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# FutureGen Alliance Class VI Injection Project: Evaluation of Area of Review Delineation and Corrective Action

## Prepared to Support U.S. EPA Region 5 Permitting Decisions

March 2014

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## EXECUTIVE SUMMARY

This document describes the area of review (AoR) delineation modeling evaluation for the FutureGen Alliance project (i.e., for four injection wells) located in Morgan County, IL, 11 miles northeast of the City of Jacksonville, IL. The evaluation represents the first stage of the AoR modeling conducted for a Class VI project which is submitted with the initial permit application as required by 40 CFR 146.82(a) and 146.84. This document provides a basic description of the injection project and the AoR modeling evaluation process as well as the projects' hydrogeologic setting and site conceptual model in comparison to the site characterization information submitted by the permit applicant. The FutureGen Alliance applied a computational modeling tool, Subsurface Transport Over Multiple Phases (STOMP), to delineate the AoR and evaluate the associated area of elevated pressure. Similarly, EPA conducted an independent assessment using STOMP to evaluate the AoR and evaluate the associated area of elevated pressure.

In summary, the findings of this report are:

- The permit application information, site characterization data, proposed operating data and supporting information submitted by the FutureGen Alliance are consistent with the conceptual model;
- The results of FutureGen Alliance's modeling for the representative-base case indicate a plume area of 6.35 $mi^2$ at the end of injection (20 years) and a maximum plume extent of 6.46 $mi^2$ at 22 years;
- The pressure front is conservatively defined for regulatory purposes by the maximum extent of the 10 psi contour at 60 years covering an area of 1,814 $mi^2$;
- The FutureGen Alliance's evaluation and assessment of the location and depth of wells within the AoR resulted in the conclusion that no wells within the AoR require corrective action;
- EPA's independent assessment modeling and sensitivity analyses using STOMP are in close agreement with the FutureGen Alliance's analyses;
- This preliminarily delineated AoR is appropriate for this first stage of Class VI well permitting and will benefit from additional site characterization data gathered by the FutureGen Alliance during logging, sampling, testing and well construction and submitted to EPA pursuant to 40 CFR 146.82(c);
- Revisions captured in the final AoR delineation should account for and reduce uncertainties related to the Mt. Simon and St. Peter Formation characteristics and inform the critical pressure assessment and, thus, the pressure front delineated AoR boundary.

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## 1. INTRODUCTION

This document describes the area of review (AoR) delineation modeling evaluation conducted by the FutureGen Alliance as discussed in their Class VI geologic sequestration permit application(s) and subsequent submittals to the EPA during permit application review.

Due to the nature of the Class VI permitting process (where project owners or operators first receive a permit authorizing well construction and subsequently authorizing injection), AoR information is submitted in two stages. First, the preliminary AoR delineation and associated modeling information must be submitted with the initial Class VI permit application [40 CFR 146.82(a)(2) and (13); 146.84(b)]. Second, the final AoR delineation, incorporating data obtained during well construction and testing, must be submitted and approved before the UIC Program Director authorizes operation of the injection well or wells [40 CFR 146.82(c)(1)]. The information discussed in this document presents a review of information submitted during the first of these two stages.

Following this introductory section (which provides a basic description of the injection project and the AoR modeling evaluation process), the document presents the project's hydrogeologic setting, the site conceptual model, quantitative model design, a discussion of critical pressure front calculation and assessment, corrective action, and a synthesis and analysis of results.

### 1.1 Project Summary

The proposed Class VI wells, four in total, are located in Morgan County, IL, 11 miles northeast of the City of Jacksonville, IL. The FutureGen Alliance proposes to inject $CO_2$ supplied from the Meredosia, IL coal-fired power plant retrofitted with oxy-combustion capture technology.

| **Table 1. Class VI Permit Application Quick Reference Table** | |
|---|---|
| **Basic Information** | |
| Permit Applicant | FutureGen Industrial Alliance |
| Permit Application ID | INSERT |
| Date of Initial Permit Application | March 2013 |
| | |
| **Proposed Project Location** | |
| County | Morgan County, Illinois |
| | |
| **Proposed Injection Details** | |
| Proposed Number of Wells | Four |
| Proposed Injection Duration | 20 years |
| Cumulative Injection Amount | 22 million metric tons (MMT) |
| Average Injection Rate | 1.1 MMT/annually |
| Injection Zone | Mount Simon and Elmhurst Formations |
| Approx. Injection Zone Depth | 3785-4432 ft below kelly bushing |
| Primary Confining Zone | Eau Claire Formation |
| Approx. Confining Zone Depth | 3439 -3786 ft below kelly bushing |

| | |
|---|---|
| Lowermost USDW | St. Peter Sandstone |
| Approx. USDW Depth | 1740-1942 ft below ground surface |
| Proposed PISC Duration | 50 years |

### 1.2 AoR Evaluation Process

Pursuant to 40 CFR 146.81(d), the AoR refers to the region surrounding the GS project where USDWs may be endangered by the injection activity, which may include leakage from the CO2 plume and/or pressure-induced migration of native formation fluids/brine. The AoR is delineated using computational modeling that accounts for the physical and chemical properties of all phases of the injected carbon dioxide stream, displaced fluids, the associated area of elevated pressure, and is based on available site characterization, monitoring, and operational data.

Reviewing the AoR modeling and delineation information submitted with the permit application is necessary to determine whether the submitted information:

- Is adequate and accurate;
- Is consistent with the requirements in the Class VI Rule at 40 CFR 146.84; and
- Supports a determination that the proposed injection project will not endanger USDWs.

The AoR modeling information must also be reviewed to ensure its consistency with other aspects of the permit application. For example:

- The geologic model used in the AoR delineation should be consistent with and incorporate site characterization data and data collected during pre-injection testing;
- The AoR model inputs should be consistent with the proposed operating data and data collected during pre-injection testing;
- The project plans (particularly the AoR and Corrective Action Plan) should encompass the entire delineated AoR; and
- Financial responsibility should be adequate to address all required corrective action.

This report summarizes the modeling information's consistency with the site characterization information and operating data submitted under 40 CFR 146.82(a). However, following this quantitative assessment, it is important to ensure that the submitted project plans (particularly the AoR and Corrective Action Plan and the site-specific Testing and Monitoring Plan) and the financial responsibility documentation are also consistent with the delineated AoR.

In the absence of existing project monitoring data (because AoR modeling activities take place in the pre-injection phase, before initiation of the project), AoR delineation model evaluations depend on both a qualitative and quantitative assessment of the available information. This process is illustrated in

Figure 1. The initial assessment, discussed in this report, encompasses the quantitative evaluation step of this process and is shown inside the red dashed box in the figure.

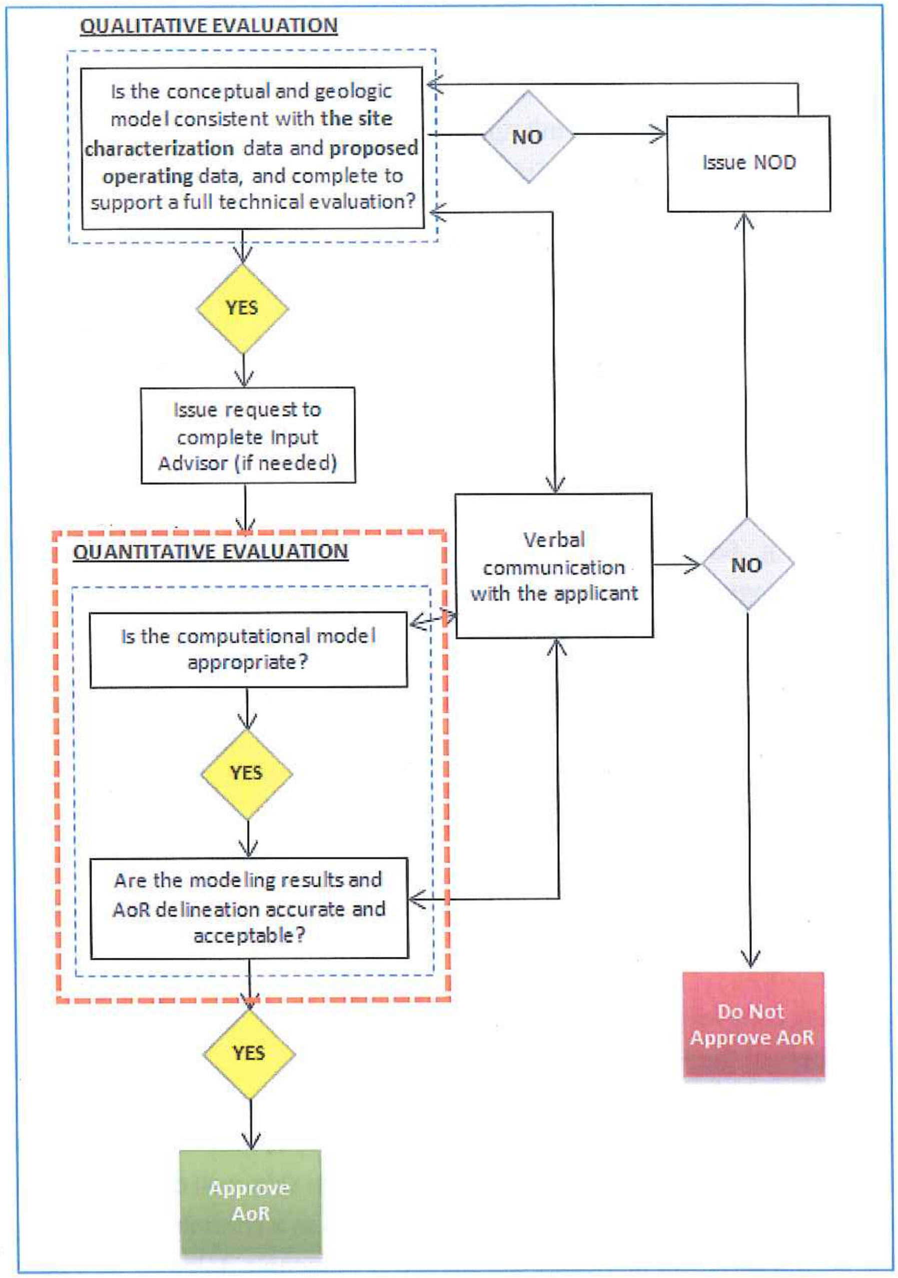



**Figure 1. The Evaluation Process for AoR Delineation Modeling (the stage of the evaluation captured in this report is shown within the red dashed box)**

For this permit application, after completing the qualitative assessment, the UIC Program Director requested detailed modeling information from the permit applicant using the Input Advisor tool within the EPA-Velo content management system. This information was needed to complete a detailed quantitative assessment of the AoR modeling using the multiphase simulator Subsurface Transport Over

Multiple Phases (STOMP). The Input Advisor was developed to identify and collect specific information related to AoR modeling, to support the full technical evaluation of AoR modeling efforts.

### 1.3 Information Submitted by the Permit Applicant

The permit application process for the FutureGen injection wells included multiple submittals and official communication between the permit applicant and EPA. All submittals and records of communication are available in the administrative record for this permit.

## 2. AOR PLUME MODELING INFORMATION AND PARAMETERS

### 2.1 Geologic Setting

The proposed Class VI wells target an injection zone in the Cambrian Mt. Simon Sandstone and the Elmhurst Sandstone of the Illinois Basin. The FutureGen Alliance used data from wells in the project area including a dedicated stratigraphic well that was drilled near the proposed injection site and published literature (e.g., Bowen et al., 2011; Birkholzer et al., 2008; Leetaru et al., 2009; Willman et al., 1975; Illinois State Geological Survey [ISGS] resources).

