# An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins

## Knox Project: Wellbore Management and Geomechanical Input

Topical Report

November 1, 2013 through January 5, 2013

Jim Kirksey[1], Sajjad A. Ansari[2], Nick Malkewicz[1]

[1]Schlumberger Carbon Services
14090 SW Freeway, Suite 240,
Sugar Land, TX 77478

[2]Schlumberger Canada PetroTechnical Services,
125 9th Ave SE, Calgary,
AB T2G 0P6. Canada

Report Issued: January 28, 2014

Report Number: DOE/FE0002068-4
U.S. DOE Cooperative Agreement Number: DE-FE0002068
An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins

Principal Investigator: Dr. Hannes Leetaru
Business Contact: Illinois State Geological Survey
615 E. Peabody Drive
Champaign, IL 61820-7406

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# 1. Executive Summary

## 1.2 Overview

The Knox Supergroup is a significant part of the Cambrian-Ordovician age sedimentary deposition in the Illinois Basin. While there is a very small amount of oil production associated with the upper Knox, it is more commonly used as a zone for both Class I and Class II disposal wells in certain areas around the state. Based on the three penetrations of the Knox Formation at the Illinois Basin – Decatur Project (IBDP) carbon dioxide ($CO_2$) sequestration site in Macon County, Illinois, there is potential for certain zones in the Knox to be used for $CO_2$ sequestration. More specifically, the Potosi member of the Knox Formation at about –3,670 feet (ft) subsea depth would be a candidate as all three penetrations had massive circulation losses while drilling through this interval. Each well required the setting of cement plugs to regain wellbore stability so that the intermediate casing could be set and successfully cemented to surface. Log and core analysis suggests significant karst porosity throughout the Potosi member. The purpose of this study is to develop a well plan for the drilling of a $CO_2$ injection well with the capability to inject 3.5 million tons per annum (3.2 million tonnes per annum [MTPA] $CO_2$ into the Knox Formation over a period of 30 years.

# 2. Well Design

## 2.1 Well Design Summary

The design for an injection well into the Potosi member of the Knox Formation would require that the well be drilled in such a manner that the karst porosity would not be damaged and that the well could be designed to ensure wellbore integrity. To start the design process, simulations were run to size the injection tubing so that the rate of 3.5 (3.2) MTPA could be injected below the critical erosional velocity of the tubulars. Once the injection tubing was sized, the casing strings and borehole could be optimized. The flow simulations suggested that 5 ½ inches (in.) injection tubing could be used. With that diameter selected, the other well parameters easily fall into place as the long casing string would be 9 ⅝ in. inside a 12 ¼ in. borehole and the surface casing would be 13 ⅜ in. inside a 17 ½ in. borehole. To prevent damaging the karst porosity of the Potosi, the long casing string would be top set at the top of the Potosi and an 8 ½ or 8 ¾ in. borehole would be drilled to the base of the Potosi using under-balanced drilling (UBD) methods. After the 8 ½ in. hole is completed the 5 ½ injection tubing and packer would be installed inside the long casing string and the well would be completed using an openhole injection completion. There are several benefits to constructing the well in this manner: it would allow the long string of casing to have a competent casing seat; the well could be successfully cemented back to surface ensuring wellbore integrity; and a good seal in both the primary and secondary caprock seals. Using UBD techniques would prevent drilling fluids from causing damage to the karst porosity. The UBD technique would also make it possible to obtain a fluid sample from the very top of the karst porosity section for analysis.

## 2.2 Potential Drilling Hazards

There are very few hazards associated with drilling in the area. Previous penetrations have encountered no surface or drift gas. The well section from 1,000 to 1,250 ft can produce brackish water that, if allowed to enter the wellbore, can lead to wellbore stability problems. The upper Knox can be very hard drilling, with chert and pyrite streaks that can cause premature bit wear. The planned well should be cased and cemented before reaching the Potosi, then potential loss of drilling fluid circulation would not be an issue. The well design becomes a bit more complicated after the long string is set and UBD begins. This technique is not common to this area so drilling crews must be coached in the use of the UBD methodology. The completion of the well as an openhole injector should be done while the drilling rig is still in place so that, after the well drilling is finished, any injection tests can be carried out without involving a rig. As in any drilling operation, good planning and attention to detail will be very important. A "Drill Well on Paper" exercise is recommended so that all parties involved with the drilling process can offer input and fully understand the scope of the planned drilling operation. A pre-spud safety and operations meeting is also recommended just prior to the commencement of drilling to review the drilling plan and outline and review all safety expectations.

## 2.3 Geomechanical Input to Well Plan

Since 2010, cores have been taken from three wells in the Cambrian-Ordovician age Knox Group. These cores include samples of the Maquoketa shale formation and more specifically the Potosi Dolomite, and will help to understand the potential of the Potosi as a possible carbon sequestration reservoir and the Maquoketa as a caprock sealing formation. Extensive studies were undertaken to evaluate the stability and strength of the Maquoketa as a confining unit and the Potosi (with its karst porosity) as a target sequestration reservoir. A summary of the results of these studies can be found in *Appendix A*. The concerns were regarding wellbore stability and how the various formation properties could affect wellbore integrity. Additionally, there were concerns that fluid movement through the karst porosity might cause a breakdown of the sealing cement sheath and a loss of wellbore integrity. Drilling records, well logs, and caliper logs from the three wells were incorporated into the study to more fully understand how best to drill and complete a well for carbon sequestration using the karstic Potosi member of the Knox formation as the sequestration reservoir. The results of the investigation have led to a specialized well design (summarized in section 2.1 and detailed in section 2.5 of this report) that would eliminate wellbore integrity concerns in the Potosi Formation through the karst interval. Concerns about the stability of the Maquoketa shale were also addressed. The resultant well design has surface casing through the shallow aquifers and then a long casing string set into the top of the Potosi. The Upper Potosi is a very dense low permeability rock that should provide an excellent casing seat. Results of drilling and cementing across the Maquoketa shale in the above referenced penetrations indicate that the Maquoketa has the stability to be well cemented to the casing string and provide the necessary wellbore integrity across the interval that is required of a sealing caprock formation. The very dense Maquoketa at the long string casing point would, in itself, be a very good barrier to flow as its permeability is very low. After the casing point, the well would be drilled out through the long string casing shoe using UBD methodology to total depth (TD), avoiding loss of drilling fluids and cement thereby preserving the karst porosity of the Potosi. The conclusion from these studies, which incorporate geomechanical core testing, well log analysis, drilling records analysis, and cementing reports, indicate that the Potosi has the required strength to provide a stable wellbore for an openhole type completion.

## 2.4 Safety

It is critical in projects such as this that all operations are carried out in the safest and most professional manner. A Safety Bridging document should be prepared to bring together the safety programs and policies of the drilling contractor, the engineering company in charge of field operations, and all other project partners. A safety meeting should be conducted with each tour. Job Safety Analysis (JSAs) should be conducted before each unique operation. An appropriate level of Personal Protective Equipment (PPE) should be required and anyone who fails to abide to the established standards should be asked to leave the site. All visitors should be met and briefed and field trips should be coordinated with the well site supervisor as well as the rig manager. Job hours and miles driven for the project should be accumulated and an end-of-well statistical report should be prepared and become a part of the permanent well record. It is suggested that a third-party safety supervisor be employed to assist in the safety efforts. The emphasis on safety must be constant and re-emphasized regularly.

## 2.5 Generalized Well Plan

The following is a generalized well plan by section of the hole. The sections proposed are the surface hole, TD section, and lastly the openhole section through the karstic Potosi member of the Knox. This well plan is designed to be a guide in drilling a Knox injection well based upon experiences from the IBDP in Macon County, Illinois. The proposed well diagram is shown in Figure 1 and a curve summarizing the drilling is shown in Figure 2. A generalized well Authorization for Expenditure (AFE) based on this well design is shown in Figure 3. The following sections give a more detailed description for construction of each portion of the well.

