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McDonald, Jeffrey

From: Gilmore, Tyler J [Tyler.Gilmore@pnnl.gov]
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Cc: Bayer, MaryRose; Saieh, Patrick; Akhavan, Maryam; Greenhagen, Andrew; Deniz.Demirkanli@cadmusgroup.com; Bonneville, Alain; Williams, Mark D; Spane, Frank A; Appriou, Delphine; Vermeul, V R (Vince)
Subject: Analysis of Pressure Impacts and Protection of USDW
Attachments: FGen_AoR_DRAFT.pdf

All,
Thank you for the discussion this morning on our conference call. As follow-up, attached is a DRAFT of our "*Analysis of Impacts on Lowermost USDW from Focused Leakage of Brine from Plugged and Abandoned or Poorly Constructed Wells at the FutureGen 2.0 Site*" This report is in support of our AoR designation in the UIC application. The attached copy is only a draft and we plan to update it with a sensitivity analysis of Chian's 2011 validated model outputs with outputs from his newer 2013 model. We will also update the permeability values used for the Potosi based on available literature and permit records. We will send you a "final" version when we've completed these updates before the end of next week.

Under separate cover we will send you more information on the well bore pressure calculations and the shape file for the AoR. We'll also load the shapefile on the Input Advisor for GS3. Let me know if there are other items that you need which will help in your evaluation.
Thanks
Tyler

Tyler Gilmore
Battelle Manager FutureGen Storage Site
Pacific Northwest National Laboratory
509 371 7171
509 430 9898 (cell)

Analysis of Impacts on Lowermost USDW from Focused Leakage of Brine from Plugged and Abandoned or Poorly Constructed Wells at the FutureGen 2.0 Site

Introduction

The objective of the analyses described below was to assess whether the Area of Review (AoR) determination based on the maximum extent of the supercritical carbon dioxide ($scCO_2$) plume is also protective of the lowermost underground source of drinking water (USDW) from the induced pressure front from $scCO_2$ injection. This calculation must consider the potential for brine migration along plugged and abandoned or poorly constructed wells that penetrate the caprock, driven by the reservoir pressure increases associated with $scCO_2$ injection. As noted by many authors, and shown in results from our injection modeling, the extent of the pressure increase during $scCO_2$ injection is larger than the extent of the $scCO_2$ plume. However, this extended region of increased pressure does not in and of itself result in an increased risk to USDWs from brine migration over the entire region when mitigating factors are considered.

As discussed by Birkholzer et al. (2011), a static critical threshold pressure determination for brine flow up an open conduit or damaged borehole (e.g., substandard well completion, deteriorating seal in abandoned well, near borehole drilling-related formation damage) may not be applicable for cases where permeable units exist between the injection reservoir and lowermost USDW, because the open conduit approach does not account for lateral flow outside the conduit or casing and into these permeable zones. The effective permeability around a damaged plugged and abandoned or poorly constructed well would be smaller than in an unplugged well casing (i.e., open conduit) and permit brine to flow into intervening permeable formations (i.e., thief zones). Birkholzer et al. (2011) stated that a model is required to analyze these dynamic and transient impacts.

At the FutureGen 2.0 site in Morgan County, Illinois, many potential thief zones exist between the injection reservoir and the lowermost USDW, including 1) the Ironton Sandstone, 2) the Potosi Dolomite (which was identified as a very challenging lost-circulation zone during drilling activities related to the FutureGen 2.0 stratigraphic borehole [FGA#1], indicating extremely high-permeability conditions), and 3) the New Richmond Sandstone.

Approach

The study reported here followed the approach detailed by Birkholzer et al. (2013) for analyzing the impacts of the focused leakage of brine up an abandoned and damaged or poorly constructed well based on the pressure buildup caused by $scCO_2$ injection. The analysis used by Birkholzer et al. (2013) applied an analytical model, ASLMA (Cihan et al. 2011, 2013), which was developed specifically for these types of focused leakage problems. We selected the ASLMA analytical model for our analysis because of its capabilities and published prior use, which included verification cases with other models for these types of problems. In this study for the FutureGen2.0 site, we conducted an assessment of the impacts on the lowermost USDW from focused leakage for the closest well that penetrates the caprock outside the maximum extent of the $scCO_2$ plume (at the Waverly field, which is 26 km from the center of the

FutureGen 2.0 injection wells). We also ran cases for a borehole that will be completed as a monitoring well that is near the maximum extent of the predicted $scCO_2$ plume (the monitoring well completion that will be located at stratigraphic borehole FGA#1), which is located approximately 2 km from the centroid of the injection well laterals). Figure 1 shows the location of the closest wells that penetrate the Eau Claire caprock around the FutureGen 2.0 site. The results of the cases run at these two selected locations can provide guidance on the adequacy of the FutureGen 2.0 site AoR, which was defined based on the maximum predicted $scCO_2$ extent in the Underground Injection Control (UIC) Permit Application, to be protective of the lowermost USDW based on the scenario of focused brine leakage from abandoned and damaged or poorly constructed wells.

Model Description

The analytic model used for this analysis, ASLMA_V3, was developed by Cihan et al. (2011) and additional examples of its use are described by Cihan et al. (2013). Pacific Northwest National Laboratory (PNNL]) has obtained the source code, executable computer file, and sample problems from the authors at Lawrence Berkeley National Laboratory (LBNL). The model is for single-phase, isothermal fluid flow for focused leakage around wells and/or diffuse leakage through aquitards in a multilayered aquifer system from the transient pressure field created during reservoir injection. The model requires specification of the permeability, specific storage, and unit thickness of the reservoir, aquifers, and aquitards. Because the simulation option of solving only for focused leakage into aquifers around a borehole was used in this analysis, aquitard permeability and specific storage were not used in the model. The model also requires borehole radii and effective permeabilities for the damaged zone around the borehole for each segment of the aquifers and aquitards it encounters. Initial conditions for the model assume a hydrostatic pressure gradient. The model does not account for brine density differences, but this simplifying assumption is conservative because the volume of freshwater leakage calculated for each permeable unit would be larger than if higher-density reservoir fluid were used in the calculation.

The ASLMA_V3 executable supplied by LBNL was verified by rerunning the test cases published by Cihan et al. (2011). The test cases developed and discussed by Cihan et al. (2011) for verification included cases for comparison with earlier published models and results. The output files of the simulation runs at PNNL for these test cases were the same as the output files of these test cases supplied by LBNL.

Model Parameters

Site data for the upper layers (Ironton to St. Peter) are limited at the FutureGen 2.0 site because the focus of the detailed characterization of the first stratigraphic borehole (FGA#1) was on the reservoir and caprock. Detailed characterization of the upper layers is planned for the next drilling campaign. Some sidewall core permeability measurements of these upper layers were used, along with published regional values or conservative estimates (i.e., using lower ranges of permeability estimates for the aquifers below the USDW).

Direct measurements of the effective permeability of plugged and abandoned or poorly constructed wells are limited. Vertical Interference Tests have recently been used to help quantify this measurement for a range of wells (e.g., Crow et al. 2010; Gasda et al. 2013; Duguid et al. 2013). Effective permeability estimates for the damaged zone around a borehole for this study were based on published ranges of groupings of wells with different leakage potentials (low, medium, high, extreme), as reported in Table 2 of Celia et al. (2011), which used the categories defined by Watson and Bachu (2008). Celia et al. (2011) used a stochastic modeling study with a large number of realizations for wells in the Wabamun Lake area of Alberta, Canada. Data from Crow et al. (2010) were also used by Celia et al. (2011) to develop these effective permeability estimates, which also highlighted the few measurements available. The high end of the high (0.5 to 8 mD) and extreme (8 to 10,000 mD) leakage potential ranges (Celia et al. 2011) were investigated in this modeling effort. Single values of effective permeability for the borehole were assigned for all the aquifer/aquitard segments (instead of variable borehole permeability for each segment), which provide conservative results based on the analysis of Celia et al. (2011).