The Mt. Simon Sandstone overlies Precambrian granitic basement rock in the proposed project area. The Mt. Simon and the Elmhurst Sandstone which directly overlies the Mt. Simon form the injection zone for the FutureGen project. The permit applicant indicates that Mt. Simon which ranges, regionally, between conglomerate, sandstone and shale "represents continental and shallow marine environments of deposition that reflect gentle basin subsidence and gradual transgressive marine encroachment..." over the Precambrian basement rock (Chapter 2 of the March 2013 permit application); while the Elmhurst Sandstone is a porous, permeable, fine- to medium-grained sandstone interbedded with shale and minor dolomite.

The primary confining zone identified and characterized at the FutureGen project site are the Proviso and Lombard members of the Eau Claire Formation. These formations are described by the permit applicant as "tan to light brown, dense, occasionally glauconitic microcrystalline, slightly dolomitic limestone" [the Proviso] and "thinly bedded to laminated siltstone and mudstone" [the Lombard]. The permit applicant provided permeability and porosity data from side-wall cores and logging results to substantiate the appropriateness of the Proviso and Lombard as a confining zone for this project. Additionally, the permit applicant identified the shallower Franconia dolomite as a secondary confining zone of low porosity and permeability.

The FutureGen Alliance identified and EPA confirmed that the St. Peter Sandstone is the lowermost underground source of drinking water (USDW) at the location of the proposed project site. A fluid sample collected from the St. Peter during drilling of the stratigraphic test well resulted in a laboratory-measured total dissolved solids (TDS) value of 3,400 mg/L which falls within the scope of waters afforded protection under the Safe Drinking Water Act as being below 10,000 mg/L TDS. Additional information submitted by the permit applicant (Chapter 2 of the March 2013 permit application) yielded a TDS value of 2,778 mg/L at the Waverly Gas Storage Field, 16 miles to the southeast of the proposed FutureGen project site. At the proposed project site, the St. Peter (the lowermost USDW) is approximately 1,740 ft below ground surface (bgs) to 1,942 ft (bgs) and is separated from the injection zone by 1,900 ft of rock column.

## 2.2 Model Domain

The FutureGen Alliance used a laterally homogeneous (layer cake) geologic model which consists of the injection zone (the Mount Simon and the Elmhurst Formations), the primary confining zone (the Lombard and Proviso Formations), the Ironton-Galesville Formation, and the secondary confining zone (the Davis-Ironton (Davis Member of the Franconia Formation) and the Franconia Formations).

A 100- x 100-mi conceptual model gridded in EarthVision was executed in the STOMP-CO2 simulator. Input data including hydrology and transport properties of model layers were based on borehole data from the FutureGen stratigraphic well and data from regional boreholes and published regional contour maps. The FutureGen Alliance defined the conceptual model hydrogeologic layers for each stratigraphic layer based on zones of similar hydrologic properties. They used the lithology, deduced from wireline logs and core data to subdivide each stratigraphic layer of the model.

Based on these data, the Mount Simon Sandstone was subdivided into 17 layers and the Elmhurst Sandstone (member of the Eau Claire Formation) was subdivided into 7 layers (Figure 2). These units form the injection zone. The Lombard and Proviso members of the Eau Claire Formation were subdivided respectively into 14 and 5 layers. The Ironton Sandstone was divided into four layers, the Davis Dolomite into three layers, and the Franconia Formation into one layer. Some layers (indicated in Figure 2 as "split") have similar properties but were subdivided to maintain a reasonable thickness of layers within the injection zone as represented in the computational model.

The thickness of the layers varies from 4 to 172 ft, with an average of 26 ft. Figure 3 shows the numerical model grid for the entire 100- x 100-mi domain and also for the 3- x 3-mi area with higher grid resolution and uniform grid spacing of 200 ft x 200 ft. The model grid contains 125 nodes in the x-direction, 125 nodes in the y-direction, and 51 nodes in the z-direction for a total number of nodes equal to 796,875.

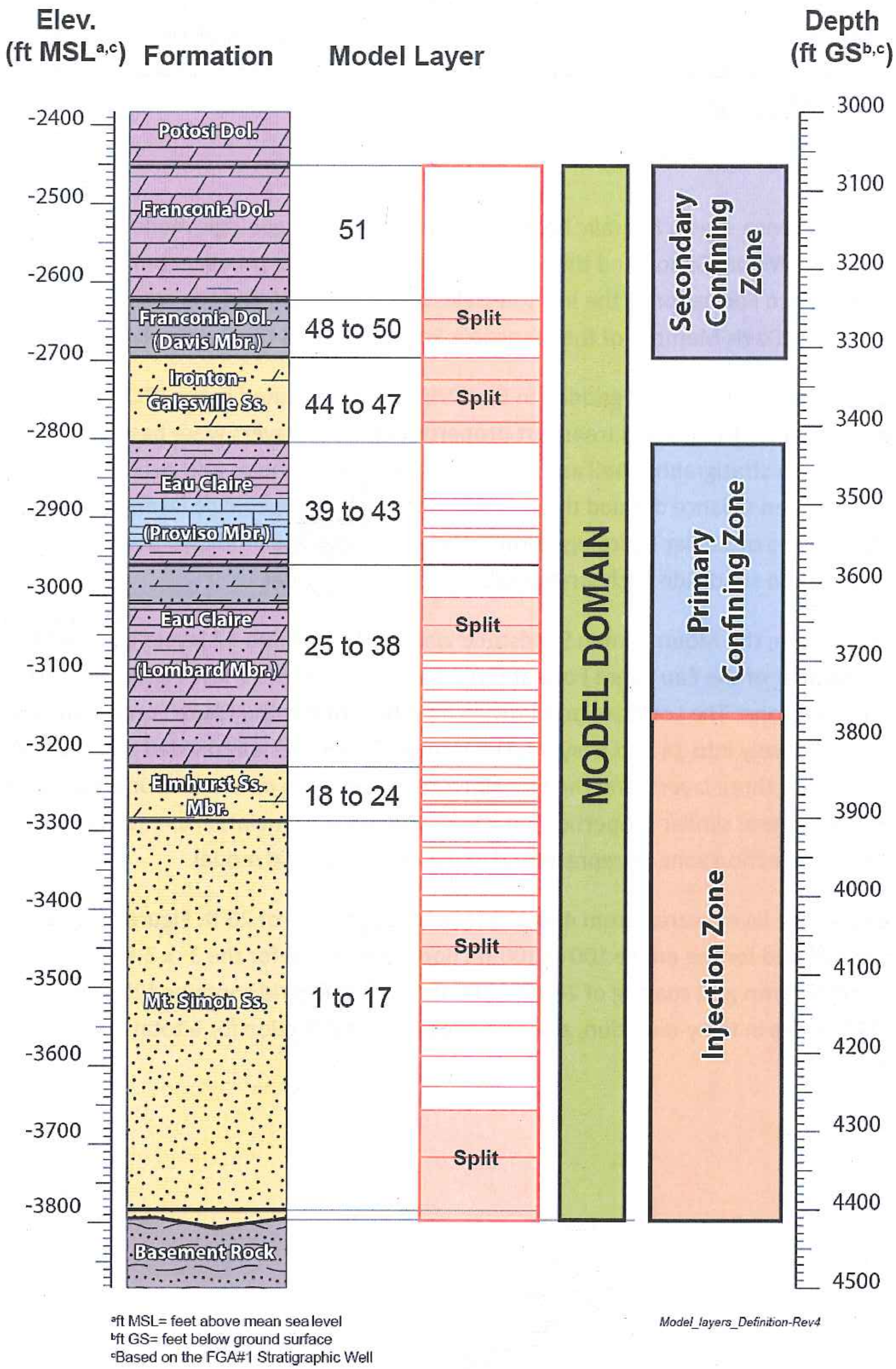
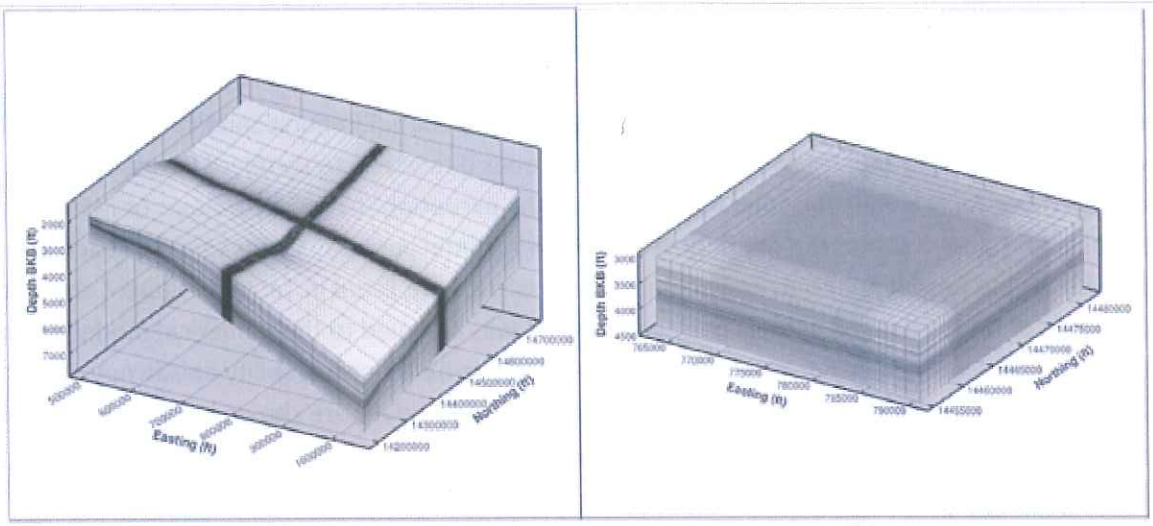



**Figure 2. Division of Stratigraphic Layers to Create Computational Model Layers**



(a) (b)

**Figure 3. Numerical Model Grid for: a) Full Domain; b) Finer Resolution Area Containing the Injection Wells**

For EPA's independent assessment and AoR delineation, the same 100- x 100-mi conceptual model (i.e., 125 nodes in the x-direction, 125 nodes in the y-direction, and 51 nodes in the z-direction) was conducted in STOMP-CO2 simulator. The grid information including active and inactive nodes were entered into STOMP using external grid files (fg_uic_200.dat, fg_uic_200_inact.dat) provided by the FutureGen Alliance in Input Advisor.

STOMP Syntax Box- Model Domain Input for the Full Domain

```
~Grid Card
earthvision sampled input,  # Type of the external data file
125,125,51,                 # Number of X- Y- Z-Dir Nodes
fg_uic_200.dat,ft,          # Name of the external file, unit

~Inactive Nodes Card
file,fg_uic_200_inact.dat,  # Name of the external data file
```

## 2. 2 Rock Properties

The FutureGen Alliance realized hydrologic properties (permeability, porosity) from geophysical well logs and side-wall cores. A number of characterization data sources and methods were used by the permit applicant to assign hydrologic properties to the various model layers. Available data sources for the Morgan County site include results from continuous wireline surveys (e.g., compensated magnetic resonance [CMR], Elemental Analysis [ELAN]), standard and side-wall cores (SWCs), and hydrologic tests (Modular Formation Dynamics Tester [MDT]and packer tests).

### 2. 2 .1 Permeability

The FutureGen Alliance used the wireline ELAN permeability model permKCal to calculate intrinsic permeability of model layers within the injection reservoir section (Elmhurst Sandstone and Mount Simon Sandstone). The sources of data for confining zones (Franconia to Lombard Formations) are similar to those for the injection zone reservoir, with the exception that no hydrologic or MDT test data are available. Figure 3 shows the depth profile of the horizontal permeability assigned to each layer of the model by the permit applicant and actual values assigned are listed in Table 2. Figure 4 shows the distribution of horizontal and vertical permeability as it was assigned to the numerical model grid by the FutureGen Alliance. The permit applicant used the literature-based permeability anisotropy values to assign kv and kh to each layer of the model (Table 3). Assigned values are shown in Table 2. The same permeability values were applied in the independent assessment model.