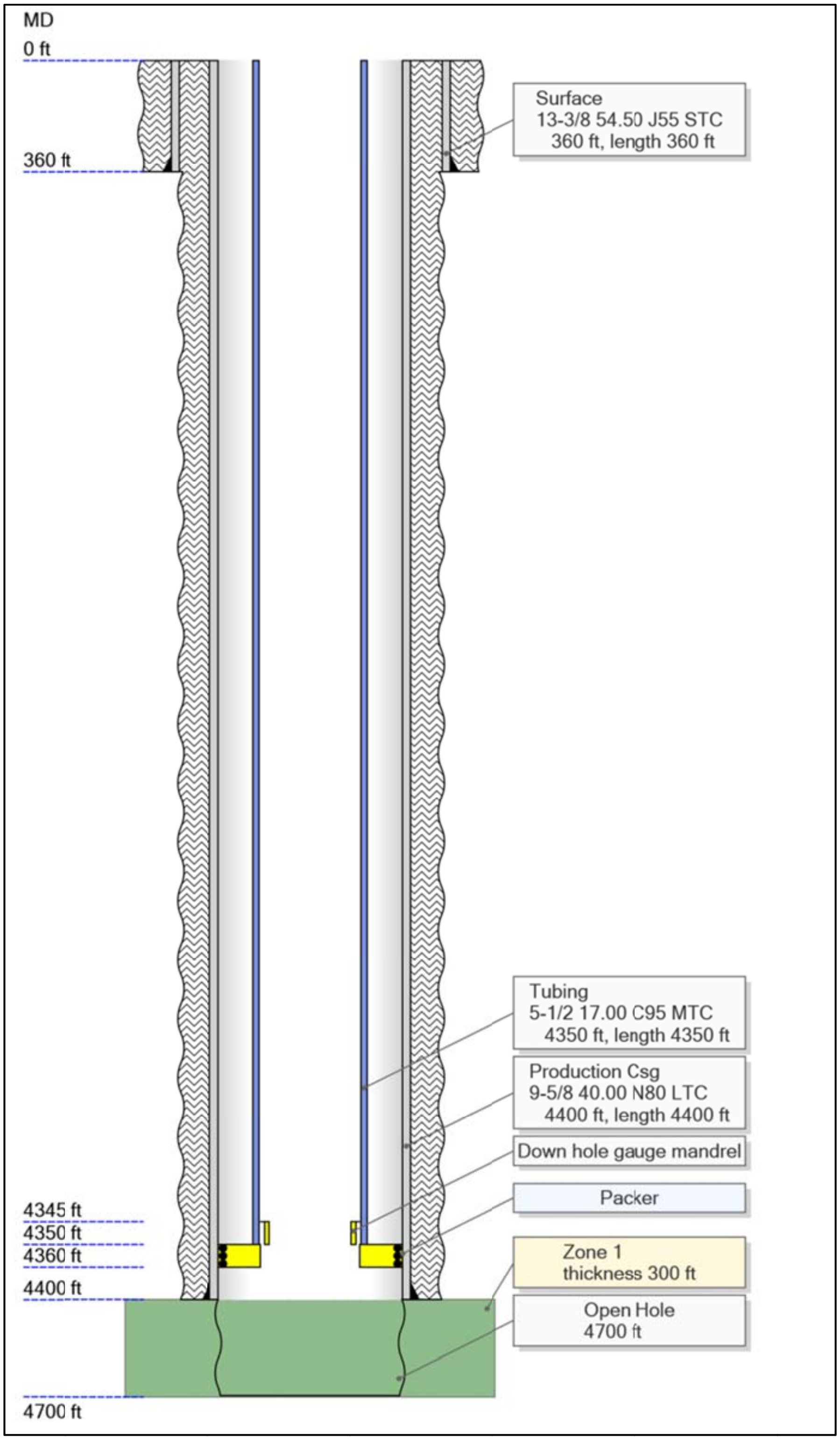


Figure 1: Well schematic for Knox injection test.

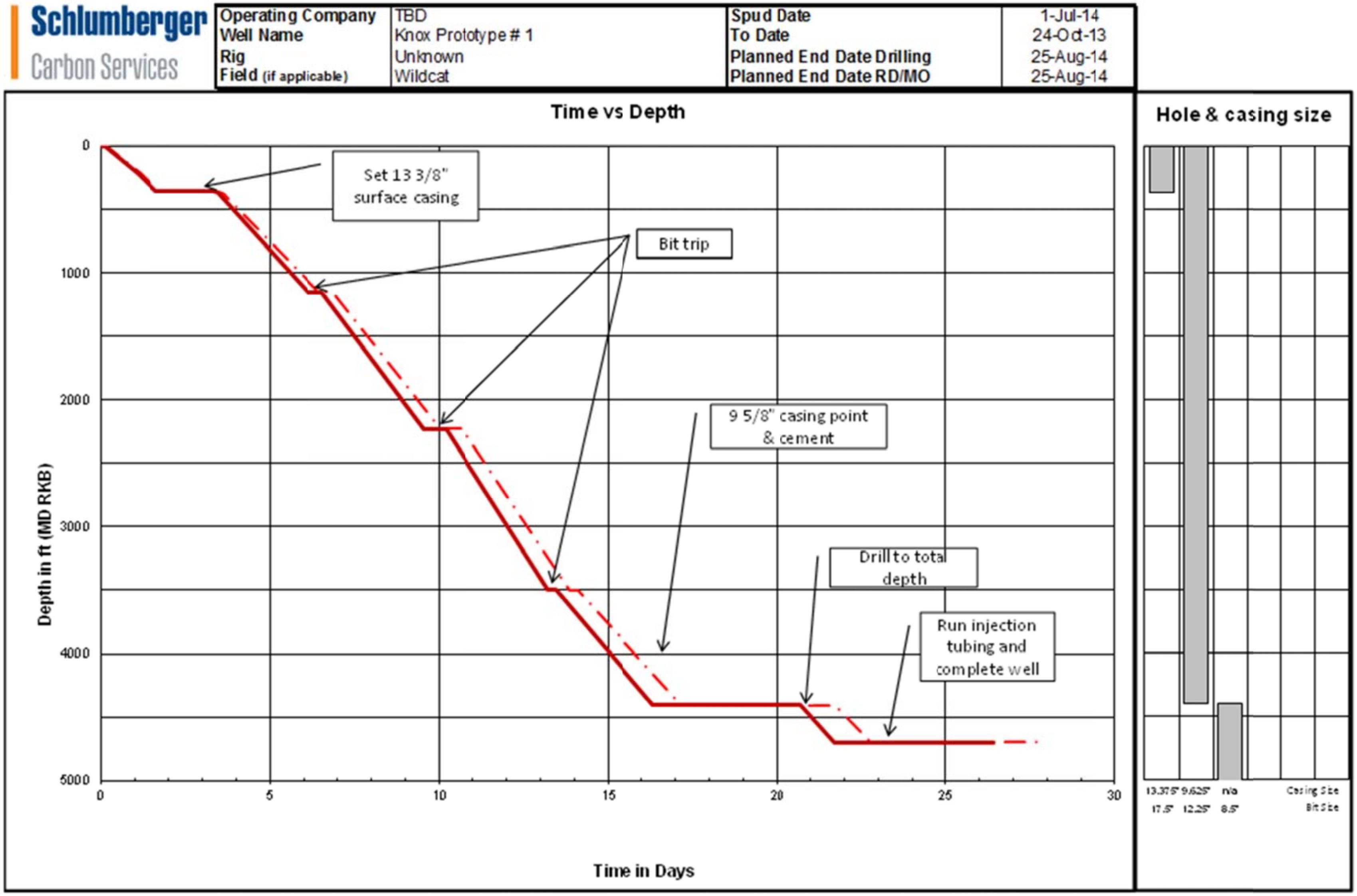


Figure 2: Knox well drilling time versus depth curve.