The results from our analysis are reported as the volume of fluids leaked over time from the reservoir into each of the overlying aquifers (including the St. Peter, the lowermost USDW) for the two well distances (~2 km and 26 km) using conservative estimates for the site parameters and the borehole effective permeabilities as discussed above. Well locations are shown in Figure 1. The two wells used in this analysis were 1) the Criswell borehole at the Waverly field 26 km southeast of the center of the FutureGen 2.0 injection wells, the closest borehole that penetrates the Mt. Simon Formation outside the predicted $scCO_2$ plume, and 2) the FGA#1 borehole that will be completed as a monitoring well located at a distance of 2 km from the center of the injection wells, which is near the maximum extent of the predicted $scCO_2$ plume. Borehole diagrams are shown in Figures 2 and 3.

Thicknesses and properties for the layers in the model are shown in Table 1. Layer thicknesses are taken from the characterization/stratigraphic borehole (FGA#1) drilled at the FutureGen 2.0 site (Table 6.1 of Battelle Pacific Northwest Division 2012). Adjacent aquitards are lumped into a single unit as required for the model because it only allows for alternating aquifers and aquitards. The thickness of the reservoir was calculated by combining the upper permeable portion of the Mt. Simon that was targeted in the UIC permit injection model and the Elmhurst member of the Eau Claire Formation.

Hydraulic properties are not listed in Table 1 for the aquitards because flow into these units is not calculated for the focused leakage-only model of ASLMA. Aquifer property determinations for the units other than the injection reservoir are listed in the footnotes of Table 1. Hydraulic properties for the single-layer injection reservoir were based on fitting the simulated reservoir pressure responses from the injection model used in the UIC Permit Application at the two well locations of interest (described in more detail below).

Because the ASLMA model is a single-phase model, an equivalent water-injection rate was calculated from the $scCO_2$ injection rate of 1.1 MMT/yr for 20 years. The volumetric water-injection rate was calculated using $scCO_2$ densities at two pressures (see Figures 4 and 5) because the UIC permit model shows a significant pressure buildup around the injection well. The first $scCO_2$ density (Figure 5) was applied for the first 5 years while injection pressures were rapidly increasing, and the second $scCO_2$

density (calculated at 400 psi higher) was applied from 5 to 20 years. The resulting water-injection rates were 0.0470 m^3/s (years 0 to 5) and 0.0439 m^3/s (years 5 to 20).

Hydraulic conductivity and specific storage were adjusted in the ASLMA model for the composite Mt. Simon/Elmhurst injection layer to fit the pressure responses from the UIC permit injection model at the FGA#1 borehole (2 km from the center of the injection well laterals) and Waverly field Criswell borehole (26 km from the center of the injection well laterals). A manual fitting process was used (see comparison in Figure 6). It was difficult to exactly fit both wells with the same parameters; therefore, parameters were chosen so that the overall fit of the ASLMA pressure results in the injection layer were slightly higher than the UIC permit model. This is conservative for this analysis because slightly greater pressures in the injection reservoir would lead to greater leakage at the well locations. The ASLMA model-predicted pressure at the injection well is much greater than the UIC permit model-predicted injection because we simulated only a single vertical well (instead of the four horizontal wells in the UIC permit model) and water injection (with a higher density and viscosity than $scCO_2$) with the equivalent reservoir displacement of the $scCO_2$. Leakage at the injection well was not part of this analysis, so this pressure difference did not affect the results (i.e., only transient pressures at the Waverly well and FGA#1 borehole were used in calculating the focused leakage into the upper units along these wells).

Results

Results for the simulated leakage for the Waverly (Criswell borehole, 26 km from the center of the injection well laterals) are shown in Figure 7 for the High Potential Leakage Category (8 mD). Figure 7 shows the total leakage from the reservoir and leakage into each of the permeable units above the caprock up to the St. Peter (lowermost USDW). The plots in Figure 7 show the fluxes over the 100-year simulation period and the cumulative leakage volume. A plot is also included, using a log scale, of cumulative leakage for the units above the Ironton (Potosi, New Richmond, and St. Peter), because these values are much lower than those for the Ironton.

Similar results for the FGA#1 borehole (at the 2-km distance) for the High Leakage Potential Category (8 mD) are shown in Figure 8. The simulated fluxes and cumulative leakage volume for the FGA#1 borehole are higher than those for the Waverly well, given the higher pressures at the closer location.

Figures 9 and 10 show the simulation results for the two simulated locations (Waverly and FGA#1, respectively) using the top of the Extreme Potential Leakage Category (10,000 mD). This extreme upper bound on the effective permeability for a plugged and abandoned or poorly constructed well is comparable to unconsolidated clean sand (see Table 2.2 of Freeze and Cherry[1979]).

Table 2 shows the cumulative leakage volumes at 100 years for each of the cases and permeable units for comparison of the results.

Conclusions

Results from this modeling effort show that the leakage of brine into the lowermost USDW from a damaged plugged and abandoned or poorly constructed well, even considering extremely conservative parameter estimates, is very small as shown in Table 2 (1.55×10^{-6} m^3 [or 0.00155 L] or lower over 100 years) for the closest well outside of the simulated extent of the scCO$_2$ plume (Waverly field, 26 km from the center of the injection area). As shown by the simulation results, most of the focused leakage along a damaged borehole from the reservoir is captured in the permeable zones (thief zones), most notably the Ironton Sandstone, which is the first permeable zone above the caprock (1,350 ft below the lowermost USDW [St. Peter Sandstone]). The simulated cumulative brine leakage volume from the reservoir over 100 years for the Extreme Leakage Potential Category (2,273 m^3 total or 62 L/day over this period) was mostly into the Ironton Sandstone, as shown in Table 2. This volume represents roughly 0.008% of the total scCO$_2$ injection volume (using an equivalent water-injection volume of 2.82×10^7 m^3 for 1.1 MMT/yr of scCO$_2$ based on scCO$_2$ densities discussed above over a 20-year period) for the Extreme Leakage Potential Category and much less for the High Leakage Potential Category.

Simulation results from a well near the outer extent of the simulated scCO$_2$ plume (FGA#1, 2 km from the center of injection area) also resulted in very low volumes (3.76×10^{-5} m^3 [0.0376 L] or less over 100 years) of leakage of brine into the lowermost USDW from a plugged and abandoned or poorly constructed well. The extreme leakage potential case at this well location did show significant leakage into the Ironton Sandstone and the Potosi Dolomite units, which are both well below the lowermost USDW. For the FGA#1 borehole, the simulated cumulative brine leakage volume from the reservoir over the 100-year period for the Extreme Leakage Potential Category (16,000 m^3 total) was also mostly into the Ironton Formation (Table 2). This results in 2,190 L/day over a 20-year period, averaged over a shorter time period than was used above for the Waverly well because fluxes drop off quickly after injection is over at this location. This volume for the Extreme Leakage Potential Category represents roughly 0.06% of the total scCO$_2$ injection volume and a much smaller volume was predicted for the High Leakage Potential Category.

Cases were run with lower permeability values for the Potosi (60 mD [5 .8E-7 m/s]) based on the average listed for the Dupont Waste Injection Well in Louisville, Kentucky, for the Copper Ridge Formation, a vuggy dolomite similar to the Potosi (Greb et al. 2009). The results of these cases using the average value still showed very small amounts of leakage into the lowermost USDW for both the Waverly field distance (0.219 L) and the FGA#1 borehole distance (5.33 L) for the Extreme Leakage Potential Category.

Results from this modeling evaluation indicated that, under site conditions, operations-related pressure increases will not result in brine migration through damaged plugged and abandoned or poorly constructed wells extending beyond overlying thief zones at appreciable levels near the outer extent of the simulated scCO$_2$ plume or at the closest well outside this zone that penetrates the caprock. Therefore, the delineated scCO$_2$ AoR should also be protective of the lowermost USDW from pressure-induced brine migration under these leakage scenarios.