STOMP Syntax Box- Model Rock properties - Permeability

```
~Hydraulic Properties Card
Mtsim1,2.83E-15,m^2,2.83E-15,m^2,2.83E-16,m^2,  # Permeability in X- dir., unit, Y- dir., unit, Z- direction, unit
Mtsim2,2.83E-15,m^2,2.83E-15,m^2,2.83E-16,m^2,
...
```

Table 2. Summary of Permeability, Compressibility, and Grain Density Values Applied to Model Layers

| Lithology | Zone Name | Top Depth (ft KB) | Top Elevation (ft) | Bottom Elevation (ft) | Thickness (ft) | Layer Number | Porosity (-) | Horizontal Permeability (mD) | Vertical Permeability (mD) | Compressibility (1/Pa) | Grain Density (kg/m3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| dolo | Franconia | 3086.0 | -2453.0 | -2625.0 | 172.0 | 51 | 0.0358 | 5.50E-06 | 3.85E-08 | 7.42E-10 | 2819.2 |
| mud | Davis-Ironton3 | 3258.0 | -2625.0 | -2649.0 | 24.0 | 50 | 0.0367 | 6.26E-02 | 6.26E-03 | 3.71E-10 | 2724.9 |
| mud | Davis-Ironton2 | 3282.0 | -2649.0 | -2673.0 | 24.0 | 49 | 0.0367 | 6.26E-02 | 6.26E-03 | 3.71E-10 | 2724.9 |
| mud | Davis-Ironton1 | 3306.0 | -2673.0 | -2697.0 | 24.0 | 48 | 0.0218 | 1.25E+01 | 1.25E+00 | 3.71E-10 | 2724.9 |
| sand | Ironton-Galesville4 | 3330.0 | -2697.0 | -2725.0 | 28.0 | 47 | 0.0981 | 2.63E+01 | 1.05E+01 | 3.71E-10 | 2657.3 |
| sand | Ironton-Galesville3 | 3358.0 | -2725.0 | -2752.0 | 27.0 | 46 | 0.0981 | 2.63E+01 | 1.05E+01 | 3.71E-10 | 2657.3 |
| sand | Ironton-Galesville2 | 3385.0 | -2752.0 | -2779.0 | 27.0 | 45 | 0.0981 | 2.63E+01 | 1.05E+01 | 3.71E-10 | 2657.3 |
| sand | Ironton-Galesville1 | 3412.0 | -2779.0 | -2806.0 | 27.0 | 44 | 0.0981 | 2.63E+01 | 1.05E+01 | 3.71E-10 | 2657.3 |
| mud | Proviso5 | 3439.0 | -2806.0 | -2877.0 | 71.0 | 43 | 0.0972 | 1.12E-03 | 1.12E-04 | 7.42E-10 | 2720.0 |
| mud | Proviso4 | 3510.0 | -2877.0 | -2891.0 | 14.0 | 42 | 0.0786 | 5.50E-03 | 5.50E-04 | 7.42E-10 | 2720.0 |
| dolo | Proviso3 | 3524.0 | -2891.0 | -2915.5 | 24.5 | 41 | 0.0745 | 8.18E-02 | 5.73E-04 | 7.42E-10 | 2765.2 |
| dolo | Proviso2 | 3548.5 | -2915.5 | -2925.5 | 10.0 | 40 | 0.0431 | 1.08E-01 | 7.56E-04 | 7.42E-10 | 2765.2 |
| dolo | Proviso1 | 3558.5 | -2925.5 | -2963.0 | 37.5 | 39 | 0.0361 | 6.46E-04 | 4.52E-06 | 7.42E-10 | 2765.2 |
| mud | Lombard14 | 3596.0 | -2963.0 | -3003.0 | 40.0 | 38 | 0.1754 | 5.26E-04 | 5.26E-05 | 7.42E-10 | 2683.6 |
| mud | Lombard13 | 3636.0 | -3003.0 | -3038.0 | 35.0 | 37 | 0.0638 | 1.53E-01 | 1.53E-02 | 7.42E-10 | 2683.6 |
| mud | Lombard12 | 3671.0 | -3038.0 | -3073.0 | 35.0 | 36 | 0.0638 | 1.53E-01 | 1.53E-02 | 7.42E-10 | 2683.6 |
| mud | Lombard11 | 3706.0 | -3073.0 | -3084.0 | 11.0 | 35 | 0.0878 | 9.91E+00 | 9.91E-01 | 7.42E-10 | 2683.6 |
| mud | Lombard10 | 3717.0 | -3084.0 | -3094.0 | 10.0 | 34 | 0.0851 | 1.66E+01 | 1.66E+00 | 7.42E-10 | 2683.6 |
| mud | Lombard9 | 3727.0 | -3094.0 | -3120.5 | 26.5 | 33 | 0.0721 | 1.00E-02 | 1.00E-03 | 7.42E-10 | 2683.6 |
| mud | Lombard8 | 3753.5 | -3120.5 | -3137.5 | 17.0 | 32 | 0.0663 | 2.13E-01 | 2.13E-02 | 7.42E-10 | 2683.6 |
| mud | Lombard7 | 3770.5 | -3137.5 | -3145.0 | 7.5 | 31 | 0.0859 | 7.05E+01 | 7.05E+00 | 7.42E-10 | 2683.6 |
| mud | Lombard6 | 3778.0 | -3145.0 | -3152.5 | 7.5 | 30 | 0.0459 | 1.31E+01 | 1.31E+00 | 7.42E-10 | 2683.6 |
| mud | Lombard5 | 3785.5 | -3152.5 | -3161.0 | 8.5 | 29 | 0.0760 | 4.24E+02 | 4.24E+01 | 7.42E-10 | 2683.6 |

| Lithology | Zone Name | Top Depth (ft KB) | Top Elevation (ft) | Bottom Elevation (ft) | Thickness (ft) | Layer Number | Porosity (-) | Horizontal Permeability (mD) | Vertical Permeability (mD) | Compres sibility (1/Pa) | Grain Density (kg/m3) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mud | Lombard4 | 3794.0 | -3161.0 | -3181.0 | 20.0 | 28 | 0.0604 | 3.56E-02 | 3.56E-03 | 7.42E-10 | 2683.6 |
| mud | Lombard3 | 3814.0 | -3181.0 | -3188.5 | 7.5 | 27 | 0.0799 | 5.19E+00 | 5.19E-01 | 7.42E-10 | 2683.6 |
| mud | Lombard2 | 3821.5 | -3188.5 | -3193.5 | 5.0 | 26 | 0.0631 | 5.71E-01 | 5.71E-02 | 7.42E-10 | 2683.6 |
| mud | Lombard1 | 3826.5 | -3193.5 | -3219.0 | 25.5 | 25 | 0.0900 | 1.77E+00 | 1.77E-01 | 7.42E-10 | 2683.6 |
| sand | Elmhurst7 | 3852.0 | -3219.0 | -3229.0 | 10.0 | 24 | 0.1595 | 2.04E+01 | 8.17E+00 | 3.71E-10 | 2644.1 |
| sand | Elmhurst6 | 3862.0 | -3229.0 | -3239.0 | 10.0 | 23 | 0.1981 | 1.84E+02 | 7.38E+01 | 3.71E-10 | 2644.1 |
| mud | Elmhurst5 | 3872.0 | -3239.0 | -3249.0 | 10.0 | 22 | 0.0822 | 1.87E+00 | 1.87E-01 | 3.71E-10 | 2644.1 |
| sand | Elmhurst4 | 3882.0 | -3249.0 | -3263.0 | 14.0 | 21 | 0.1105 | 4.97E+00 | 1.99E+00 | 3.71E-10 | 2644.1 |
| mud | Elmhurst3 | 3896.0 | -3263.0 | -3267.0 | 4.0 | 20 | 0.0768 | 7.52E-01 | 7.52E-02 | 3.71E-10 | 2644.1 |
| sand | Elmhurst2 | 3900.0 | -3267.0 | -3277.0 | 10.0 | 19 | 0.1291 | 1.63E+01 | 6.53E+00 | 3.71E-10 | 2644.1 |
| mud | Elmhurst1 | 3910.0 | -3277.0 | -3289.0 | 12.0 | 18 | 0.0830 | 2.90E-01 | 2.90E-02 | 3.71E-10 | 2644.1 |
| sand | MtSimon17 | 3922.0 | -3289.0 | -3315.0 | 26.0 | 17 | 0.1297 | 7.26E+00 | 2.91E+00 | 3.71E-10 | 2651.1 |
| mud | MtSimon16 | 3948.0 | -3315.0 | -3322.0 | 7.0 | 16 | 0.1084 | 3.78E-01 | 3.78E-02 | 3.71E-10 | 2651.1 |
| sand | MtSimon15 | 3955.0 | -3322.0 | -3335.0 | 13.0 | 15 | 0.1276 | 5.08E+00 | 2.03E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon14 | 3968.0 | -3335.0 | -3355.0 | 20.0 | 14 | 0.1082 | 1.33E+00 | 5.33E-01 | 3.71E-10 | 2651.1 |
| sand | MtSimon13 | 3988.0 | -3355.0 | -3383.0 | 28.0 | 13 | 0.1278 | 5.33E+00 | 2.13E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon12 | 4016.0 | -3383.0 | -3404.0 | 21.0 | 12 | 0.1473 | 1.59E+01 | 6.34E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon11 | 4037.0 | -3404.0 | -3427.0 | 23.0 | 11 | 0.2042 | 3.10E+02 | 1.55E+02 | 3.71E-10 | 2651.1 |
| sand | MtSimon10 | 4060.0 | -3427.0 | -3449.0 | 22.0 | 10 | 0.1434 | 1.39E+01 | 4.18E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon9 | 4082.0 | -3449.0 | -3471.0 | 22.0 | 9 | 0.1434 | 1.39E+01 | 4.18E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon8 | 4104.0 | -3471.0 | -3495.0 | 24.0 | 8 | 0.1503 | 2.10E+01 | 6.29E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon7 | 4128.0 | -3495.0 | -3518.0 | 23.0 | 7 | 0.1311 | 6.51E+00 | 1.95E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon6 | 4151.0 | -3518.0 | -3549.0 | 31.0 | 6 | 0.1052 | 2.26E+00 | 6.78E-01 | 3.71E-10 | 2651.1 |
| sand | MtSimon5 | 4182.0 | -3549.0 | -3588.0 | 39.0 | 5 | 0.1105 | 4.83E-02 | 4.83E-03 | 3.71E-10 | 2651.1 |
| sand | MtSimon4 | 4221.0 | -3588.0 | -3627.0 | 39.0 | 4 | 0.1105 | 4.83E-02 | 4.83E-03 | 3.71E-10 | 2651.1 |
| sand | MtSimon3 | 4260.0 | -3627.0 | -3657.0 | 30.0 | 3 | 0.1727 | 1.25E+01 | 1.25E+00 | 3.71E-10 | 2651.1 |
| sand | MtSimon2 | 4290.0 | -3657.0 | -3717.0 | 60.0 | 2 | 0.1157 | 2.87E+00 | 2.87E-01 | 3.71E-10 | 2651.1 |
| sand | MtSimon1 | 4350.0 | -3717.0 | -3799.0 | 82.0 | 1 | 0.1157 | 2.87E+00 | 2.87E-01 | 3.71E-10 | 2651.1 |

Table 3. Summary of the Kv/Kh Ratios Applied to Model Layers

| Model Layer | Kv/Kh |
|---|---|
| Franconia Carbonate | 0.007 |
| Davis-Ironton | 0.1 |
| Ironton-Galesville | 0.4 |
| Proviso (layers 4 & 5) | 0.1 |
| Proviso (layers 1 to 3) | 0.007 |
| Lombard | 0.1 |
| Elmhurst | 0.4 |
| Mount Simon (Layers 12,13,14,15,17) | 0.4 |
| Mount Simon (Layer 16) | 0.1 |
| Mount Simon (Layer 11, injection zone) | 0.5 |
| Mount Simon (Layers 6,7,8,9,10) | 0.3 |
| Mount Simon (Layers 1,2,3,4,5) | 0.1 |