# Knox Prototype Injection Well

## AUTHORIZATION FOR EXPENDITURES - Est Cost

Schlumberger Carbon Services

In US $

| | | | | | |
|---|---|---|---|---|---|
| Operator: | TBD | Project Type : | CO2 Injection into Knox | | |
| Contract Area: | | Well Name : | KnoxPrototype Well #1 | | |
| Contract Area #: | | Well Type : | CO2 Injection into Knox | | |
| Prepared by | JMK | Platform/Tripod : | | AFE #: | 1 |
| | | Field/Structure : | Decatur | Date: | 30-Aug-13 |
| | | Basin : | Illinois | | |

Location ________ Surface Coordinate ________

Surface Elev. ________ Elevation ________

| | PROGRAM | ACTUAL |
|---|---|---|
| Spud Date | | |
| Compl Date | | |
| In Service | | |
| Drilling Days | | |

| | PROGRAM | ACTUAL |
|---|---|---|
| Rig Days | | |
| Total Depth | 4700 | |
| Well Cost $/Ft. | $0.00 | |
| Well Cost $/Day | | |

Close Out Date: ________ Completion Type: Open Hole Well Status: Pre Permit

| | Description | Dry Hole Budget | Completed Budget | Total Budget | Actual Expenditure | Actual Over/Under | % Over/Under |
|---|---|---|---|---|---|---|---|
| 1 | TANGIBLE COSTS | | | | | | |
| 2 | Casing | 187,100 | 0 | 187,100 | $0 | 187,100 | 100% |
| 3 | Casing Accessories; Float Equip & Liners | 21,168 | 0 | 21,168 | $0 | 21,168 | 100% |
| 4 | Tubing | | 261,800 | 261,800 | $0 | 261,800 | 100% |
| 5 | Well Equipment - Surface | 27,000 | 136,500 | 163,500 | $0 | 163,500 | 100% |
| 6 | Well Equipment - Subsurface | 0 | 310,000 | 310,000 | $0 | 310,000 | 100% |
| 7 | Other Tangible Costs | 0 | 0 | 0 | $0 | 0 | |
| 8 | Contingency | 10,072 | 37,065 | 47,137 | $0 | 47,137 | 100% |
| 9 | **Total Tangible Costs** | **$245,340** | **$745,365** | **$990,705** | **$0** | 990,705 | 100% |
| 10 | INTANGIBLE COSTS | | | | | | |
| 11 | PREPARATION & TERMINATION | | | | | | |
| 12 | Surveys | 8,500 | 0 | 8,500 | $0 | 8,500 | 100% |
| 13 | Location Staking & Positioning | 5,000 | 0 | 5,000 | $0 | 5,000 | 100% |
| 14 | Wellsite & Access Road Preparation | 81,950 | 15,000 | 96,950 | $0 | 96,950 | 100% |
| 15 | Service Lines & Communications | 25,250 | 0 | 25,250 | $0 | 25,250 | 100% |
| 16 | Water Systems | 0 | 0 | 0 | $0 | 0 | |
| 17 | Rigging Up/Rigging Down/ Mob/Demob | 140,000 | 0 | 140,000 | $0 | 140,000 | 100% |
| 19 | **Total Preparations/MOB** | **$260,700** | **$15,000** | **$275,700** | **$0** | 275,700 | 100% |
| 20 | DRILLING - W/O OPERATIONS | | | | | | |
| 21 | Contract Rig | 699,208 | 0 | 699,208 | $0 | 699,208 | 100% |
| 22 | Drlg Rig Crew/Contract Rig Crew/Catering | 0 | 0 | 0 | $0 | 0 | |
| 23 | Mud, Chem & Engineering Servs | 163,500 | 5,000 | 168,500 | $0 | 168,500 | 100% |
| 24 | Water | 27,036 | 9,384 | 36,420 | $0 | 36,420 | 100% |
| 25 | Bits, Reamers & Coreheads | 194,100 | 0 | 194,100 | $0 | 194,100 | 100% |
| 26 | Equipment Rentals | 67,650 | 30,000 | 97,650 | $0 | 97,650 | 100% |
| 27 | Directional Drlg & Surveys | 126,000 | 0 | 126,000 | $0 | 126,000 | 100% |
| 28 | Diving Services | 0 | 0 | 0 | $0 | 0 | |
| 29 | Casing & Wellhead Installation & Inspection | 18,150 | 12,900 | 31,050 | $0 | 31,050 | 100% |
| 30 | Cement, Cementing & Pump Fees | 194,216 | 0 | 194,216 | $0 | 194,216 | 100% |
| 31 | Misc. H2S Services | 0 | 0 | 0 | $0 | 0 | |
| 32 | **Total Drilling Operations** | **$1,489,860** | **$57,284** | **$1,547,144** | **$0** | 1,547,144 | 100% |
| 33 | FORMATION EVALUATION | | | | | | |
| 34 | Coring | 93,500 | 0 | 93,500 | $0 | 93,500 | 100% |
| 35 | Mud Logging Services | 40,000 | 0 | 40,000 | $0 | 40,000 | 100% |
| 36 | Drillstem Tests | 0 | 0 | 0 | $0 | 0 | |
| 37 | Open Hole Elec Logging Services | 244,000 | 0 | 244,000 | $0 | 244,000 | 100% |
| 39 | **Total Formation Evaluation** | **$377,500** | **$0** | **$377,500** | **$0** | 377,500 | 100% |
| 40 | COMPLETION | | | | | | |
| 41 | Casing, Liner, Wellhead & Tubing Installation | 0 | 0 | 0 | $0 | 0 | |
| 42 | Cement, Cementing & Pump Fees | 0 | 0 | 0 | $0 | 0 | |
| 43 | Cased Hole Elec Logging Services | 0 | 0 | 0 | $0 | 0 | |
| 44 | Perforating & Wireline Services | 0 | 20,000 | 20,000 | $0 | 20,000 | 100% |
| 45 | Stimulation Treatment | 0 | 0 | 0 | $0 | 0 | |
| 46 | Production Tests | 0 | 0 | 0 | $0 | 0 | |
| 48 | **Total Completion Costs** | **$0** | **$20,000** | **$20,000** | **$0** | 20,000 | 100% |
| 49 | GENERAL | | | | | | |
| 50 | Supervision | 95,805 | 0 | 95,805 | $0 | 95,805 | 100% |
| 51 | Insurance | 0 | 0 | 0 | $0 | 0 | |
| 52 | Permits & Fees | 49,000 | 0 | 49,000 | $0 | 49,000 | 100% |
| 53 | Marine Rental & Charters | 0 | 0 | 0 | $0 | 0 | |
| 54 | Helicopter & Aviation Charges | 0 | 0 | 0 | $0 | 0 | |
| 55 | Land Transportation | 13,600 | 0 | 13,600 | $0 | 13,600 | 100% |
| 56 | Other Transportation | 0 | 0 | 0 | $0 | 0 | |
| 57 | Fuel & Lubricants | 0 | 0 | 0 | $0 | 0 | |
| 58 | Camp Facilities | 14,000 | 0 | 14,000 | $0 | 14,000 | 100% |
| 59 | Allocated Overhead - Field Office | 3,000 | 0 | 3,000 | $0 | 3,000 | 100% |
| 60 | Allocated Overhead - Main Office | 10,000 | 10,000 | 20,000 | $0 | 20,000 | 100% |
| 61 | Allocated Overhead - Overseas | 0 | 0 | 0 | $0 | 0 | |
| 62 | Technical Services From Abroad | 0 | 0 | 0 | $0 | 0 | |
| 64 | **Total General Costs** | **$185,405** | **$10,000** | **$195,405** | **$0** | 195,405 | 100% |
| 65 | TOTAL INTANGIBLE COSTS | $2,313,465 | $102,284 | $2,415,749 | $0 | 2,415,749 | 100% |
| | TOTAL TANGIBLE COSTS | $245,340 | $745,365 | $990,705 | $0 | 990,705 | 100% |
| 66 | **TOTAL WELL COST** | | | **$3,406,454** | **$0** | **3,406,454** | **100%** |
| 67 | **Timed Phased Expenditures** | | | | | | |
| 68 | **This Year** | | | | | | |
| 69 | **Future Years** | | | | | | |
| 70 | **Total** | | | | | | |

| | | | | |
|---|---|---|---|---|
| Operator | | | | **Remarks** |
| | Approved By: | | | |
| | Position | | | |
| | Date | | | |
| Operator Approval | | | | |
| | Approved By: | | | |
| | Position | | | |
| | Date | | | |

Figure 3: Sample authorization for expenditure for a Knox well.

## 2.5.1 Surface Hole

The need for a conductor casing will depend upon the actual ground condition at the drill site. If the soil in the area is competent and there are no gravel beds near the surface, then surface hole could be drilled without a conductor. However, if the ground in the area of the drill site is not competent, then at least 30 ft of conductor casing should be set. A 20-in. piece of casing or culvert pipe of similar dimension could be used. If possible, the conductor should be set and grouted before moving in the drilling rig. If that is not possible, then care must be taken when drilling the conductor hole so as not to wash out the area immediately beneath the rig itself. The conductor could also be driven by the rig and gravel packed in place. After setting the conductor pipe, the rig will finish rigging up and drill the rat and mouse holes.