Summary

Following the approach detailed by Birkholzer et al. (2013), we conducted a study of the impacts of the scenario of focused brine leakage from damaged plugged and abandoned or poorly constructed wells due to increased pressured from $scCO_2$ injection on the lowermost USDW at the FutureGen2.0 site. This study looked at cases for two wells: one well near the outermost edge of the predicted maximum extent of the $scCO_2$ plume (FGA#1 borehole, 2 km from the center of the injection well laterals) and another for the closest well that penetrates the caprock outside the predicted maximum extent of the $scCO_2$ plume (Waverly field, 26 km from the site). The results of the analysis of the scenario of focused brine leakage using conservative parameter estimates showed very little impact on the lowermost USDW (St. Peter Sandstone) near the outer boundary of the AoR delineated in the FutureGen 2.0 UIC Permit Application (<0.0376 L over 100 years) and for the closest well that penetrates the primary caprock outside the AoR (<0.00155 L over 100 years). These results are due to brine losses in the three aquifers between the injection reservoir and the lowermost USDW (thief zones), in particular the first zone above the caprock (Ironton Sandstone). Based on this analysis of focused brine leakage up a plugged and abandoned or poorly constructed well scenario, the AoR delineated based on the maximum predicted extent of the $scCO_2$ plume should also be protective of the lowermost USDW from the pressure front.

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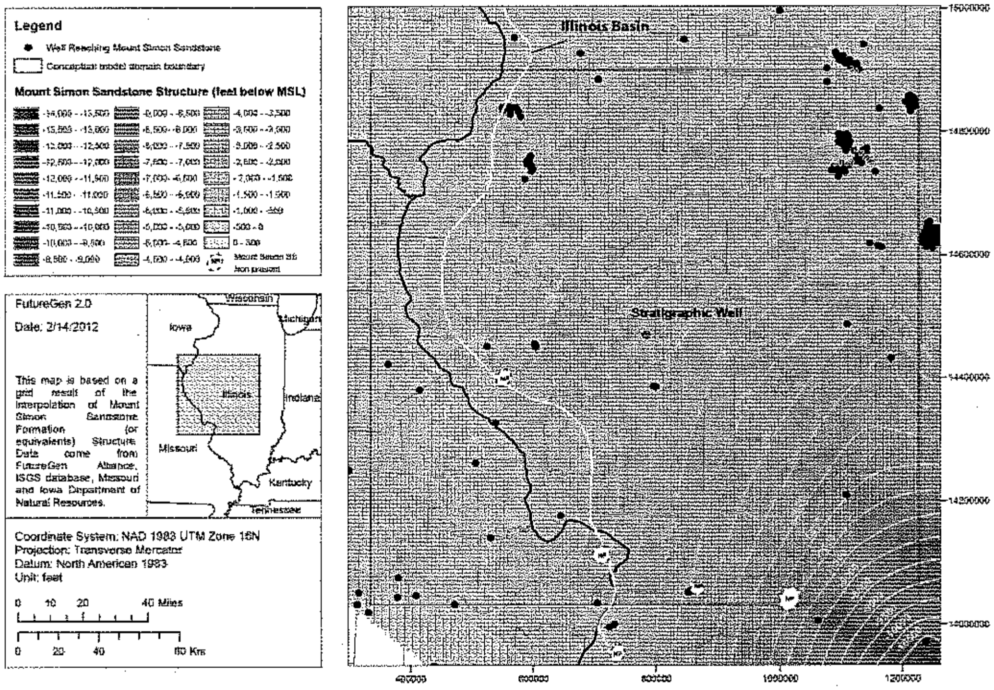
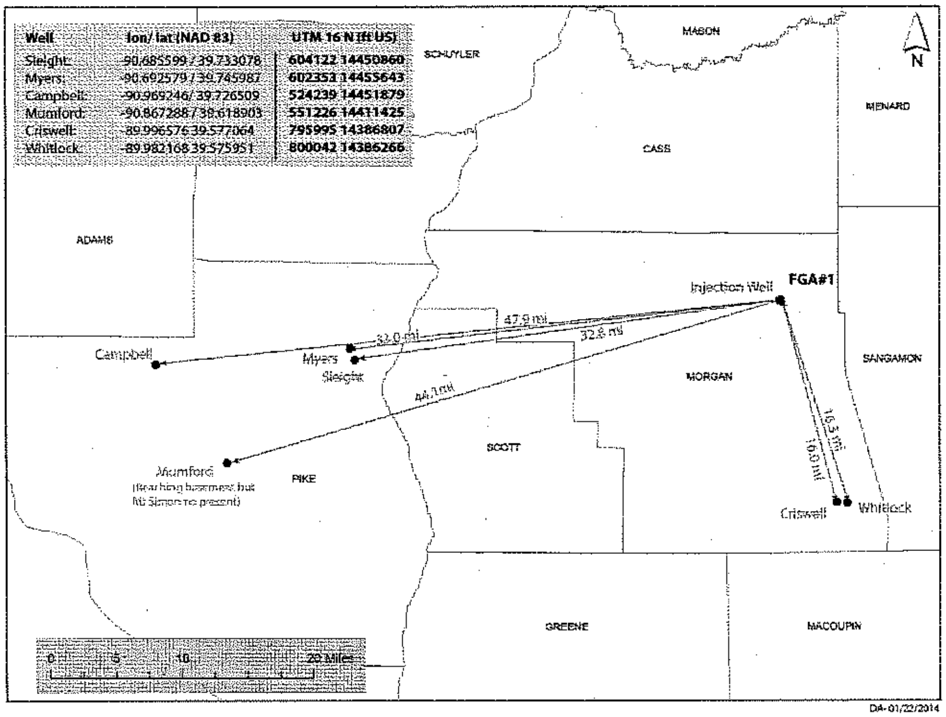
Mount Simon Sandstone Structure Contour Surrounding FutureGen 2.0 Site