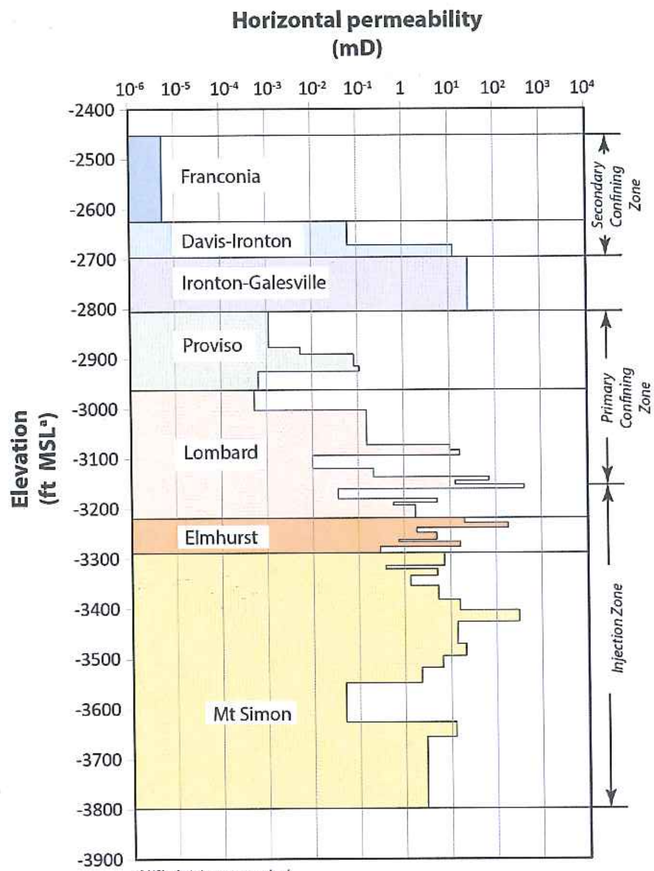
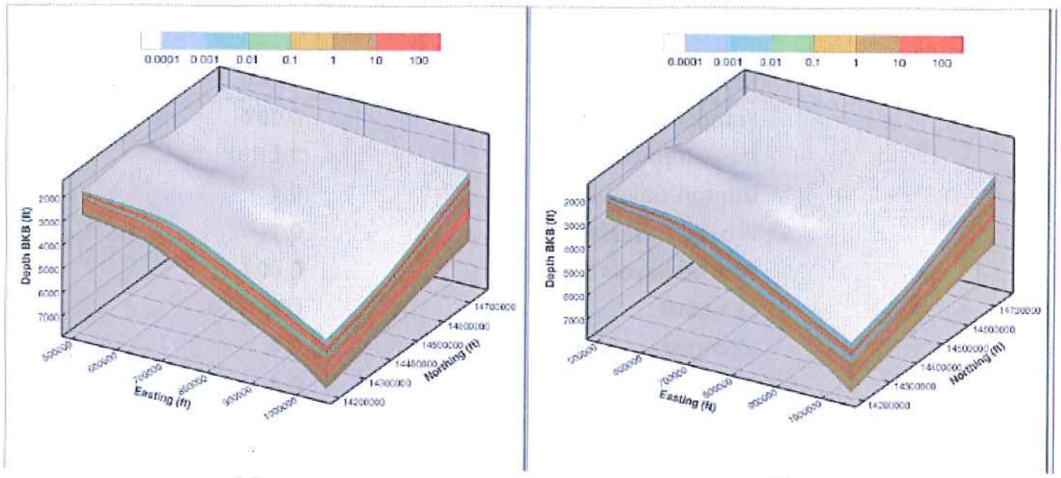



Figure 4. Horizontal Permeability Versus Depth for Each Model Layer




(a) (b)

**Figure 5. Permeability Assigned to the Numerical Model: a) Horizontal Permeability; b) Vertical Permeability**

### 2. 2 .2 Porosity

The FutureGen Alliance used Schlumberger ELAN porosity log results and laboratory measurements of porosity determined from side wall cores and core plugs to assign porosity values for the FutureGen numerical model layers. Figure 6 shows the depth profile of the assigned model layer porosities. The actual values assigned for each layer are listed in Table 2. The same porosity values were applied in the independent assessment model.

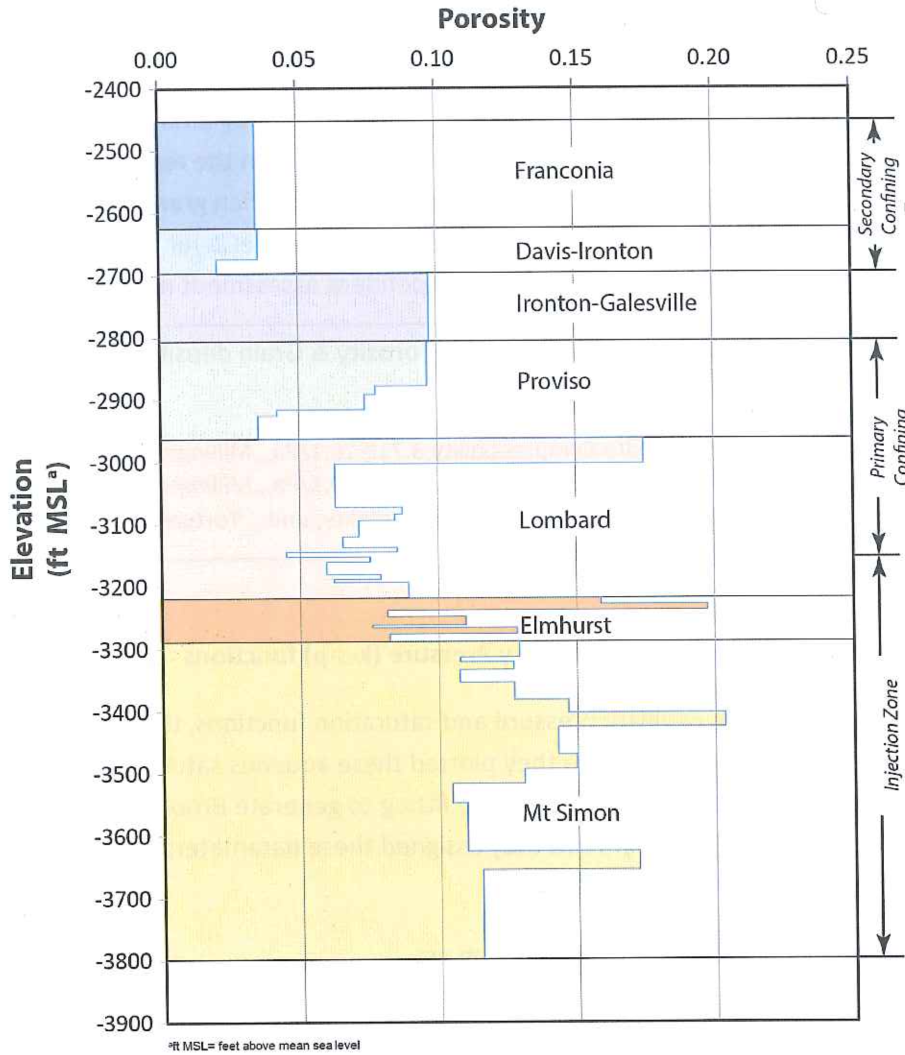



**Figure 6. Porosity Versus Depth in Each Model Layer**

### 2. 2 .3 Rock (Bulk) Density and Grain Density

Grain density data were calculated from laboratory measurements of side wall cores. The data were then averaged (arithmetic mean) for each main stratigraphic layer in the model. Only the Proviso member (Eau Claire Formation) has been divided in two sublayers to be consistent with the lithology changes. Figure 10 shows the calculated grain density with depth. The actual values assigned to each layer of the model are listed in Table 2. Grain density is the input parameter specified in the simulation input file, and STOMP-CO2 calculates the bulk density from the grain density and porosity for each model layer. The same values were used for rock density and grain density in the independent assessment model.

### 2.2.4 Formation Compressibility

Because of the limited information available about formation (pore) compressibility estimates, the permit applicant used back-calculated pore-compressibility estimate by Birkholzer et al. (2008) for the Mount Simon of 3.71E−10 $Pa^{-1}$ assuming that it is spatially constant in the reservoir. They used a value of 7.42E−10 $Pa^{-1}$ for both the Eau Claire Formation and the Precambrian granite based on Zhou et al. (2010). Table 2 lists the hydrologic parameters assigned to each model layer by the permit applicant. The same compressibility values were used in the independent assessment model.

STOMP Syntax Box- Model Rock properties – Porosity & Grain density & Compressibility

```
~Mechanical Properties Card
Mtsim1,2651.1,kg/m^3,0.1157,0.1157,Pore Compressibility,3.71E-10,1/Pa,,,Millington and Quirk,
Mtsim2,2651.1,kg/m^3,0.1157,0.1157,Pore Compressibility,3.71E-10,1/Pa,,,Millington and Quirk,
# Grain density, unit, total porosity, diffusive porosity, compressibility, unit,,, Tortuosity function,
```

### 2.2.5 Relative Permeability-Saturation-Capillary Pressure (k-s-p) functions

To obtain parameter values for capillary pressure and saturation functions, the FutureGen Alliance used the data for the Manlove Hazen well where they plotted these aqueous saturation and capillary pressure values and performed a user-defined curve fitting to generate Brooks-Corey parameters for four different permeabilities (Figure 7). Then they assigned these parameters to layers based on a permeability range as shown in Table 4.

The Brooks-Corey (1964) saturation function is given as:

$$S_{ew} = \begin{cases} (P_e / P_c)^{\lambda} & if \quad P_c > P_e \\ 1 & otherwise \end{cases}$$

where $S_{ew}$ is effective aqueous saturation, $P_c$ is capillary pressure, $P_e$ is gas entry pressure, and $\lambda$ is the pore-size distribution parameter. Combined with the Burdine (1953) relative permeability model, the relative permeability for the aqueous phase, $k_{rw}$, and that for the non-aqueous phase, $k_{rn}$, are:

$$K_{rw} = (S_{ew})^{3+2/\lambda}$$

$$K_{rn} = (1 - S_{ew})^2 (1 - S_{ew}{}^{1+2/\lambda})$$

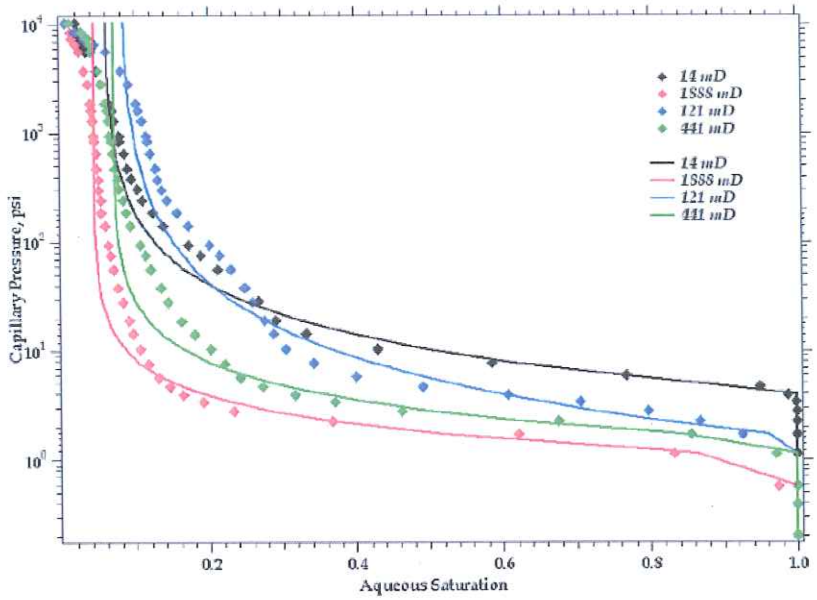



**Figure 7. Aqueous Saturation Versus Capillary Pressure Based on Mercury Injection Data from the Hazen No. 5 Well at the Manlove Gas Field in Champaign County, Illinois**