Before first "mudding up", the drilling fluid (also referred to as "mud") engineer from the selected company should provide a detailed inventory of all additives on location and also provide a detailed drilling fluid program to the project technical team. In the area at the IBDP site no conductor was required. The well should be spudded, taking care to make sure the drill string is straight. The rig would then proceed to drill the 17 ½ in. surface hole, picking up adequate drill collars to provide weight on the bit and ensure that the hole is straight. A deviation survey should be run every 100 ft drilled to be sure the well is on track. Frequent wiper trips should be taken and the "spud mud" should be adjusted as needed to keep hole in good condition.

The surface hole should be drilled to the point of competent bedrock; a depth of 360 ft below ground surface has been a good point for the three previous penetrations in the area. The actual drill site positioning will determine the surface casing depth requirement. The surface hole must be in competent rock when the casing set point is reached. Upon reaching the casing set point for the surface hole, the well should be circulated clean and a short trip back to surface should be made. Another trip back in the well should be taken to circulate the well clean again before coming out of the well to run the surface casing. The well logs should be acquired at this point. The rig should then set up to run surface casing. It is proposed to run 13 ⅜ in. 54.50 pound (lb.)/ft, LT&C J-55 casing with a guide shoe and float collar on bottom joint. It is proposed to run centralizers on the bottom three joints and every other joint to surface. A centralizer should be run with a stop ring on the bottom joint. The bottom two joints should have thread lock applied or should be tack welded. Casing should be circulated to the bottom of the well and, once at bottom, casing should be picked up 2 ft off bottom in preparation for cementing. The well should be cemented according to chosen cement company design using 100% excess. Cement should be displaced with fresh water. The cement company should be prepared to "top out" with 1 in. pipe in the annulus in case the cement falls back. The rig should wait on cement for 8 to 12 hours or until 500 pounds per square inch (psi) compressive strength is reached before proceeding to the next task. The suggested cement system would be Class A cement with ¼ (lb.)/sack cellophane flake and 1% $CaCl_2$.

## 2.5.2 TD Section

The surface casing should be cut and a 13 ⅝ 3,000 psi "C type" flanged wellhead should be installed. The rig should nipple up a 13 ⅝ in. Blowout Preventer (BOP) and flow stack. The BOP should be a double-ram with a minimum of 3,000 psi working pressure (WP) rating. It is also suggested to run an annular blowout preventer (Hydril type) on top of the double-ram stack. The BOPs should be function and pressure tested before proceeding. The rig should pick up a 12 ¼ in. bit as per the chosen bit companies recommendation and 6 and 8 in. drill collars should be made up as needed for the proper amount of weight on the bit. (Note: the bottomhole assembly should be jointly agreed upon by drilling contractor, bit provider, and wellsite engineer.) The drilling company should proceed to drill out one-half of shoe track and pressure test the casing and stack to 1,000 psi. The drilling company should then proceed to drill out the surface casing shoe and approximately 8 to 10 ft of formation and perform a Formation Integrity Test (FIT) and Leakoff Test (LOT). No pressure data is available for the Potosi member of the Knox at the site. The observed gradients in the area down to the top of the Eau Claire shale have showed 0.433 psi/ft down to 0.435 psi/ft in the Ironton-Galesville sandstone. The St. Peter Sandstone showed a gradient of 0.41 psi/ft on a drill stem test in the CCS#1 well. The tests designer should use these numbers as a starting point for test design. The test results should be recorded and kept visible in the rig doghouse. The drilling company should proceed to drill the 12 ¼ in. openhole running deviation surveys every 300 ft in order to maintain a maximum deviation below 3°. The drilling company should not exceed 80% of the collar weight as weight applied to bit. The drilling fluid system should be built following the drilling fluid engineer's design and kept within specifications. In previous wells, the drilling fluid system has been 8.5 pound per gallon (ppg) to 8.8 ppg fresh water dispersed gel. A KCl system has also been used and has shown some benefits in maintaining well bore stability and in helping to keep the hole from washing out while drilling. The drilling and drilling fluid company should maintain solids control in order to keep drilling fluid weight from exceeding 9.0 ppg. The drilling fluid loggers (mudloggers) should be called out to location at this time. The drilling fluid engineer should maintain detailed records of the drilling fluid system including all additives used during drilling operations. The BOPs should be function tested on each tour and this test should be noted in the daily report. The drilling company should work any tight connections before drilling ahead. When a bit trip is necessary the well should be kept full at all times. The mudloggers should catch samples at 10 ft intervals. The drillers should proceed to approximately 4,400 ft measured depth at the top of the Potosi member of the Knox Group (as indicated by the mudloggers). The wellsite geologist should make the TD call based upon cuttings. This is a very important step as the well design depends upon casing point being at the top of the Potosi in a competent formation. At TD the hole should be circulated clean and drilling fluid should be built to the drilling fluid engineer's specifications. The drilling company should make a short trip for a minimum of 2,000 ft and again circulate the hole clean. The drilling company should proceed to trip out of the well to log making sure the well is full at all times.

Wireline logs should be acquired with a minimum of a basic triple combo logging suite. Additional logs might be required as deemed necessary by the engineering company and any permit requirements. If a bridge is encountered during logging, the drilling company should trip in hole with drill pipe and clean the well out to TD, and circulate and improve drilling fluid properties. After the wireline logging is complete, the drilling company should trip back into the well and circulate to bottom. The well should be circulated and conditioned in preparation for running the casing string.

Once complete the drilling company should trip out of the well, laying down any 8 in. collars from the drill string. If the rig's set back capacity will not allow racking back the drill string, then the driller should lay down all the drill string before running casing. The drilling contractor can supply this information. The rig should proceed to run 9 ⅝ in., LT&C, N-80 40 (lb.)/ft casing. An additional option would be to run 500 ft of CR13 chrome casing at the bottom of the string but thoughts are that this is probably not required; however, this is dependent on the permit requirements and the engineering company. It is recommended to run two joints for a shoe track. A float shoe should be installed on the first joint and a float collar should be installed on top of the second joint. Centralizers should be run as per the cementing companies simulation design which should be based upon actual hole trajectory. Once the casing is on bottom, the well should be circulated to condition the mud. The well should then be cemented to surface using a typical lead slurry of 65/35 Class A/Pozzolan at 12.5–13.0 ppg and a tail slurry of $CO_2$ resistant cement. The $CO_2$ resistant cement should cover the lower 750–1,000 ft of the well. A drilling fluid flush should be run and with spacers ahead of the cement. The cementing company should wash the lines on top of the wiper plug. The well should then be displaced with fresh water. The cement plug should be bumped 1,000 psi over the final lift pressure. Careful planning and preparation should be put into the design and execution of the cementing of the well. The floats should be checked. Once complete the casing slips should be set and operations should halt to wait on cement for 12 hours.

### 2.5.3 Openhole Section

After waiting for 12 hours, the driller should nipple down the BOP stack and nipple up an 11 in., 3,000 psi, stack consisting of a double ram BOP, an annular BOP, and a rotating head on top of stack. A blooey should be laid, leading to the pit, to conduct cuttings away from the well. The BOP stack should be tested to 2,000 psi. Cement bond logs should be acquired at this point to evaluate the cement job on the 9 ⅝ in. casing string. An ultrasonic cement imaging log could be run as well, again depending on permit requirements and the judgment of the well engineering company. The driller should proceed to pick up an 8 ½ in. insert bit with 6-in. drill collars and proceed to drill out one-half of the shoe track. The driller should test the casing and BOP stack to 2,000 psi. The driller should then proceed to drill out the remaining shoe track and 3–5 ft of new formation and run FIT and LOT. Test results should be recorded and posted in the doghouse.

The air drilling package should be rigged up and include compressors and a foam unit. The driller should trip out of hole and pick up the final 8 ½ in. bit and proceed to trip in hole, blowing hole dry at 750–1,000 ft intervals until back to TD. The driller should proceed with drilling the Potosi using air. The standpipe pressure should be monitored closely and, at the first sign of stand pipe pressure building, the driller should pick up and blow well. The driller should be prepared at this point to collect fluid samples from blooey line for formation fluid analysis in the Potosi. The driller should continue drilling until the rate of air circulation capacity removing formation fluid can no longer keep up with rate of formation fluid influx into the well (the well will no longer stay unloaded).

At this point, foam injection should be started and drilling should be continued using air/foam medium through the remainder of the Potosi Formation. The well should be drilled to the base of the Potosi below the karst interval. If the Potosi is karstic throughout, then TD should be adjusted to the top of the Davis shale formation. While drilling through the karst interval, drill string torqueing will likely become a problem. This interval should be control drilled and the driller should work the string frequently to prevent any problems. Once TD is reached, the air compressors and foam unit can be shut down and the driller should spot a pill of 8.5 ppg brine in the well for logging. The drill string should be brought to surface and wireline logs should be acquired. Logs should, at a minimum, include the basic triple combo with a formation microimager and sonic porosity. Final program will depend on the permit and well engineering company. After logging, the driller should trip back into the well and come back out of the well laying down the drill string.