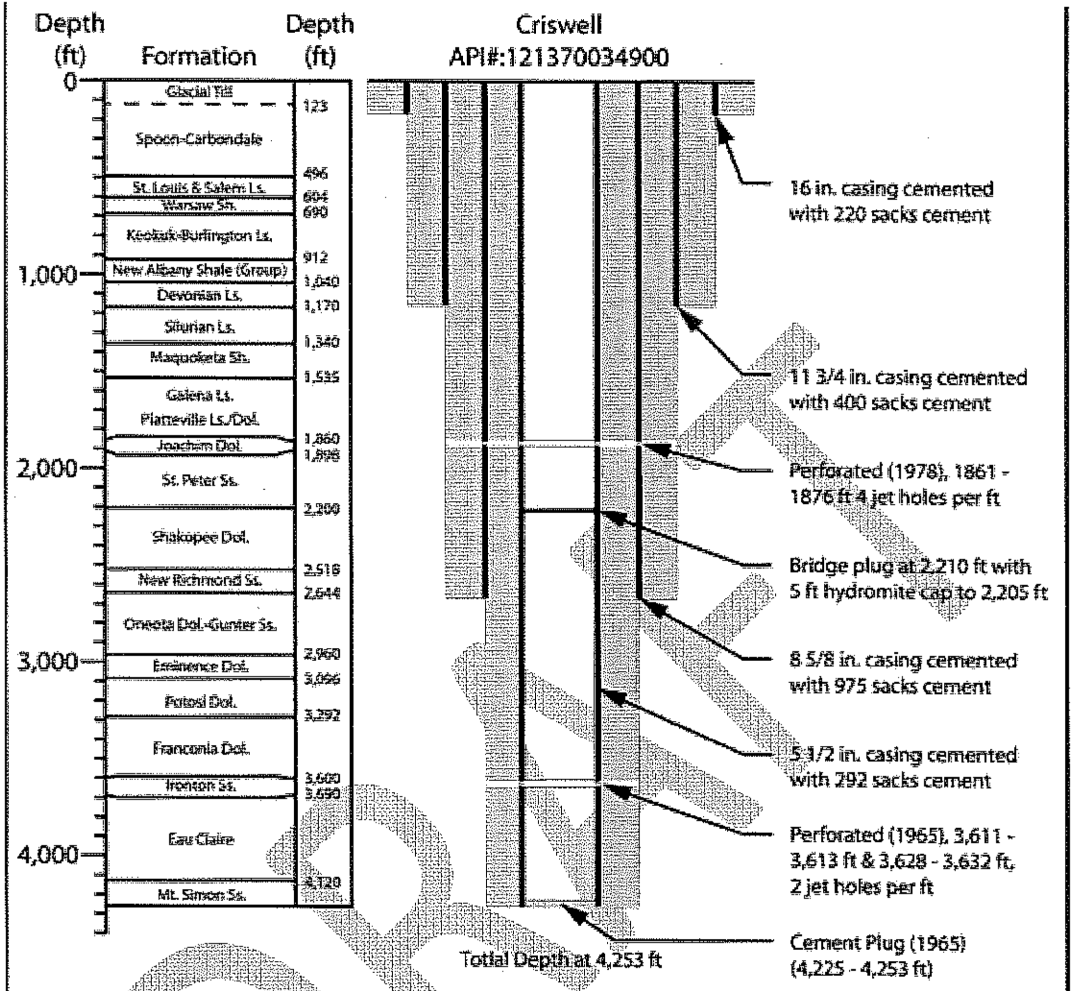


Wells Reaching the Mt Simon Ss. Closest to the FutureGen 2.0 Site



Well	lon/ lat (NAD 83)	UTM 16 N (ft US)
Sleight:	-90.685599 / 39.733078	604122 14450860
Myers:	-90.692579 / 39.745987	602353 14455643
Campbell:	-90.969246/ 39.726509	524239 14451879
Mumford:	-90.867288 / 39.618903	551226 14411425
Criswell:	-89.996576 39.577064	795995 14386807
Whitlock:	-89.982168 39.575951	800042 14386266

Figure 1. Location of the FutureGen 2.0 site and closest wells that penetrate the Eau Claire caprock.



Completion Summary: In 1965 this well was drilled and cased to a total depth of 4,253 feet. A cement plug was set in the bottom of the well from 4,253 ft to 4,225 ft and then perforated within the Ironton Sandstone. In 1978 the well was reworked and completed as an observation well within the Joachim "B" zone. A bridge plug was set at 2,210 ft with a 5-ft hydromite cap placed from 2,210 ft to 2,205 ft.

Not to Scale

Figure 2. Diagram **of the** Criswell **borehole** at Waverly field (September 2012).

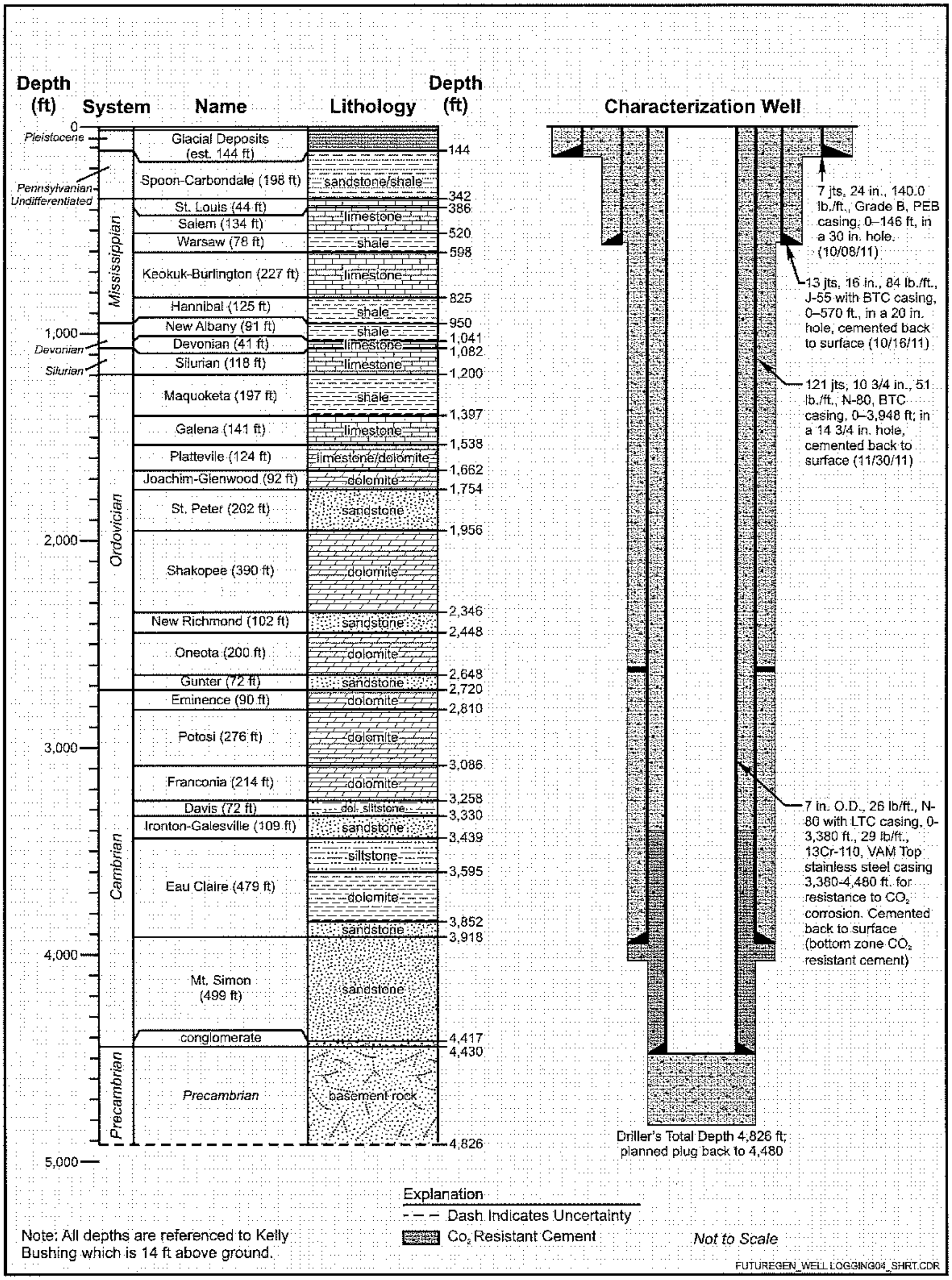
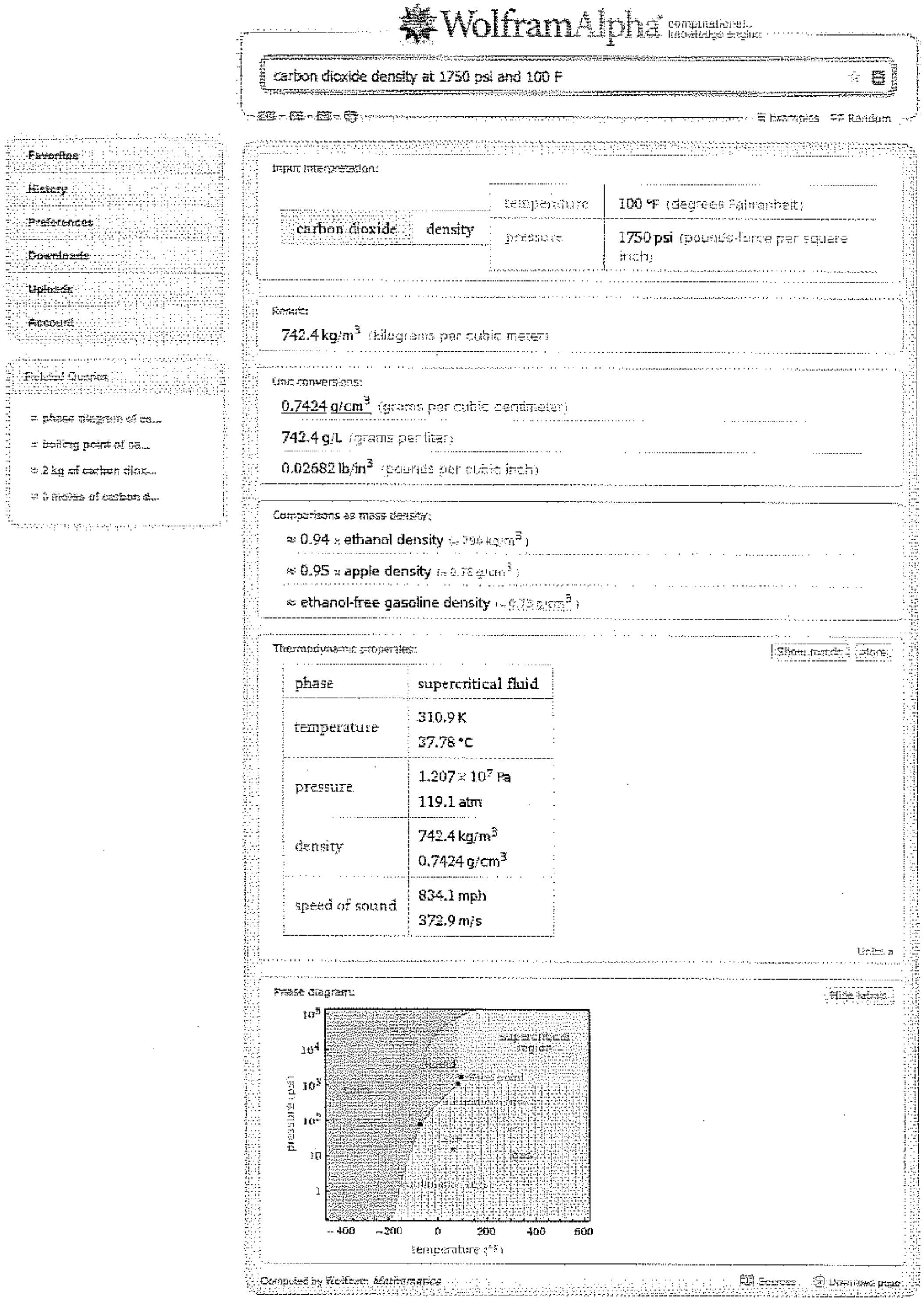