**Table 4. Summary of Values Applied to Model Layers for Saturation Function and Relative Permeability Function Parameters**

| Zone Name | Gas Entry (m) | Lambda | Residual Water Saturation (-) | Max. Trapped Gas Saturation (-) |
|---|---|---|---|---|
| Franconia | 234.426 | 0.8311 | 0.0597 | 0.2 |
| Davis-Ironton3 | 11.968 | 0.8311 | 0.0597 | 0.2 |
| Davis-Ironton2 | 11.968 | 0.8311 | 0.0597 | 0.2 |
| Davis-Ironton1 | 1.938 | 0.8311 | 0.0597 | 0.2 |
| Ironton-Galesville4 | 1.076 | 0.8311 | 0.0597 | 0.2 |
| Ironton-Galesville3 | 1.076 | 0.8311 | 0.0597 | 0.2 |
| Ironton-Galesville2 | 1.076 | 0.8311 | 0.0597 | 0.2 |
| Ironton-Galesville1 | 1.076 | 0.8311 | 0.0597 | 0.2 |
| Proviso5 | 47.748 | 0.8311 | 0.0597 | 0.2 |
| Proviso4 | 27.637 | 0.8311 | 0.0597 | 0.2 |
| Proviso3 | 9.291 | 0.8311 | 0.0597 | 0.2 |
| Proviso2 | 8.462 | 0.8311 | 0.0597 | 0.2 |
| Proviso1 | 47.269 | 0.8311 | 0.0597 | 0.2 |
| Lombard14 | 61.968 | 0.8311 | 0.0597 | 0.2 |
| Lombard13 | 8.793 | 0.8311 | 0.0597 | 0.2 |
| Lombard12 | 8.793 | 0.8311 | 0.0597 | 0.2 |
| Lombard11 | 2.096 | 0.8311 | 0.0597 | 0.2 |
| Lombard10 | 1.755 | 0.8311 | 0.0597 | 0.2 |
| Lombard9 | 22.494 | 0.8311 | 0.0597 | 0.2 |
| Lombard8 | 7.858 | 0.8311 | 0.0597 | 0.2 |
| Lombard7 | 1.067 | 0.6215 | 0.0810 | 0.2 |
| Lombard6 | 1.905 | 0.8311 | 0.0597 | 0.2 |
| Lombard5 | 0.576 | 1.1663 | 0.0708 | 0.2 |
| Lombard4 | 14.538 | 0.8311 | 0.0597 | 0.2 |
| Lombard3 | 2.619 | 0.8311 | 0.0597 | 0.2 |
| Lombard2 | 5.594 | 0.8311 | 0.0597 | 0.2 |
| Lombard1 | 3.792 | 0.8311 | 0.0597 | 0.2 |
| Elmhurst7 | 1.182 | 0.8311 | 0.0597 | 0.2 |
| Elmhurst6 | 0.525 | 0.6215 | 0.0810 | 0.2 |
| Elmhurst5 | 3.718 | 0.8311 | 0.0597 | 0.2 |
| Elmhurst4 | 1.991 | 0.8311 | 0.0597 | 0.2 |
| Elmhurst3 | 5.090 | 0.8311 | 0.0597 | 0.2 |
| Elmhurst2 | 1.284 | 0.8311 | 0.0597 | 0.2 |
| Elmhurst1 | 7.064 | 0.8311 | 0.0597 | 0.2 |
| MtSimon17 | 1.732 | 0.8311 | 0.0597 | 0.2 |
| MtSimon16 | 6.447 | 0.8311 | 0.0597 | 0.2 |
| MtSimon15 | 1.975 | 0.8311 | 0.0597 | 0.2 |

| Zone Name | Gas Entry (m) | Lambda | Residual Water Saturation (-) | Max. Trapped Gas Saturation (-) |
|---|---|---|---|---|
| MtSimon14 | 3.236 | 0.8311 | 0.0597 | 0.2 |
| MtSimon13 | 1.941 | 0.8311 | 0.0597 | 0.2 |
| MtSimon12 | 1.298 | 0.8311 | 0.0597 | 0.2 |
| MtSimon11 | 0.434 | 1.1663 | 0.0708 | 0.2 |
| MtSimon10 | 1.362 | 0.8311 | 0.0597 | 0.2 |
| MtSimon9 | 1.362 | 0.8311 | 0.0597 | 0.2 |
| MtSimon8 | 1.171 | 0.8311 | 0.0597 | 0.2 |
| MtSimon7 | 1.803 | 0.8311 | 0.0597 | 0.2 |
| MtSimon6 | 2.664 | 0.8311 | 0.0597 | 0.2 |
| MtSimon5 | 11.015 | 0.8311 | 0.0597 | 0.2 |
| MtSimon4 | 11.015 | 0.8311 | 0.0597 | 0.2 |
| MtSimon3 | 1.419 | 0.8311 | 0.0597 | 0.2 |
| MtSimon2 | 2.439 | 0.8311 | 0.0597 | 0.2 |
| MtSimon1 | 2.439 | 0.8311 | 0.0597 | 0.2 |

The permit applicant obtained values for the residual aqueous saturation ($S_{rw}$) and the two other parameters used in the Brooks-Corey capillary pressure-saturation function (i.e., the non-wetting fluid entry pressure and a pore-size distribution parameter) by fitting mercury (Hg) intrusion-capillary pressure data from the Manlove gas storage site in Champaign County. The same values applied to model layers for saturation function and relative permeability function parameters applied in the independent assessment model.

### 2.3 Operational Information

The permit applicant proposed to inject $CO_2$ into four lateral wells with a well-bore radius of 4.5 in. with the lateral leg of each well being located within the best layer of the injection zone to maximize injectivity. Figure 8 shows the proposed well design for the refined area of the model domain in both plan and 3D view. The coordinates of the screened portion of the injection wells and the $CO_2$ mass injection rate distributed among the four injection wells are shown in Table 5 and Table 6 for a total injection rate of 1.1 MMT/yr for 20 years. The FutureGen Alliance assigned a maximum injection pressure of 2,252.3 psi at the top of the open interval (depth of 3,850 ft bgs), based on 90 percent of the fracture gradient (0.65 psi/ft) 0.585 psi/ft. Final representative case simulations were executed for a period of 100 years. The same operational parameters were used in the independent assessment model.

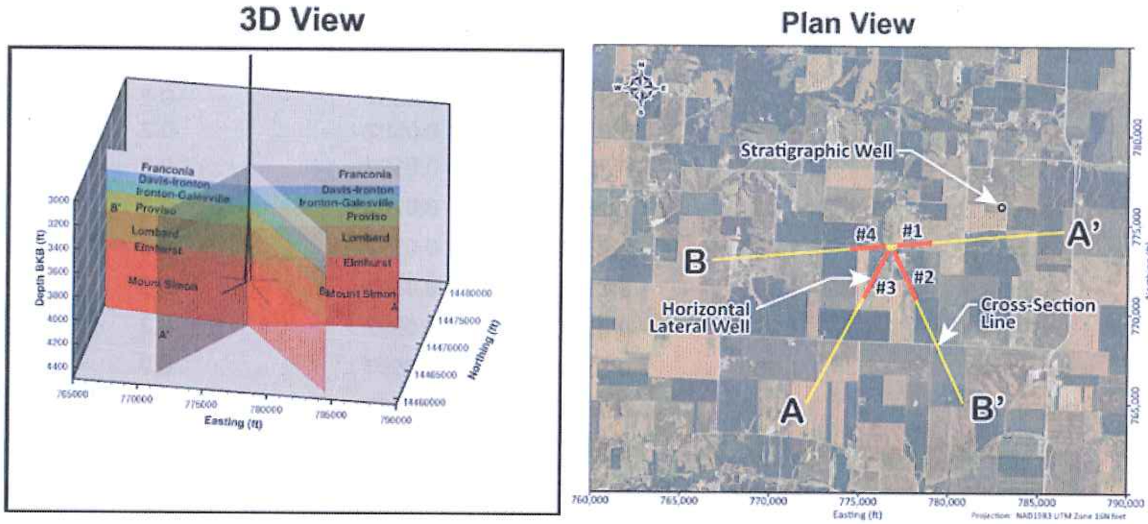



**Figure 8. Operational Well Design for Representative Case Scenario as Implemented by Permit Applicant (with the lateral legs of the injection wells shown in red and the cross section lines shown in yellow)**

**Table 5. The Coordinates of the Screened Portion of the Injection Wells**

| | X (ft) | Y (ft) | Z (ft) |
|---|---|---|---|
| Well #1 | 777079.4 | 14468884.5 | -3220 |
| | 777263.1 | 14468900.6 | -3330 |
| | 777591.8 | 14468929.3 | -3387 |
| | 779086.1 | 14469060.1 | -3394 |
| Well #2 | 776898.4 | 14468571.0 | -3220 |
| | 776976.3 | 14468403.8 | -3330 |
| | 777115.8 | 14468104.8 | -3388 |
| | 778172.3 | 14465839.0 | -3396 |
| Well #3 | 776616.8 | 14468578.4 | -3220 |
| | 776530.3 | 14468415.5 | -3330 |
| | 776375.3 | 14468124.2 | -3382 |
| | 775201.6 | 14465916.8 | -3377 |
| Well #4 | 776450.6 | 14468829.5 | -3220 |
| | 776266.9 | 14468813.4 | -3330 |
| | 775938.2 | 14468784.7 | -3377 |
| | 774443.9 | 14468653.9 | -3368 |

**Table 6. Mass Rate of $CO_2$ Injection for Each of the Four Lateral Injection Wells**

| Well | Length Lateral Leg (ft) | Mass Rate of $CO_2$ Injection Wells (MMT/yr) |
|---|---|---|
| Injection well #1 | 1500 | 0.2063 |
| Injection well #2 | 2500 | 0.3541 |
| Injection well #3 | 2500 | 0.3541 |
| Injection well #4 | 1500 | 0.1856 |

STOMP Syntax Box- Injection Well Operating Conditions

```
~Coupled Well Card,
4,                    # Number of coupled wells
CO2 Injection Well,Water Relative Saturation,1.0,1.0,1.0,4.126,MMT,  # Coupled well type, Water-vapor option, X-
# Y- Z- direction well fraction factor, Total mass injection limit, unit
2,                    # Number of well intervals
777079.4,ft,14468884.5,ft,-3220,ft,777263.1,ft,14468900.6,ft,-3330,ft,9.0,in,0.0,screened,  # First X- Y- Z-
# transition  point, unit, First X- Y- Z-  transition  point, unit, Interval skin factor, Interval skin option
777591.8,ft,14468929.3,ft,-3387,ft,779086.1,ft,14469060.1,ft,-3394,ft,9.0,in,0.0,screened,
2,                    # Number of well time points
0,yr,0.2063,MMT/yr,2252.3,psi,0.0,    # Well time., unit, Injection rate, unit, Maximum well-top pressure, unit
20,yr,0.2063,MMT/yr,2252.3,psi,0.0,
...
```

### 2.4 Initial Conditions

The permit applicant assumed that the reservoir is initially under hydrostatic conditions with no regional or local flow conditions. Thus, the hydrologic flow system was considered to be at steady state until the start of injection. FutureGen Alliance used the hydrostatic option, specifying pressure, temperature, and salinity at a reference depth, to assign initial conditions. A summary of the initial conditions is presented in Table 7. Reference depths presented in Table 7 show depth below KB whereas all z-coordinate values submitted in STOMP represent elevations relative to mean sea level, so reference depths in Table 6 were converted to elevation. The same initial conditions were applied in the independent assessment model.