### 2.5.4 Completion

The rotating head should be rigged down and the BOPs should be re-dressed with 5 ½ in. pipe rams. A 9 ⅝ in. seal bore type packer should be deployed using wireline to a depth of approximately 4,350 ft. The packer should be deployed with a tail pipe with X and X-N profiles with a wireline re-entry guide. There should be a plug in X nipple below the packer. The driller should pick up the seal assembly and any additional accessories being installed on the tubing string. It is suggested to run a downhole gauge and a distributed temperature sensing (DTS) fiber optic line on the injection tubing. Another X profile above the downhole gauge should be installed. The injection tubing should then be run being very carefully and torqued to the manufacturer's specifications. The tubing should sting into the seal bore and be landed into the wellhead being careful to avoid damaging control lines. The driller should then nipple down the BOP stack and nipple up the upper well head assembly. The annulus should be filled with treated brine and pressure tested. At this point the drilling rig can rig down and be released.

### 2.5.5 Testing

After the rig is off the well, a slickline unit should be mobilized to pull the plug out of the lower completion. The downhole gauge and DTS fiber optic cable can be connected and monitored for baseline data. To confirm injectivity, an injection test should be developed that would also include a step rate test to establish fracturing pressure. The estimated fracture gradient for the Knox is .8 psi/ft. The downhole gauge can be used to monitor downhole pressure during the test.

Wireline spinner surveys might also be used to more closely identify the injection intervals. If the zone is heavily karstic, it may be difficult to pump at a rate high enough to establish a fracture gradient. If so, an injection rate should be achieved to be equivalent to approximately 1.5 times the expected volumetric injection rate of the $CO_2$ while monitoring the downhole pressure. If the bottomhole injection pressure is below any know fracture gradient in the area then testing can proceed without the step rate test. Due to basin wide heterogeneities, each well will behave differently so decisions will have to be made at the well site regarding maximum injection rate to attempt to establish fracturing pressure.

# 3. Conclusion

A well design for injection into the Knox-Potosi formation was developed based on experience from drilling several wells in the Decatur area as well as log, caliper, and core data. The well design involves an openhole completion through the Potosi. The well tubular's and bore sizes were designed to accommodate an injection rate of 3.5 (3.2) MTPA $CO_2$. Depending on formation testing and response in the area drilled, multiple wells may be required to accommodate this rate. An approximate price was developed to construct the well.

# Appendix A - Core Test Interpretation

## INTRODUCTION

Rock mechanical properties tests were performed on core samples collected from the Geophysical Monitor #2 (GM2) and Verification Well #1 (VW1) wells. These tests were performed to evaluate the Maquoketa shale as a seal and the Potosi Dolomite in the Knox group as a potential reservoir for $CO_2$ sequestration. The physical and mechanical response of a material is dependent on the rate at which it is loaded and the applied stress and strain amplitude. Logging-based measurements are in the kilohertz range; whereas actual physical loading rates acting on a wellbore are generally much slower (pseudo-static). Rock failure (tensile or shear) is a pseudo-static process. This is the rationale for performing laboratory pseudo-static testing on the core samples.

The testing program consisted of (i) indirect tensile strength (TSTR) tests (Brazilian method) with stress oriented perpendicular, parallel, and oblique to bedding (ASTM D3967-95a, 2008); (ii) unconfined compressive strength (UCS) (ASTM D7012-10, 2013), and (iii) Multistage triaxial compression tests with concurrent ultrasonic velocity measurements on as-received vertical samples (ASTM D7012-10, 2013; ASTM STP402, 1966).

## OBJECTIVE

The objective of performing these rock mechanical properties tests on core samples was as follows:

- In order to help answer, assess and make a prediction of
    - the integrity of the Maquoketa shale as a caprock (i.e., the caprock functions without any breach either due to deformation and/or failure);
    - the wellbore integrity during drilling, logging and completions (i.e., the borehole stays stable); and
    - the integrity of Potosi formation as a reservoir (i.e., the reservoir functions as a good sequestration target).

  The answers to these questions are supported by the results of the core tests which yield the following poro-elastic parameters of the core tested:
    - peak compressive and tensile strength;
    - quasi-static elastic properties (Young's modulus and Poisson's ratio); and
    - Mohr-Coulomb failure envelope delineation (cohesion and friction angle).
- The above static and dynamic mechanical property information can be used for correlating well log data and assisting in calibration of the geomechanical model. The aim is to understand and make realistic predictions and inferences of geomechanical behavior of the Maquoketa and Potosi formations based on core test data.

# QUALITATIVE IMPLICATIONS OF THE CORE RESULTS

## MAQUOKETA SHALE

Representative samples were selected for testing in both the upper and lower portions of the Maquoketa shale on core collected from the GM2 well. Only two samples were tested and, while these samples are assumed to be representative, they cannot themselves entirely capture the vertical heterogeneity and complex anisotropic properties intrinsically present in shale. They can, on the other hand, lend some insight into the expected behavior of the shale. The tensile strength of the lower Maquoketa sample tested at 2,800.4 ft is less than that of the upper Maquoketa sample tested at 2,635.55 ft (presented in Table 1). Therefore, the conclusion is that the lower Maquoketa sample is weaker than the upper Maquoketa sample tested. Furthermore, the magnitude of the tensile strength in the Maquoketa is lower than those of the Potosi Dolomite samples; however, in terms of gradient (psi/ft) they are similar 0.3 to 0.5 psi/ft. This tensile strength gradient typically implies fairly competent and strong rock consistent with respect to its depth of burial. This further suggests that, geomechanically speaking, there are no strength related abnormalities in the Maquoketa which would undermine its ability to act as a competent caprock.

Table 1: Summary of indirect tensile strength tests (Brazilian method).

| Formation | Core Depth (ft) | Orientation | Bulk Density (g/cc) | Tensile Strength | Tensile Strength Gradient (psi/ft) |
|---|---|---|---|---|---|
| Upper Maquoketa Shale | 2,635.55 | Perpendicular | 2.591 | 1,395 | 0.53 |
| | | Parallel | 2.590 | 795 | 0.30 |
| | | 45 | 2.554 | 1,007 | 0.38 |
| Lower Maquoketa Shale | 2,800.40 | Perpendicular | 2.564 | 1,232 | 0.44 |
| | | Parallel | 2.561 | 438 | 0.16 |
| | | 45 | 2.566 | 763 | 0.27 |
| Knox-Eminence Dolomite | 4,219.7 | Perpendicular | 2.781 | 2,108 | 0.50 |
| | | Parallel | 2.792 | 1,298 | 0.31 |
| | | 45 | 2.791 | 2,210 | 0.52 |
| Knox-Potosi Dolomite | 4,540.1 | Perpendicular | 2.745 | 1,748 | 0.39 |
| | | Parallel | 2.706 | 1,902 | 0.42 |
| | | 45 | 2.682 | 1,454 | 0.32 |
| Knox-Potosi Dolomite | 4,551.1 | Perpendicular | 2.810 | 2,577 | 0.57 |
| | | Parallel | 2.822 | 2,437 | 0.54 |
| | | 45 | 2.806 | 2,062 | 0.45 |

The magnitude of UCS observed in Maquoketa also signifies a generally high strength class of rock, which is a favorable quality of a good caprock (see Table 2). The tests results of UCS in the vertical direction were over $10^4$ psi for both upper (2,635 ft) and lower (2,800 ft) Maquoketa cored interval. The UCS in the horizontal direction for the lower Maquoketa is 36% less than that of the upper Maquoketa sample tested. This provides further indication that the lower Maquoketa is weaker than the upper Maquoketa sample tested.

Overall the Poisson's ratio (PR) in the samples tested in the Maquoketa shale are lower than the samples tested in the Potosi and are generally low for a typical shale (see Table 2). The implication of this is that the horizontal stresses could be lower, which may not be good for a caprock, as it would be easier to deform and fail the rock. The vertical PR is lower than the horizontal and the PR for lower Maquoketa sample (2,800.4 ft) is lower than the upper Maquoketa sample (2,635.55 ft). This indicates that it would be easier to deform vertically than horizontally, and that the lower Maquoketa interval is more prone to deformation than the upper Maquoketa interval.