Figure 3. Diagram of FGA#1 borehole at the FutureGen 2.0 site (Figure 3.1 from PNWD-4343)



carbon dioxide density at 1750 psi and 100 F

Input interpretation:

carbon dioxide density

temperature	100 °F (degrees Fahrenheit)
pressure	1750 psi (pounds-force per square inch)

Result:

742.4 kg/m^3 (kilograms per cubic meter)

Unit conversions:

0.7424 g/cm^3 (grams per cubic centimeter)

742.4 g/L (grams per liter)

0.02682 lb/in^3 (pounds per cubic inch)

Comparisons as mass density:

≈ 0.94 × ethanol density (≈ 794 kg/m^3)

≈ 0.95 × apple density (≈ 0.78 g/cm^3)

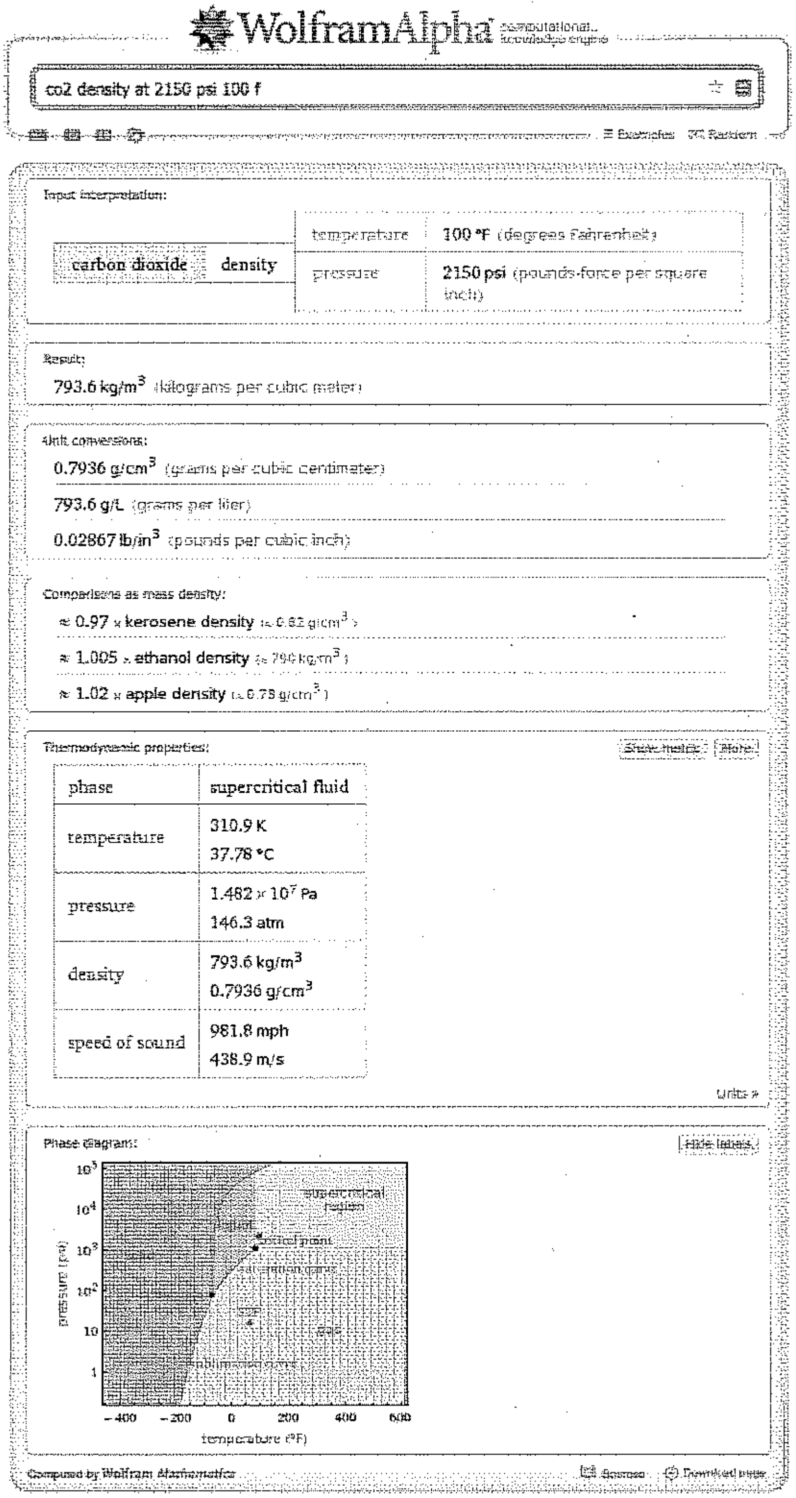
≈ ethanol-free gasoline density (≈ 0.73 g/cm^3)

Thermodynamic properties:

phase	supercritical fluid
temperature	310.9 K 37.78 °C
pressure	1.207×10^7 Pa 119.1 atm
density	742.4 kg/m^3 0.7424 g/cm^3
speed of sound	834.1 mph 372.9 m/s

Phase diagram:

Figure 4. The $scCO_2$ density calculation for ambient conditions. (www.wolframalpha.com, accessed November 19, 2013.)



WolframAlpha computational knowledge engine

co2 density at 2150 psi 100 f

Input interpretation:

carbon dioxide	density	temperature	100 °F (degrees Fahrenheit)
		pressure	2150 psi (pounds-force per square inch)

Result:

793.6 kg/m^3 (kilograms per cubic meter)

Unit conversions:

0.7936 g/cm^3 (grams per cubic centimeter)

793.6 g/L (grams per liter)

0.02867 lb/in^3 (pounds per cubic inch)

Comparisons as mass density:

≈ 0.97 × kerosene density (≈ 0.82 g/cm^3)

≈ 1.005 × ethanol density (≈ 790 kg/m^3)

≈ 1.02 × apple density (≈ 0.78 g/cm^3)

Thermodynamic properties:

phase	supercritical fluid
temperature	310.9 K 37.78 °C
pressure	1.482 × 10^7 Pa 146.3 atm
density	793.6 kg/m^3 0.7936 g/cm^3
speed of sound	981.8 mph 438.9 m/s

Phase diagram:

Figure 5. The scCO$_2$ density calculation for higher pressure conditions. (www.wolframalpha.com, accessed November 20, 2013.)