**Table 7. Summary of Initial Conditions**

| Parameter | Reference Depth (bkb) | Value |
|---|---|---|
| Reservoir Pressure | 4048 ft | 1790.2 |
| Aqueous Saturation | | 1.0 |
| Reservoir Temperature | 3918 ft | 96.6 °F |
| Temperature Gradient | | 0.00672 °F/ft |
| Salinity | | 47500 ppm |

STOMP Syntax Box- Initial Conditions

```
~Initial Conditions Card
Hydrostatic,1790.2,psi,-3415,ft,96.6,F,-3285,ft,-0.00672,F/ft,0.0475,-3415,ft,0,1/ft,
# Pressure, unit, Z- elevation, unit, Temperature, unit, Z- elevation, unit, Salt mass fraction, Unit, Z-direction salt
#mass fraction gradient, unit
```

### 2.5 Boundary Conditions

The permit applicant assigned a no-flow boundary for aqueous fluids and the $CO_2$-rich phase to the top and bottom boundaries of the model. The lateral and top boundary conditions were set to hydrostatic pressure using the initial conditions with the assumption that each of these boundaries is distant enough from the injection zone to have minimal to no effect on the $CO_2$ plume migration and pressure distribution. The same boundary conditions were selected for EPA's independent assessment model.

STOMP Syntax Box- Boundary Conditions

```
~Boundary Conditions Card
5,                  # Number of boundary condition domains
West,Aqu Initial Condition,Gas Initial Condition,Initial Condition,   #Boundary surface direction option, Aqueous-
#gas- salt phase boundary type option
1,1,1,125,1,51,1,  # I-start, I-end Index, J-start, J-end Index, K-start, K-end Index, number of boundary times
0,s,,,,,,,,,        # boundary time, unit, Aqueous pressure, unit,
East,Aqu Initial Condition,Gas Initial Condition,Initial Condition,
125,125,1,125,1,51,1,
0,s,,,,,,,,,
North,Aqu Initial Condition,Gas Initial Condition,Initial Condition,
1,125,125,125,1,51,1,
0,s,,,,,,,,,
South,Aqu Initial Condition,Gas Initial Condition,Initial Condition,
1,125,1,1,1,51,1,
0,s,,,,,,,,,
top,Aqu Initial Condition,Gas Initial Condition,Initial Condition,
1,125,1,125,51,51,1,
0,s,,,,,,,,,
```

### 2. 6 Model Outputs

Figures 9 and 10 show pressure differential relative to the initial formation pressure at the injection well at different times as submitted by the permit applicant and generated by the independent assessment model, respectively. The assessment model results are in close agreement with those of the permit applicant.

Figures 11 and 12 shows the mass of injected $CO_2$ over time submitted by permit applicant and generated by the independent assessment model. These Figures show that:

- The Integrated Mass of the Injected $CO_2$ predicted by the assessment model is generally consistent with the permit applicant's results;
- The Integrated trapped $CO_2$ gas predicted by the permit applicant indicates, relatively, higher entrapment than the results of the assessment model;
- However, the total $CO_2$ and $CO_2$-rich phase values predicted by both models, considered to be the two most important parameters affecting the AoR delineation, are in good agreement;
- The injection rate of 1.1 MMT/yr can be attained with the four lateral injection wells; and

- Residual trapping begins once injection ceases, resulting in about 15 and 10 percent of the total $CO_2$ mass being immobilized, in the applicant and independent models, respectively, at the end of 100 years.

The injection pressure at each of the four wells is shown in Figures 13 and 14. Injection pressure is reported at the top of the open interval and once injection ceases reflects the formation pressure at the node within which the well is located. The results were in good agreement.

Figures 15 and 16 show the plume area over time as submitted by permit applicant and generated by the independent assessment model, respectively. The assessment model results are in close agreement with those submitted by the permit applicant.

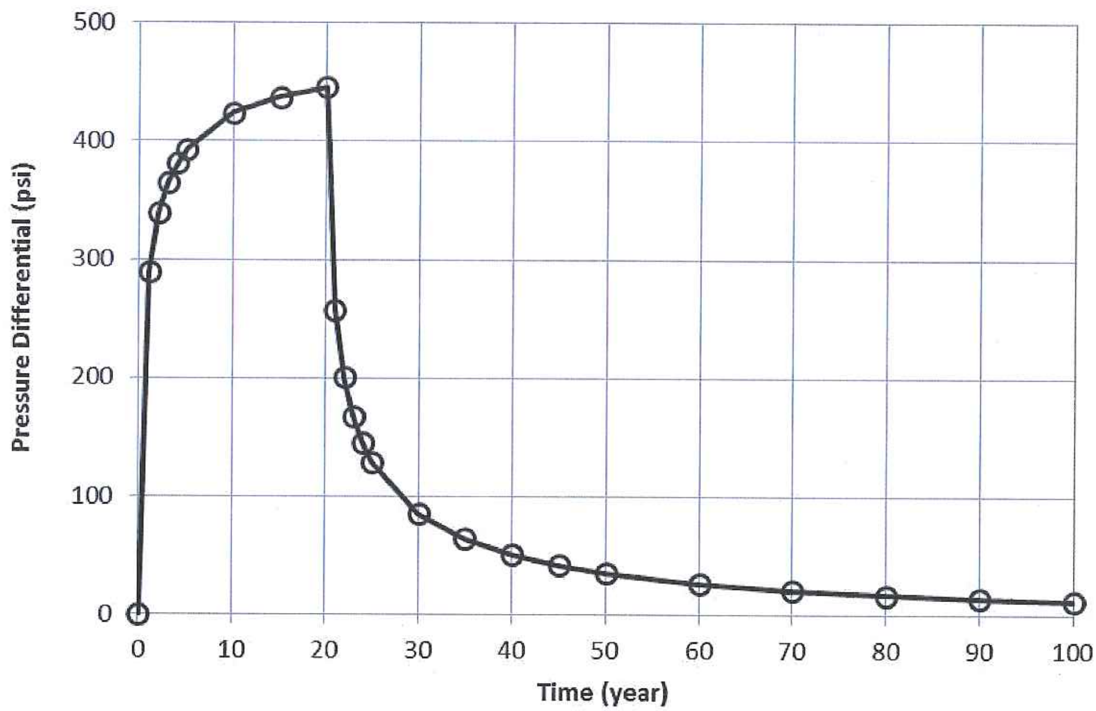



**Figure 9. Pressure Differential (relative to initial formation pressure) Versus Time at the Injection Well, Submitted by FutureGen**

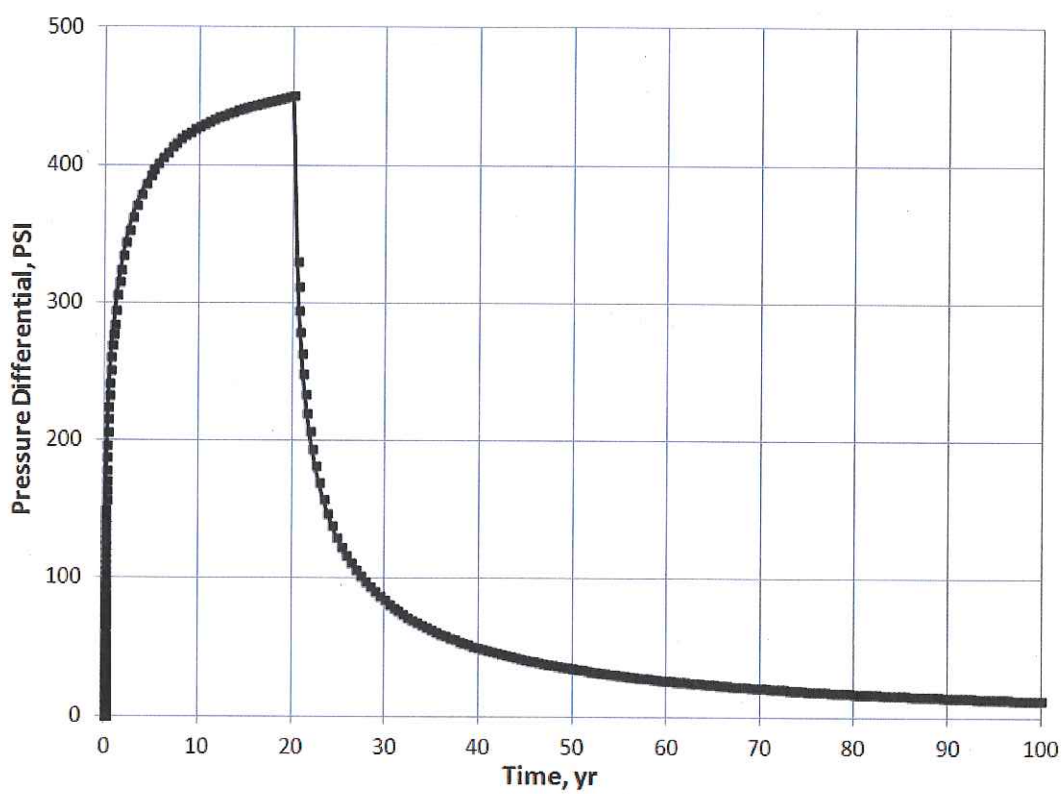



**Figure 10. Pressure Differential (relative to initial formation pressure) Versus Time at the Injection Well, Generated by the Independent Assessment Model**

