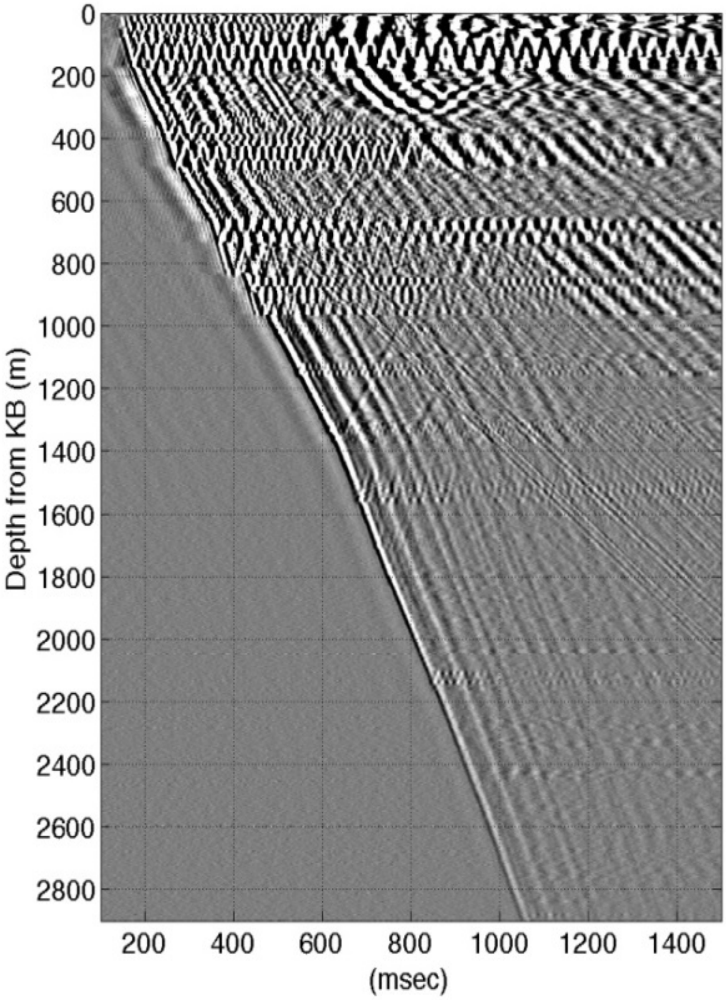

Figure 8. iDAS VSP over 2900 m on a single fiber cable at the 2013 Citronelle iDAS test. [18]

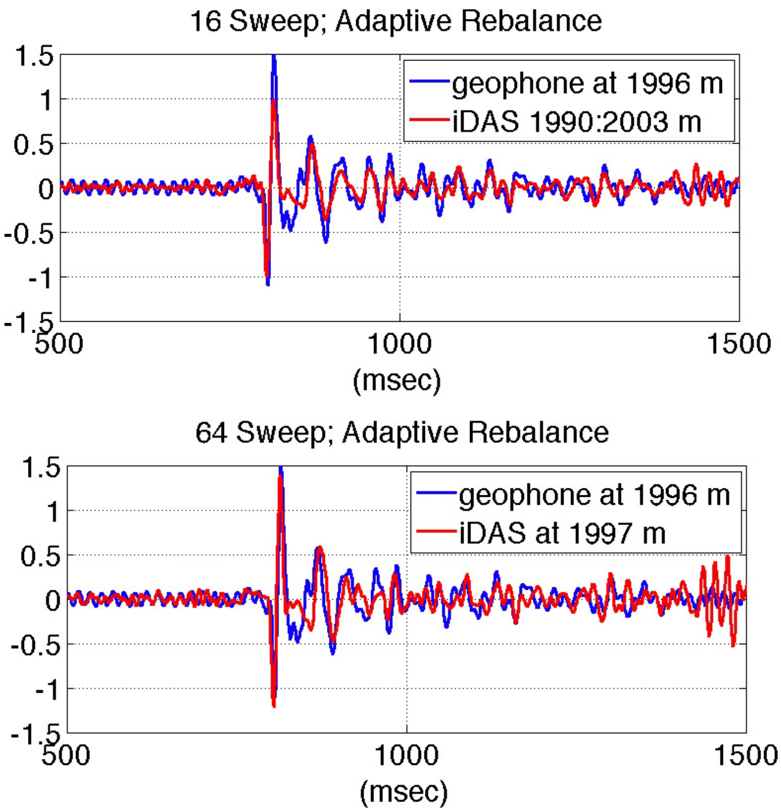

Figure 9 Comparison of iDAS (red) for a stack of 16 sweeps and 14 m (top) and 64 sweeps with 2 m (bottom) to a single geophone (blue) for 4 sweeps. Both iDAS cable and geophone were in the Citronelle MBM deployment.

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