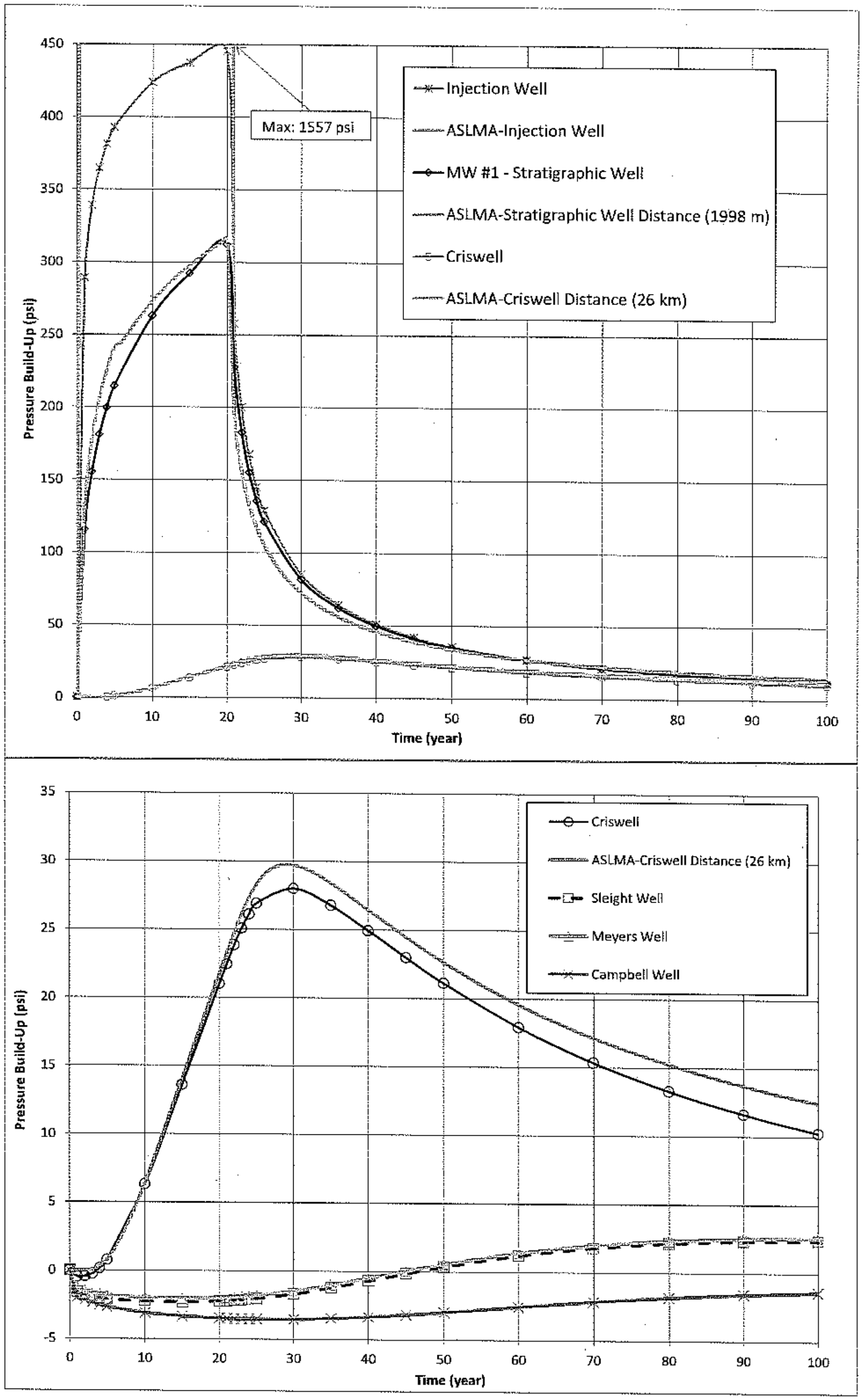


Figure 6. Comparison of pressure buildup of Mt. Simon between UIC Permit Model and ASLMA Model results for FGA#1 borehole and Criswell borehole (Waverly field).

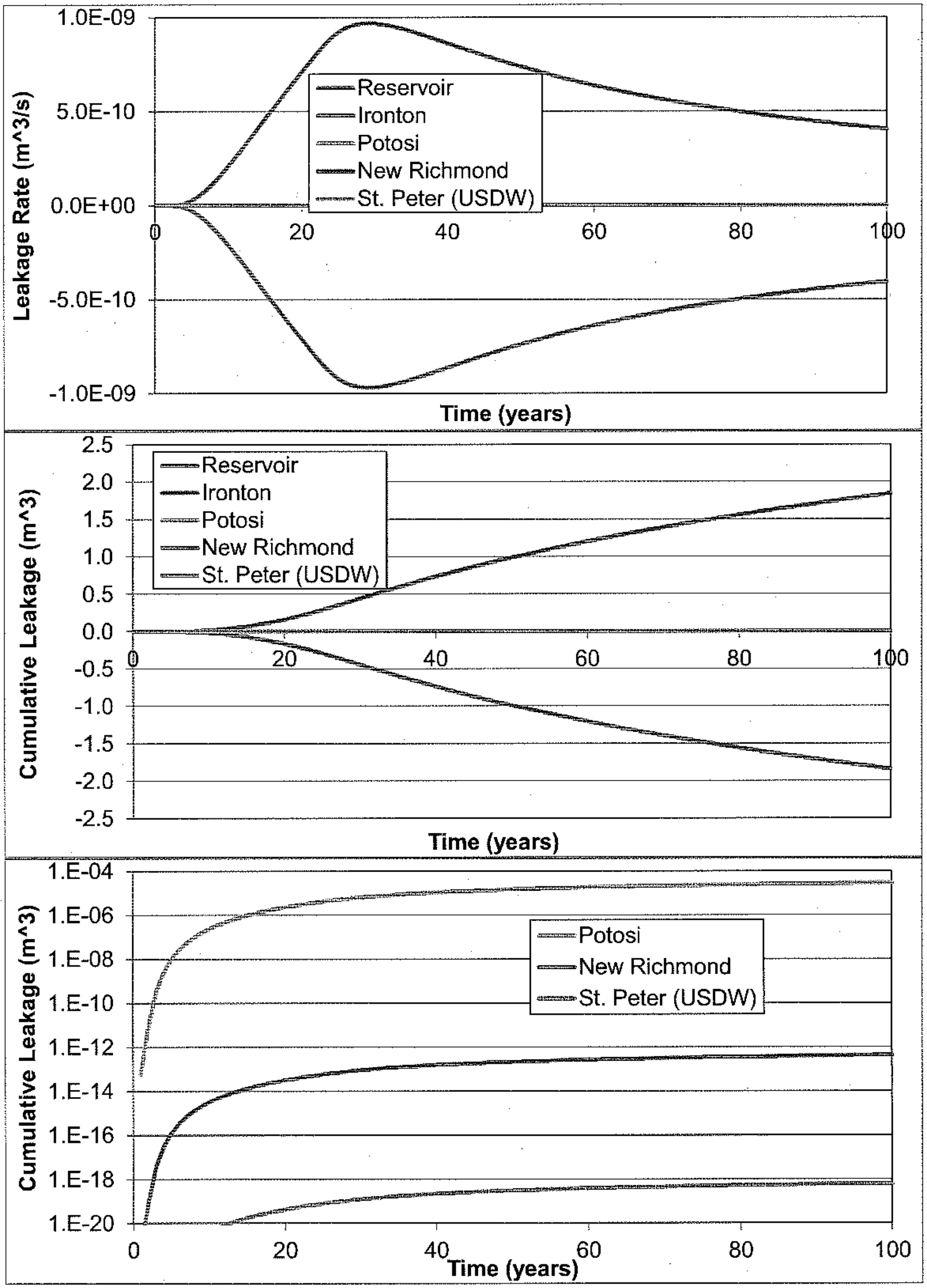


Figure 7. Waverly field well (26 km distance) – top of High Leakage Potential Category (8 mD).