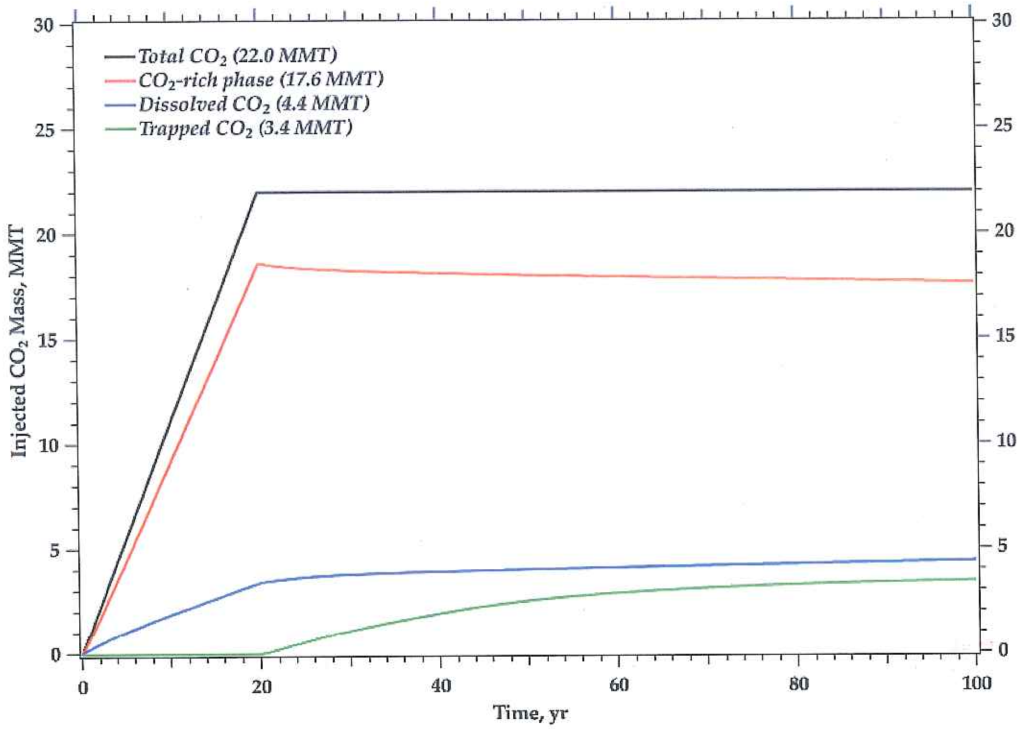



**Figure 11. Mass of Injected $CO_2$ over Time Integrated over the Entire Model Domain, Submitted by FutureGen**

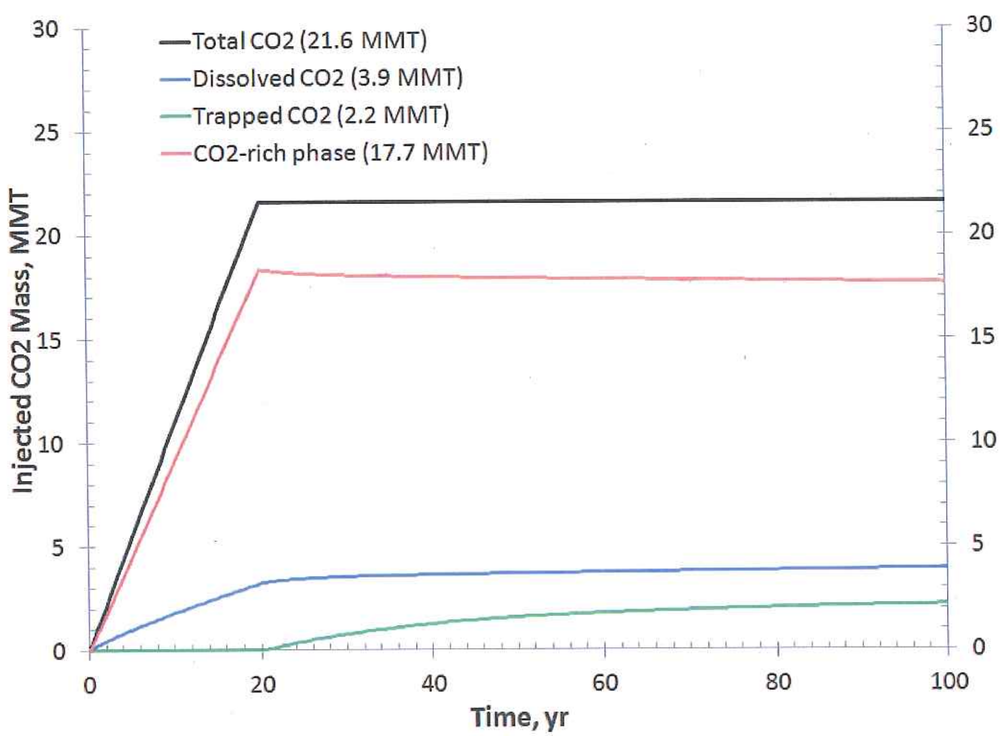



**Figure 12. Integrated Mass of Injected $CO_2$ over Time at the Injection Well, Generated by the Independent Assessment Model**

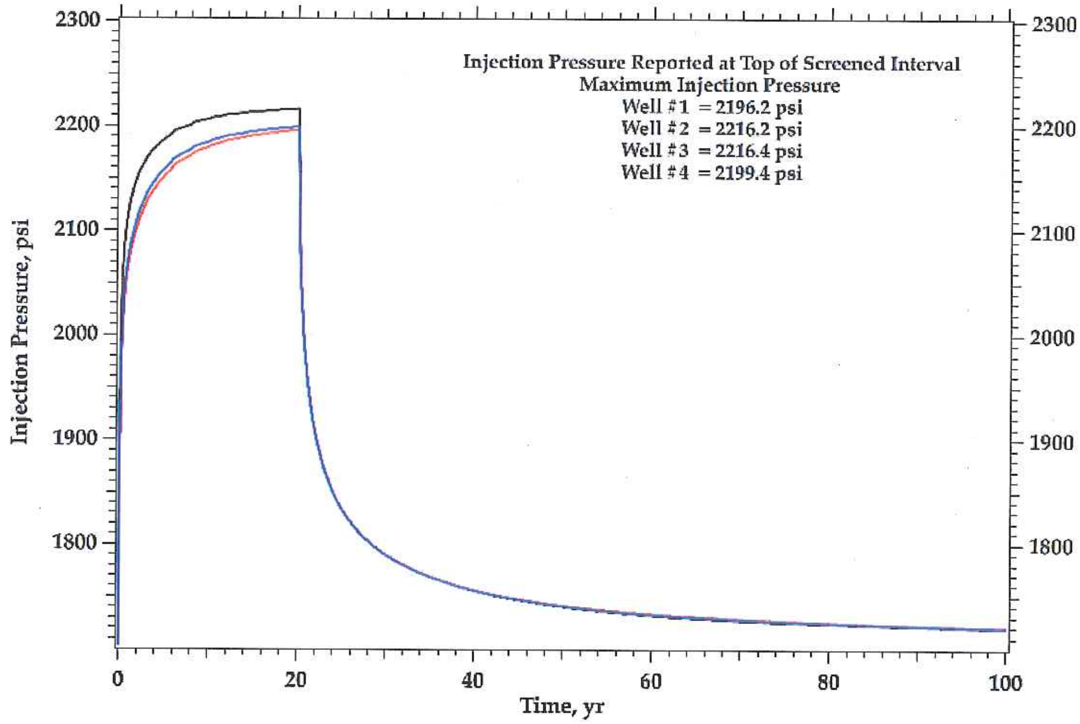



**Figure 13. Injection Pressure Versus Time for All Four Injection Wells, Submitted by FutureGen**

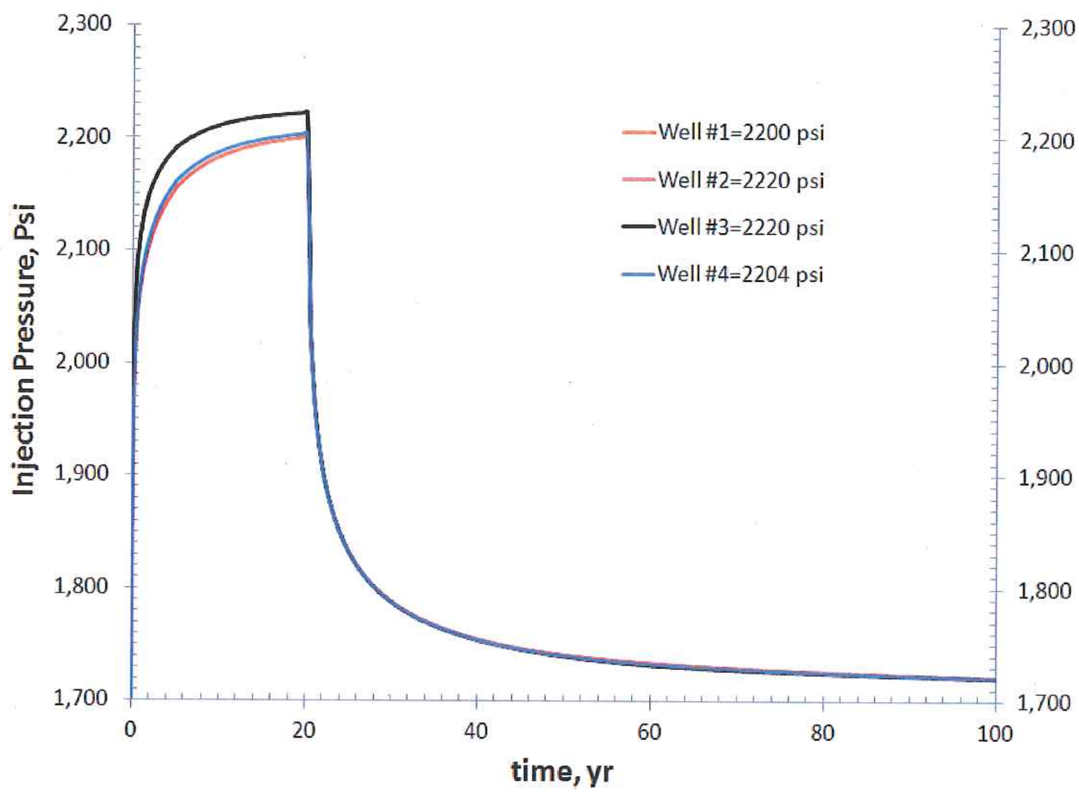



**Figure 14. Injection Pressure versus time for All Four Injection Wells, Generated by the Independent Assessment Model**

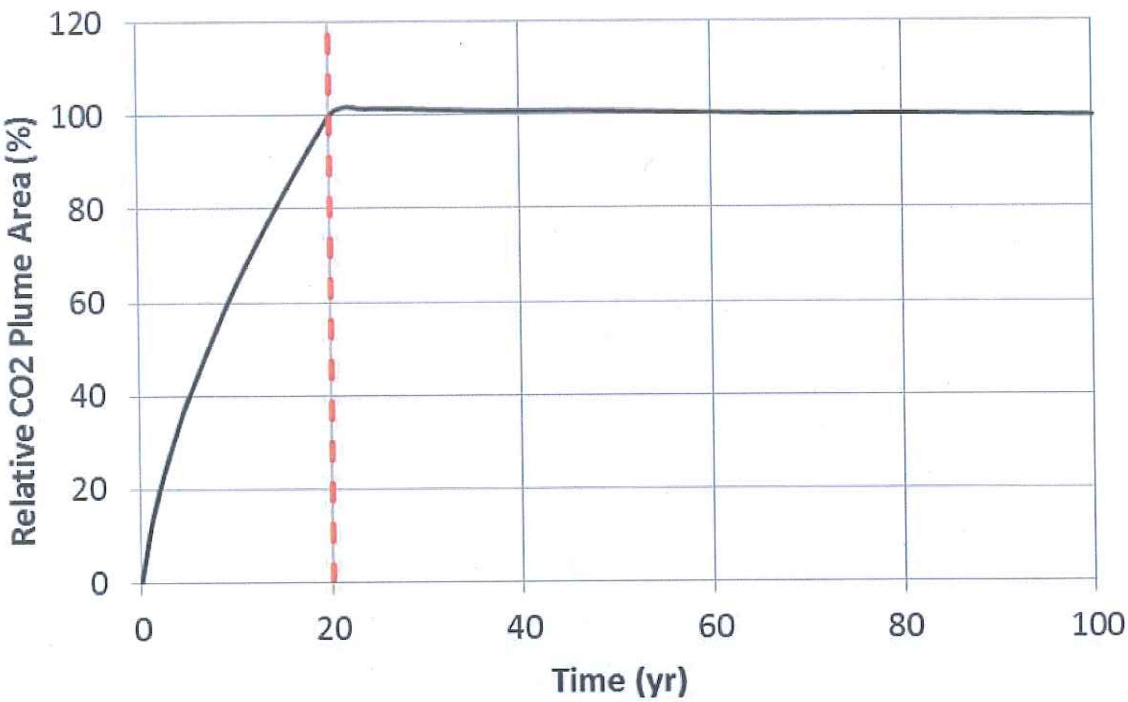



**Figure 15. $CO_2$ plume Versus Time Relative to Plume extent at End of Injection Period (20 years), Submitted by FutureGen**

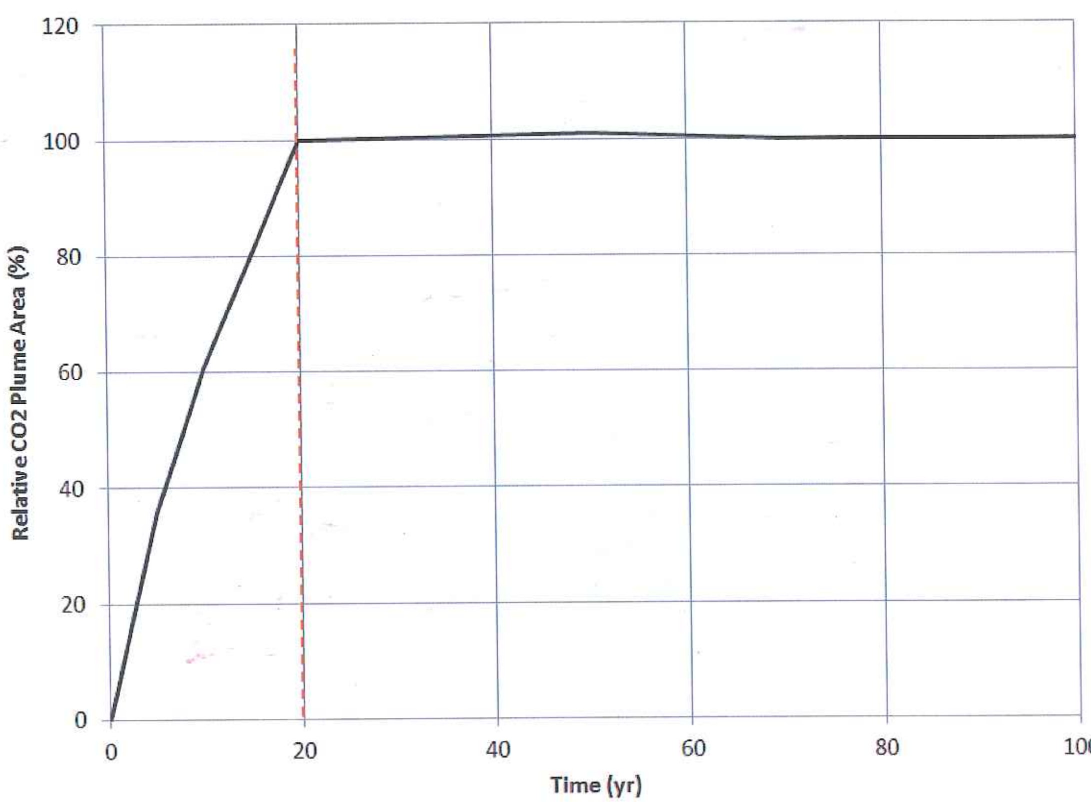



**Figure 16. $CO_2$ plume Versus Time Relative to Plume extent at End of Injection Period (20 years), Generated by the Independent Assessment Model**