Table 2: Summary of Mohr-Coulomb failure envelope parameters.

| Well | Formation | Core Depth (ft) | Orientation | Net Confining Pressure (psi) | Bulk Density (g/cc) | Triaxial Peak Strength (psi) | UCS Peak Strength (psi) *Net Confining Pressure = 0 | Young's Modulus (psi) | Poisson's Ratio | Cohesion (psi) | Friction Angle (degrees) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GM2 | Upper Maquoketa Shale | 2,635.5 +/- 0.5 | Vertical | 1647 | 2.566 | 17,338 | 10,929 | 2.63 E+06 | 0.18 | 2696 | 37 |
| | | | 45 | 1647 | 2.554 | 11,739 | 5,766 | 2.89 E+06 | 0.22 | 1834 | 31 |
| | | | Horizontal | 1647 | 2.569 | 19,214 | 11,747 | 5.3 E+06 | 0.23 | 1409 | 49 |
| GM2 | Lower Maquoketa Shale | 2,801.5 +/- 1.5 | Vertical | 1750 | 2.594 | 17,785 | 13,201 | 2.66 E+06 | 0.17 | 1205 | 47 |
| | | | 45 | 1750 | 2.578 | 13,132 | 3,935 | 3.12 E+06 | 0.23 | 560 | 44 |
| | | | Horizontal | 1750 | 2.577 | 18,345 | 7,569 | 4.89 E+06 | 0.20 | 2311 | 40 |
| VW1 | Knox-Eminence Dolomite | 4,218.75 | Vertical | 2595 | 2.614 | 39,105 | 21,040 | 8.68 E+06 | 0.32 | 3900 | 48.7 |
| VW1 | Knox-Potosi Dolomite | 4,540.1 | Vertical | 3100 | 2.825 | >75,970 | 14,660 | 14.66 E+06 | 0.31 | 2140 | 64.6 |
| VW1 | Knox-Potosi Dolomite | 4,551.6 | Vertical | 3133 | 2.779 | 56,868 | 17,640 | 13.31 E+06 | 0.33 | 2370 | 58.2 |

Mohr-Coulomb failure analysis shows that overall the cohesion and friction angles are high, which is good for a caprock (see Table 2). However, there are clear differences between the vertical and horizontal directions and between the upper and lower Maquoketa intervals. The vertical direction cohesion is higher for the upper Maquoketa sample while in the lower Maquoketa sample the horizontal cohesion is higher. Nevertheless, the lower Maquoketa is more prone to failure in vertical and oblique direction when compared to the upper Maquoketa.

As expected of an anisotropic rock like shale, the Young's modulus (see Table 2), which is a measure of stiffness, is almost twice as large in the horizontal direction compared to the vertical. Overall, a higher magnitude of the Young's modulus would imply that stiffer caprock would have higher integrity against breach.

Additionally, apart from the mechanical testing, another advanced core analysis called Tight Rock Analysis (TRA) (Schlumberger, 2011; Suarez-Rivera et al., 2012) was performed for the Maquoketa interval. The results of these tests are presented at the end of Table 3 and plotted in Figure 4. These results demonstrate that the Maquoketa shale is a low porosity and low permeability rock, which is favorable quality for hydraulic sealing capacity of a caprock.

Table 3: Summary of petrophysical reservoir properties—routine core analysis.

| Well | Sample Depth (ft) | Porosity (%) | Dry Bulk Density (g/cc) | Grain Density (g/cc) | Gas Permeability (md) | Formation | Lithology |
|---|---|---|---|---|---|---|---|
| VW1 | 4,477.00 | 1.13 | 2.785 | 2.817 | 42.69 | Potosi | LS, pale yel gy, vug, lam, vug, xls |
| VW1 | 4,481.00 | 27.25 | 1.653 | 2.272 | 0.03 | Potosi | SLST-MS, m gy, mica, carb, sl calc |
| VW1 | 4,487.00 | 0.81 | 2.813 | 2.836 | 4063.6 | Potosi | LS, dsky yel bn, vug, xls |
| VW1 | 4,564.00 | 1.73 | 2.797 | 2.846 | 0 | Potosi | LS, pale yel bn, arg, sl vug, xls, |
| VW1 | 4,587.00 | 3.32 | 2.728 | 2.822 | <.01 | Potosi | LS, dsky yel bn, arg |
| VW1 | 4,642.00 | 8.7 | 2.583 | 2.829 | 0.33 | Potosi | LS, lt ol gy, arg, vug, xls |
| VW1 | 4,661.00 | 10.02 | 2.478 | 2.753 | 64.11 | Potosi | LS, lt ol gy, arg, vug, xls, mot |
| VW1 | 4,666.00 | 2.56 | 2.73 | 2.801 | 0.01 | Potosi | LS, gy yel gn, arg, lam, tr glau lam |
| VW1 | 4,671.00 | 4.46 | 2.703 | 2.829 | <.01 | Potosi | LS, ol gy, arg, cff |
| VW1 | 4,803.00 | 1.39 | 2.8 | 2.839 | <.01 | Potosi | LS, ol gy, mot, lam, sl vug |
| GM2 | 2,635.73 | 7.55 | 2.575 | 2.682 | 0.0001 | U. Maquoketa | Sh |
| GM2 | 2,800.52 | 7.28 | 2.598 | 2.659 | 0.0002 | L. Maquoketa | Sh |

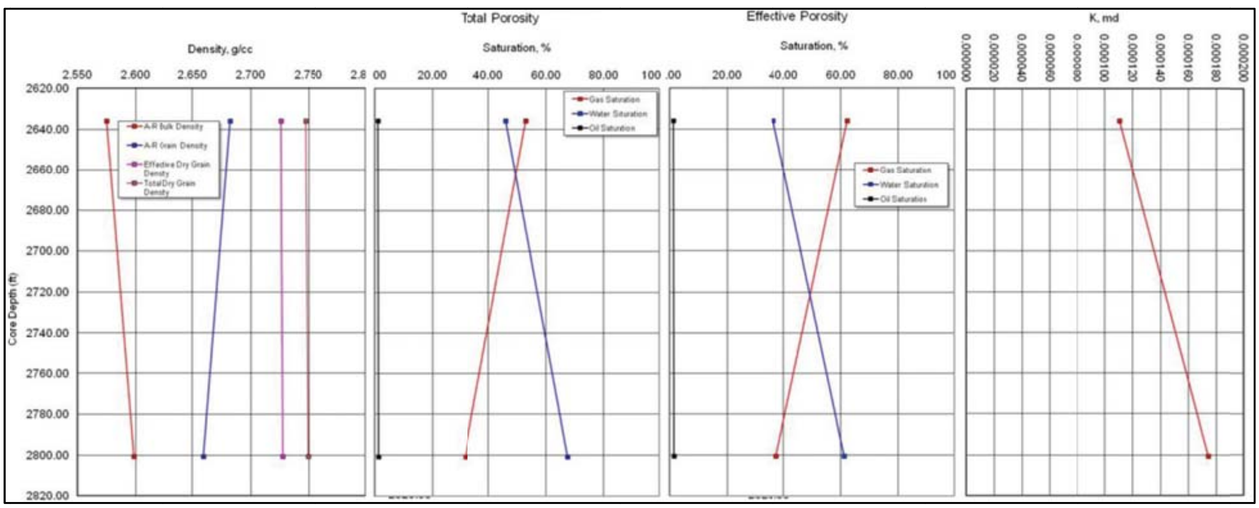


Figure 4: Plots of density, porosity, and permeability for tight rock analysis results in the Maquoketa shale.

In summary, even though the lower Maquoketa appears to be a generally weaker rock than the upper Maquoketa, the core results show high values of Young's modulus, UCS and Friction Angle in the Maquoketa, all of which are indicative of tough rock to breach with fairly high strength. With regards to wellbore integrity, core results indicate a high chance of having a stable borehole based on the high strength and stiff quality of Maquoketa shale. However, wellbore stability or integrity is heavily dependent on stress regime, stress magnitude, pore pressure, drilling fluids mud weight, borehole trajectory and drilling practice, all of which must be considered in a $CO_2$ sequestration project and well drilling.