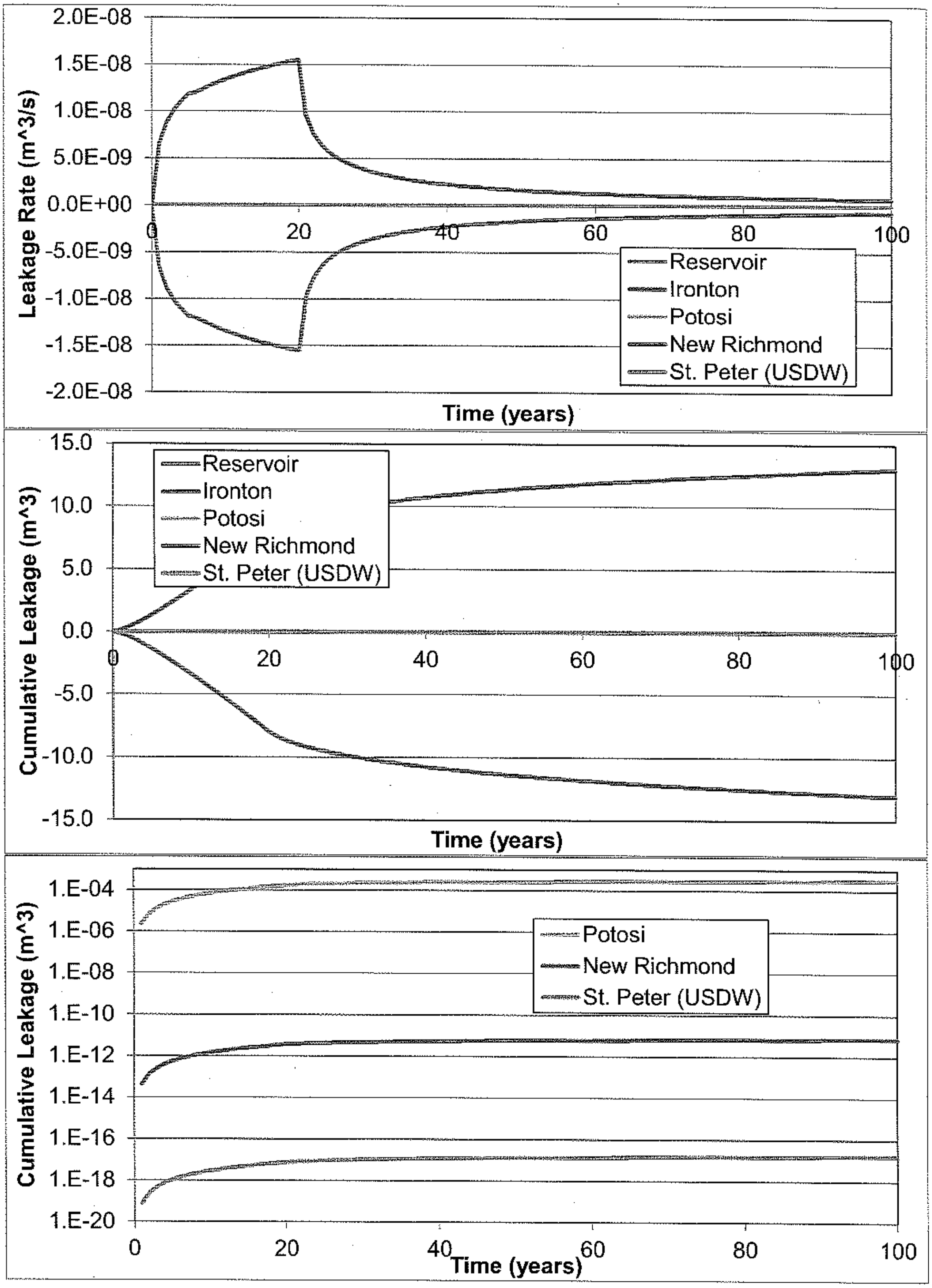


Figure 8. FGA#1 borehole (2 km distance) –top of High Leakage Potential Category (8 mD).

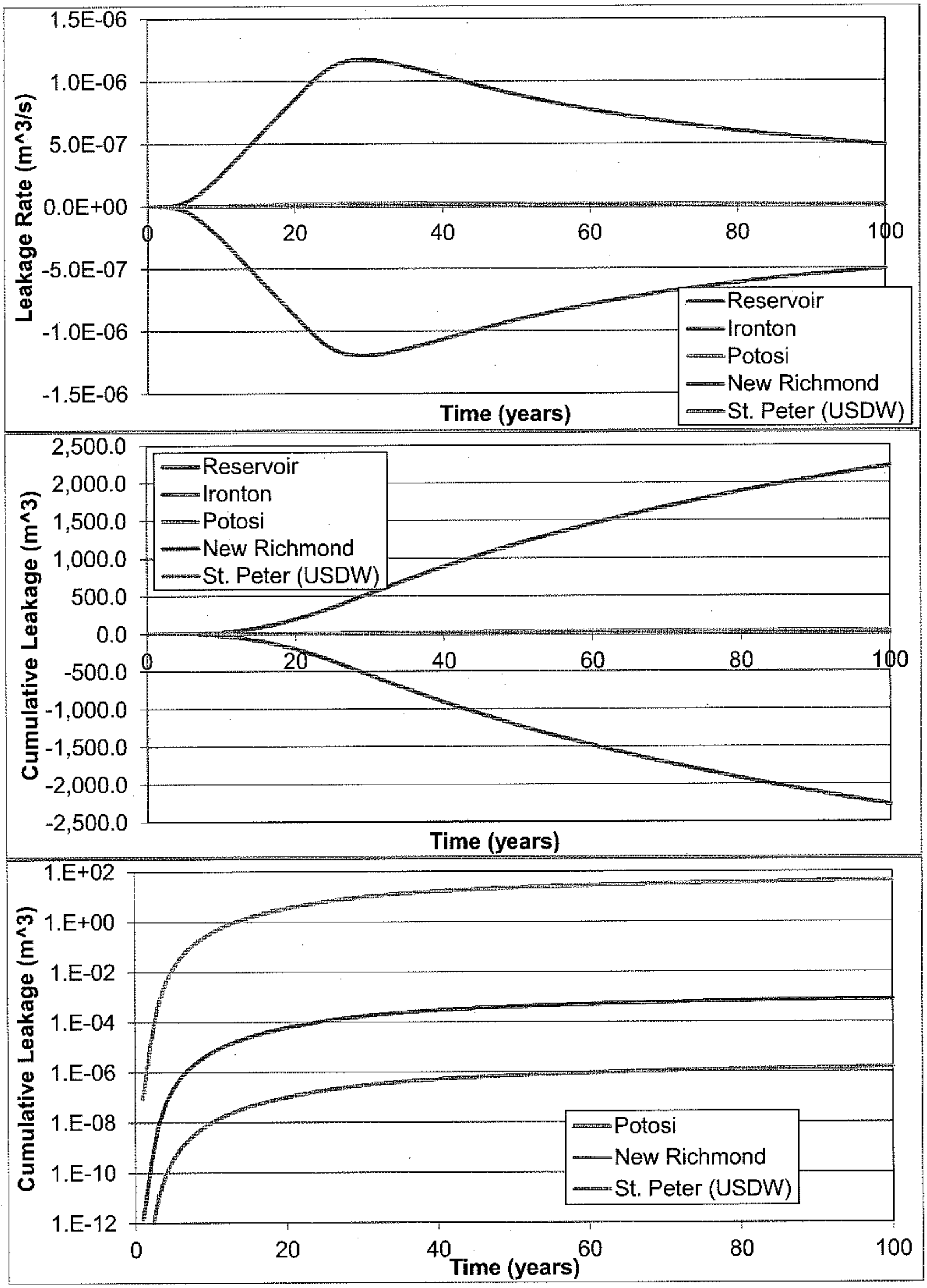


Figure 9. Waverly field well (26 km distance) – top of Extreme Leakage Potential Category (10,000 mD).

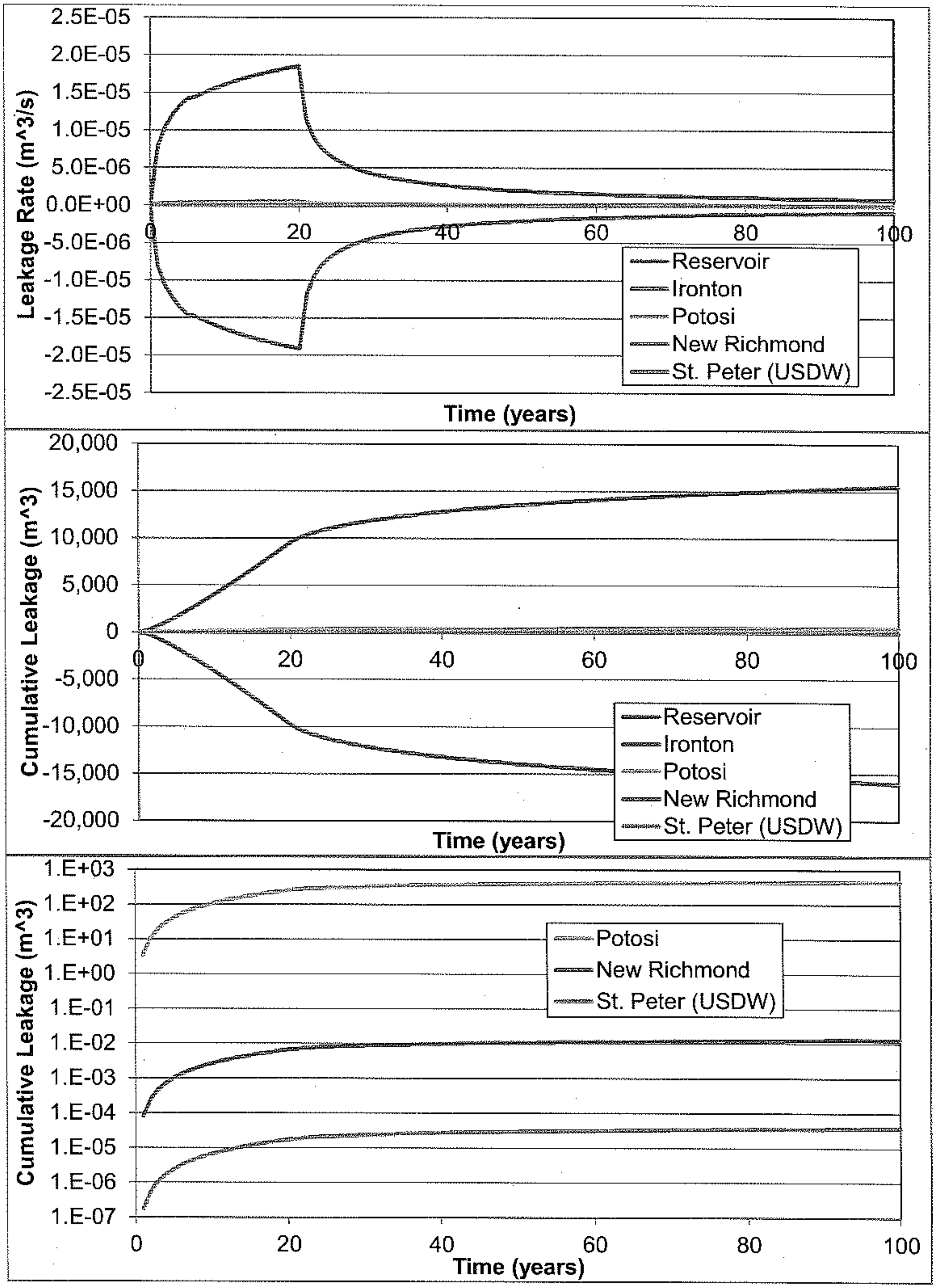


Figure 10. FGA#1 borehole (2 km distance) – top of Extreme Leakage Potential Category (10,000 mD).

Table 1 – Summary of Properties in ASLMA Focused Leakage model for FutureGen 2.0 site.

Unit	Thickness	Hydraulic Conductivity	Specific Storage[a]
St. Peter sandstone	202 ft (61.6 m)	1.18E-5 m/s (1,220 mD)[b]	1.0E-6 1/m
Shakopee dolomite	390 ft (119 m)	Aquitard	Aquitard
New Richmond sandstone	102 ft (31.1 m)	2.2E-6 m/s (230 mD)[c]	1.0E-6 1/m
Oneota dolomite, Gunter dolomite, Eminence dolomite	362 ft (110 m)	Aquitard	Aquitard
Potosi dolomite	276 ft (84.1 m)	1.E-4 m/s (10,000 mD)[d]	1.0E-6 1/m
Franconia dolomite, Davis dolomite	244 ft (74.4 m)	Aquitard	Aquitard
Ironton sandstone	109 ft (33.2 m)	2.9E-7m/s (30 mD)[e]	1.0E-6 1/m
Upper Eau Claire (Proviso and Lombard)	413 ft (126 m)	Aquitard	Aquitard
Lower Eau Clair (Elmhurst) and Upper Mt. Simon	330 ft (100 m)	7.6E-7 m/s (79 mD)[f]	2.2E-6 1/m

(a) Specific Storage for units other than reservoir: default value calculated based on mid-range of compressibility for sound rock (Table 2.5 of Freeze and Cherry [1979]). Specific Storage not used for aquitards.

(b) St. Peter: Permeability from Waverly Project listed in Buschbach and Bond (1967, 1974). Measurement could be air permeability (water permeability would be lower).

(c) New Richmond: Geometric mean of a large number of samples (38) analyzed for air permeability (water permeability would be lower) from the New Richmond Formation at the Waverly site (Core Laboratories, 1966).

(d) Potosi: Based on preliminary estimates from fluid circulation loss during drilling (updated value will be used in final version of this report)

(e) Ironton: Average of representative samples from sidewall core analyses (horizontal permeability, Klinkenberg from standard core permeability analysis and Swanson from High Pressure Mercury Injection analysis) on samples from FGA#1 (stratigraphic characterization) borehole at the FutureGen 2.0 site (Whitney et al. 2012). Similar to geometric mean of a large number of samples (53) analyzed for air permeability from the Ironton Formation at the Waverly site (Core Laboratories 1966).

(f) Reservoir: Hydraulic properties (hydraulic conductivity and specific storage) based on fit of simulation pressure results from UIC Permit Injection model (see text for details).

Table 2. Summary of simulated cumulative fluxes after 100 years.

Case	Reservoir (Mt. Simon and Elmhurst) Volume (m^3)	Ironton Sandstone Volume (m^3)	Potosi Dolomite Volume (m^3)	New Richmond Sandstone Volume (m^3)	St. Peter Sandstone Volume (m^3)
Waverly (26 km) – High Leakage Potential	-1.842	1.842	2.90E-05	4.39E-13	6.56E-19
Waverly (26 km) – Extreme Leakage Potential	-2273	2229	43.92	8.26E-04	1.55E-06
FGA#1 (2 km) – High Leakage Potential	-13.04	13.04	3.13E-04	7.16E-12	1.63E-17
FGA#1 (2 km) – Extreme Leakage Potential	-1.60E+04	1.55E+04	465.1	1.32E-02	3.76E-05