## POTOSI DOLOMITE

Representative samples were selected for testing in the Potosi Dolomite on core collected from the VW1 well. Additionally, a sample was selected for testing in the Eminence dolomite (the formation overlying the Potosi.) Similar to the Maquoketa, these samples are assumed to be representative, yet they cannot entirely capture the vugular and fracture heterogeneity present in these dolomite formations. They can, however, lend some insight into the expected behavior of the dolomite reservoir. Reservoir quality for $CO_2$ sequestration in a dolomite is heavily dependent on porosities, permeability, presence of natural fractures, vugs, pore pressure, and the ability to maintain mechanical integrity during injection. These properties were tested on the core samples taken. Figure 5 below displays Heterogeneous Rock Analysis (HRA) (Suarez-Rivera et al., 2011) performed across the core discussed. Rotary sidewall cores were taken throughout the Knox and the Maquoketa in the VW1 well. Table 3 lists the petrophysical reservoir properties from routine core analysis performed on the Potosi rotary sidewall core samples as well as the Maquoketa samples to investigate reservoir and caprock quality, respectively. The data show the Potosi reservoir to have fair sequestration with some intervals of quite high permeability and porosity (normally associated with vugs) compared to others of lower permeability and porosity as is to be expected in a vuggy dolomitic rock.

The tensile strength of the core tested at 4,219.7 ft (in the Eminence Formation) is lowest parallel to bedding in contrast to other orientations and other core depths (see Table 1). This means that (for this formation) it would be easiest to fail the rock in tensile mode vertically in this interval compared to the deeper interval. The tensile strength of the core at 4,551.1 ft (in the Potosi Dolomite which is within the zone of lost circulation zone observed during drilling) is largest when compared to the two other Knox samples tested (shallower in the Potosi Dolomite 4,540.1 ft and the Eminence dolomite 4,219.7 ft). This is a good indication that the target reservoir rock, which would be storing the $CO_2$, is a strong reservoir.

Unconfined compressive strength of the shallower Knox core (4,218.75 ft) in the Eminence dolomite is higher than that of the deeper samples (in the Potosi) which would indicate the Eminence could withstand a higher shear stress than the Potosi before failing (see Table 2). This is a desirable characteristic of a formation overlying the reservoir. The Mohr-Coulomb failure test shows that the sample tested at 4,218.75 ft in the Eminence dolomite has the highest cohesion, which gives further confidence in the overlaying formation mechanical integrity in regards to shear stresses.

The Young's modulus, which is a measure of stiffness of the rock, is smaller for the shallower Knox sample at 4,218.75 ft in the Eminence compared to deeper Potosi samples at 4,540.1 and 4,551.1 ft. In general, the higher the Young's modulus and Poisson's ratio the stronger and tougher the rock is and therefore more resistive to failure. For example, a crystalline igneous rock like granite is much tougher than a sedimentary rock such as unconsolidated sandstone. The relatively high values for the samples tested indicate a stable rock and reservoir. These would be favorable characteristics for borehole stability during drilling and $CO_2$ injection. Although as mentioned earlier, wellbore stability is also heavily dependent on stress regime, stress quantity, pore pressure, drilling fluids mud weight, borehole trajectory, and drilling practice.

Table 4 and Figure 6 below show that the quasi-static values of the Poisson's ratio are generally greater than the dynamic. The deeper sample in the Potosi (4,551.6 ft) has higher values than the shallower samples. In general, the Poisson's ratio is moderate; a high Poisson's ratio would mean the formation could support a high stress, which implies that the rock would require higher pressure to fail when compared to a formation having lower stress.

# Way Forward

In order to answer the questions (i) is the Maquoketa shale a good mechanical and hydraulic seal, and (ii) is the Potosi dolomite a good mechanical reservoir for $CO_2$ sequestration, some additional key data points are needed. The rock mechanics tests have provided some insight to make some qualitative inferences, but the data needed to quantitatively answer these questions are

a. formation pressure;
b. in-situ stresses; and
c. its rock properties and strength.

The core test results provide us with item (c) and are a key input to qualitatively assess the formation. The preliminary indication based on the rock properties and strength properties is that the Maquoketa shale would function as a good seal and that the Potosi would be a mechanically stable reservoir. The next integrated forward step towards assessing the caprock and reservoir integrity would be formation testing, which would give insight into the formation pressure and in-situ stresses. Once we know (a), (b) and (c), then, based on the planned injection pressures, one can perform a simple analytical calculation to determine under what injection pressure the rock would fail. However, because $CO_2$ injection would involve dynamic changes in pore pressure and associated effective stress changes, it is prudent to do a more advanced realistic simulation to assess the dynamic behavior of the reservoir and caprock with time as the $CO_2$ injection proceeds. This would start with building a 1D Mechanical Earth Model (MEM) (Plumb et al., 2000) and calibrate it with core results and stress test data available to make an analytical failure calculation under the planned injection scenario. It would be recommended to expand this to a full 3D reservoir and caprock integrity study using geomechanics. This would be most reliable and predictive quantitatively, as well as qualitatively, and give the highest level of insight into caprock and reservoir behavior.

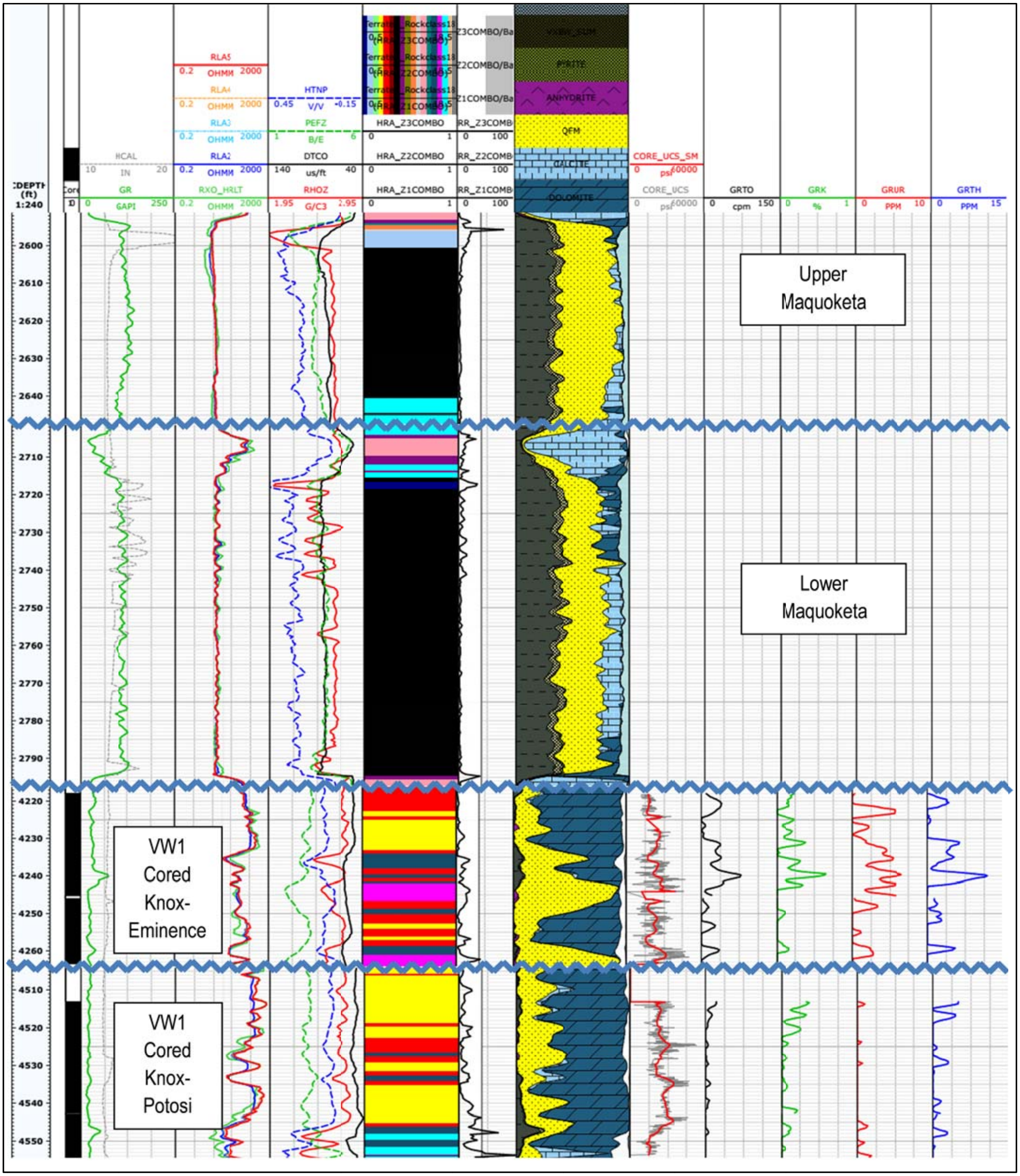


Figure 5: HRA performed across the formations of samples discussed.

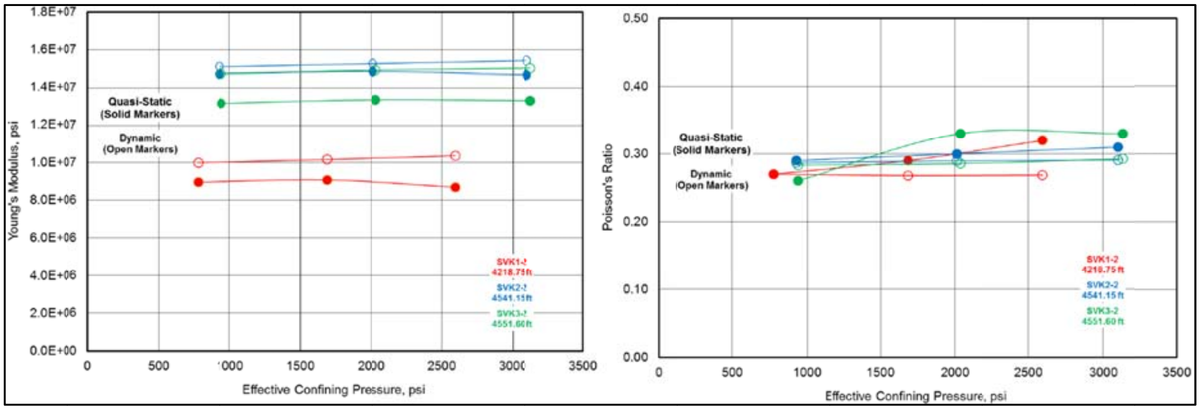


Figure 6: Quasi-static and dynamic E and v as a function of effective stress for three sets of samples (4,218.75 to 4,551.6 ft) from the triaxial testing.

Table 4: Dynamic mechanical properties determined during triaxial compression testing.

| Sample ID Depth (ft) Orientation | Axial Stress Difference (psi) | Effective Confining Pressure[9] (psi) | Effective Mean Stress (psi) | As-Tested Density (g/cm$^3$) | P-Wave Velocity (ft/s) | S-Wave Velocity (ft/s) | Poisson's Ratio | Young's Modulus ($10^6$ psi) | Bulk Modulus ($10^6$ psi) | Shear Modulus ($10^6$ psi) |
|---|---|---|---|---|---|---|---|---|---|---|
| SVK1-2 4218.75 Vertical | 0 | 778 | 773 | 2.618 | 15,388 | 9597 | 0.18 | 7.680 | 4.022 | 3.250 |
| | 286 | 778 | 874 | 2.619 | 15,594 | 9633 | 0.19 | 7.803 | 4.216 | 3.275 |
| | 3088 | 778 | 1809 | 2.621 | 17,893 | 10,202 | 0.26 | 9.258 | 6.407 | 3.676 |
| | 10,246 | 778 | 4194 | 2.623 | 18,788 | 10,551 | 0.27 | 9.991 | 7.229 | 3.934 |
| | 17,894 | 778 | 6744 | 2.624 | 18,995 | 10,644 | 0.27 | 10.183 | 7.415 | 4.005 |
| | 24,357 | 778 | 8899 | 2.624 | 19,023 | 10,615 | 0.27 | 10.151 | 7.482 | 3.984 |
| | 502 | 1686 | 1857 | 2.622 | 17,674 | 10,261 | 0.25 | 9.267 | 6.076 | 3.719 |
| | 2606 | 1686 | 2559 | 2.622 | 18,286 | 10,418 | 0.26 | 9.662 | 6.701 | 3.835 |
| | 9867 | 1686 | 4978 | 2.624 | 18,903 | 10,646 | 0.27 | 10.159 | 7.290 | 4.007 |
| | 17,893 | 1686 | 7655 | 2.625 | 19,128 | 10,709 | 0.27 | 10.315 | 7.532 | 4.055 |
| | 25,300 | 1686 | 10,122 | 2.625 | 19,218 | 10,708 | 0.27 | 10.343 | 7.656 | 4.056 |
| | 30,781 | 1686 | 11,949 | 2.625 | 19,155 | 10,633 | 0.28 | 10.216 | 7.646 | 3.999 |
| | 503 | 2595 | 2765 | 2.623 | 18,277 | 10,509 | 0.25 | 9.781 | 6.601 | 3.903 |
| | 4038 | 2595 | 3943 | 2.624 | 18,721 | 10,637 | 0.26 | 10.094 | 7.058 | 4.000 |
| | 11,792 | 2595 | 6529 | 2.625 | 19,092 | 10,743 | 0.27 | 10.355 | 7.449 | 4.082 |
| | 19,479 | 2595 | 9091 | 2.626 | 19,212 | 10,757 | 0.27 | 10.413 | 7.601 | 4.094 |
| | 26,808 | 2595 | 11,534 | 2.626 | 19,304 | 10,738 | 0.28 | 10.413 | 7.746 | 4.081 |
| | 33,324 | 2595 | 13,706 | 2.627 | 19,302 | 10,696 | 0.28 | 10.352 | 7.787 | 4.049 |
| | 10,611 | 2595 | 6135 | 2.597 | 18,377 | 10,129 | 0.28 | 9.205 | 7.032 | 3.591 |
| SVK2-2 4551.15 Vertical | 0 | 930 | 930 | 2.829 | 20,238 | 11,744 | 0.25 | 13.103 | 8.602 | 5.258 |
| | 870 | 930 | 1220 | 2.829 | 20,688 | 11,799 | 0.26 | 13.363 | 9.240 | 5.307 |
| | 11,434 | 930 | 4741 | 2.831 | 22,376 | 12,271 | 0.28 | 14.761 | 11.440 | 5.744 |
| | 24,697 | 930 | 9163 | 2.832 | 22,681 | 12,396 | 0.29 | 15.094 | 11.813 | 5.864 |
| | 37,678 | 930 | 13,490 | 2.833 | 22,827 | 12,410 | 0.29 | 15.171 | 12.052 | 5.879 |
| | 501 | 2015 | 2182 | 2.830 | 21,958 | 12,184 | 0.28 | 14.466 | 10.840 | 5.661 |
| | 7944 | 2015 | 4662 | 2.831 | 22,581 | 12,359 | 0.29 | 14.989 | 11.683 | 5.827 |
| | 21,125 | 2015 | 9056 | 2.833 | 22,871 | 12,447 | 0.29 | 15.251 | 12.081 | 5.913 |
| | 34,434 | 2015 | 13,493 | 2.834 | 22,935 | 12,461 | 0.29 | 15.303 | 12.178 | 5.929 |
| | 47,725 | 2015 | 17,923 | 2.834 | 22,978 | 12,462 | 0.29 | 15.323 | 12.255 | 5.932 |
| | 499 | 3100 | 3268 | 2.831 | 22,470 | 12,327 | 0.28 | 14.894 | 11.531 | 5.797 |
| | 9454 | 3100 | 6253 | 2.832 | 22,887 | 12,469 | 0.29 | 15.295 | 12.079 | 5.933 |
| | 22,459 | 3100 | 10,588 | 2.833 | 23,036 | 12,506 | 0.29 | 15.418 | 12.297 | 5.971 |
| | 35,608 | 3100 | 14,972 | 2.834 | 23,079 | 12,508 | 0.29 | 15.441 | 12.375 | 5.975 |
| | 61,204 | 3100 | 23,504 | 2.836 | 23,101 | 12,473 | 0.29 | 15.390 | 12.466 | 5.945 |
| | 70,688 | 3100 | 26,665 | 2.836 | 23,038 | 12,413 | 0.30 | 15.255 | 12.431 | 5.888 |
| | 64,839 | 3100 | 24,715 | 2.835 | 22,947 | 12,322 | 0.30 | 15.047 | 12.380 | 5.799 |

9 Pore pressure = 0psi inn all tests

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# Acronyms

UCS: Uniaxial or unconfined compressive strength
TSTR: Tensile strength
MEM: Mechanical Earth Model
1D: One dimensional
3D: Three dimensional
CRI: Caprock integrity
$CO_2$: Carbon dioxide
ASTM: American Standard Testing Methods
E: Young's modulus
v: Poisson's ratio