The $CO_2$-rich phase saturation contours submitted by the permit applicant and generated by the independent assessment model are presented for selected time planes in Figure 17 and 18. The $CO_2$ plumes at different times are similar in both Figures and form a cloverleaf pattern as a result of the four lateral injection-well design. The results submitted by FutureGen and generated by the independent assessment model are in good agreement.

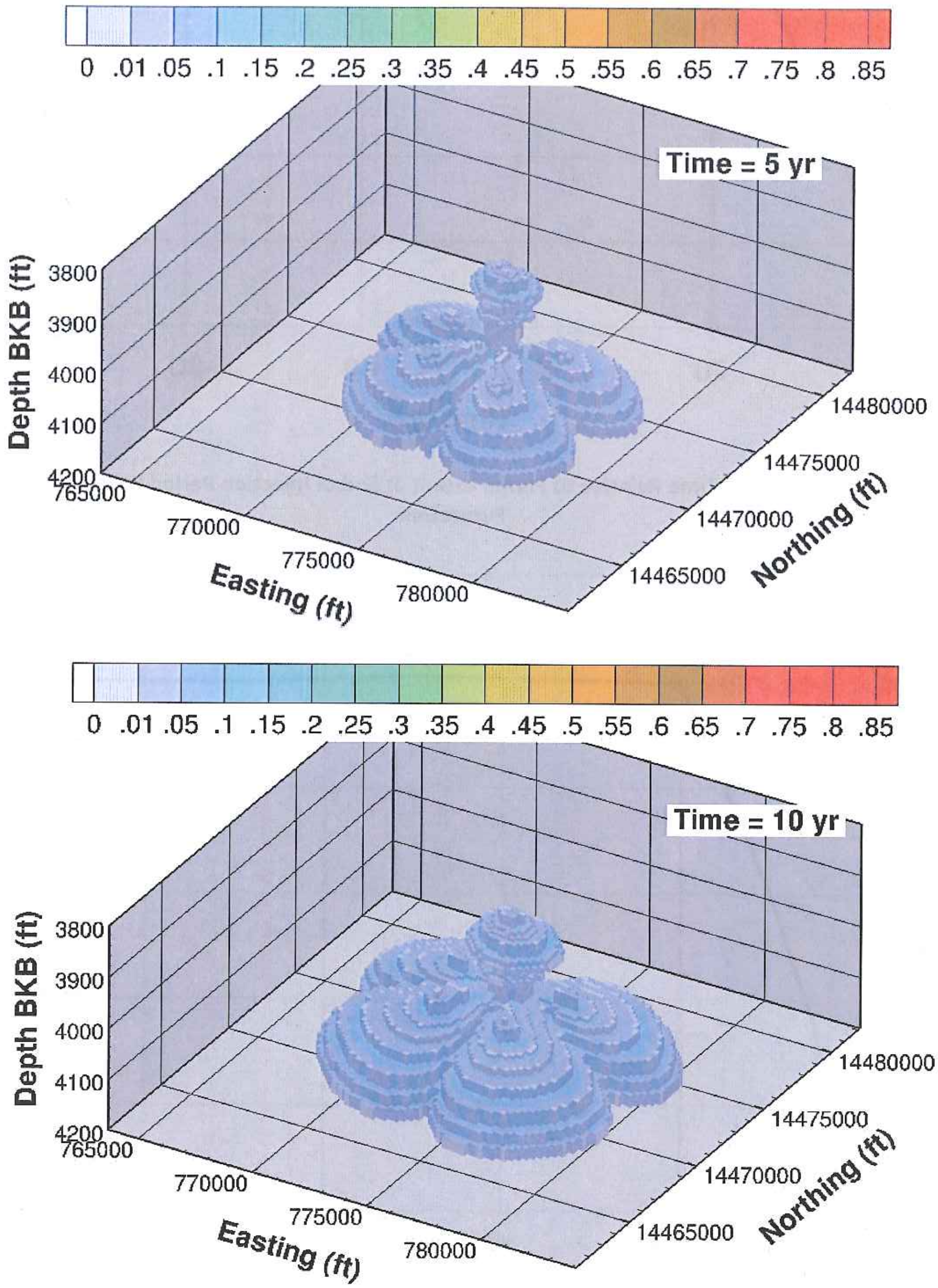



**Figure 17. $CO_2$-Rich Phase Saturation Shown at Selected Times (5 Years, 10 Years, 20 Years, and 70 Years), Submitted by FutureGen**

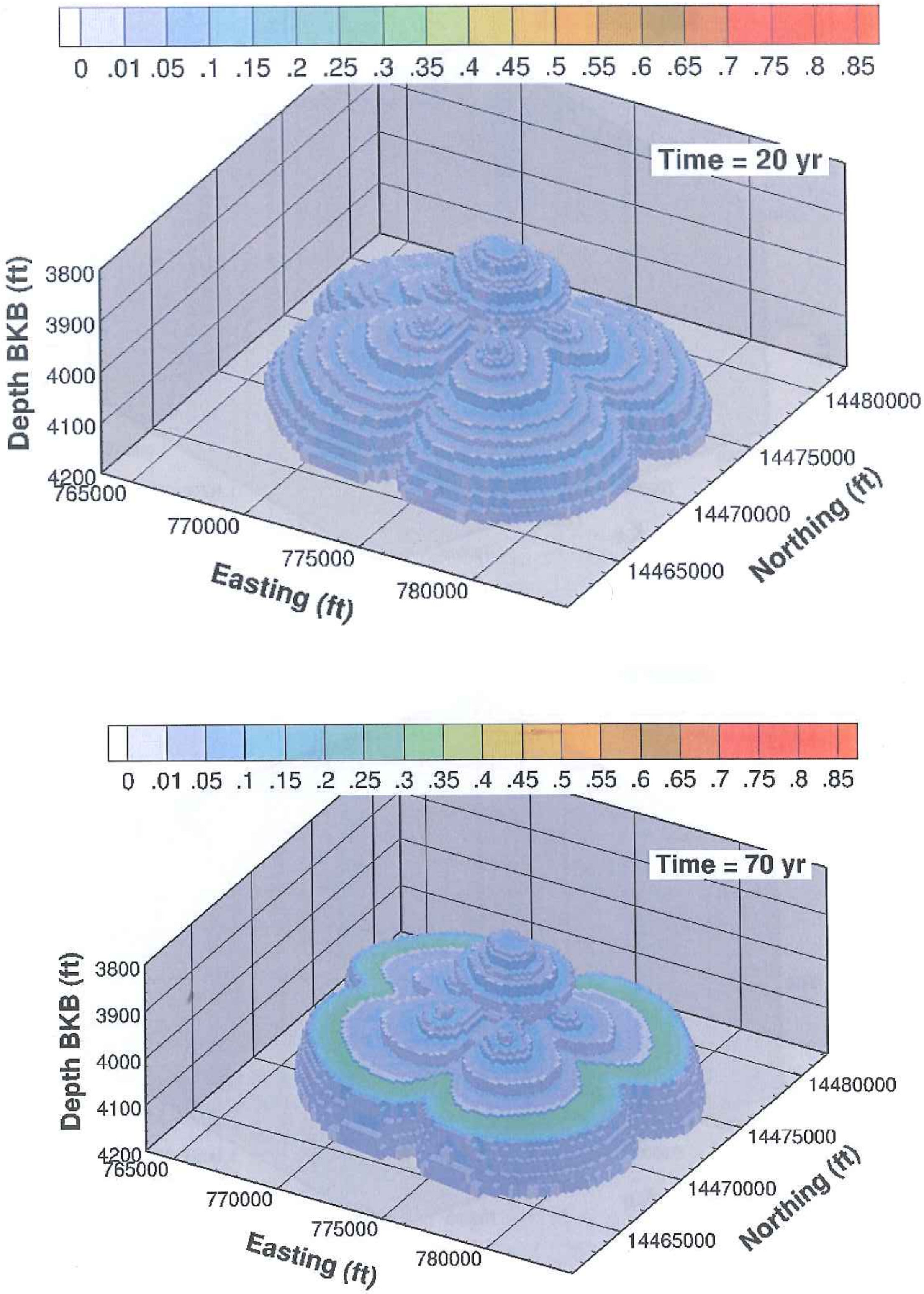
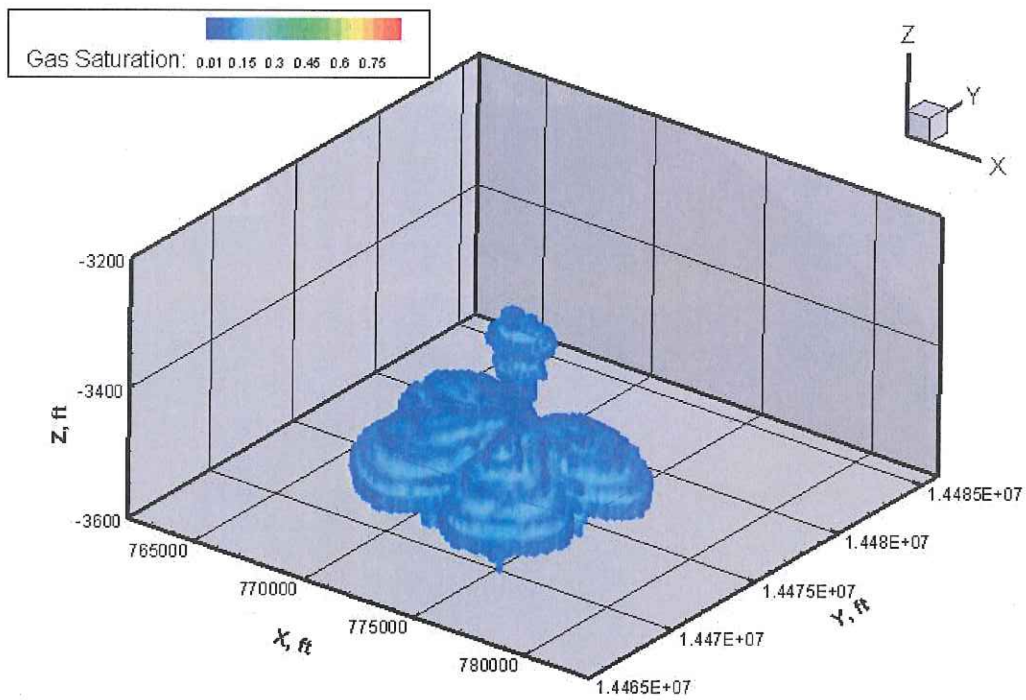
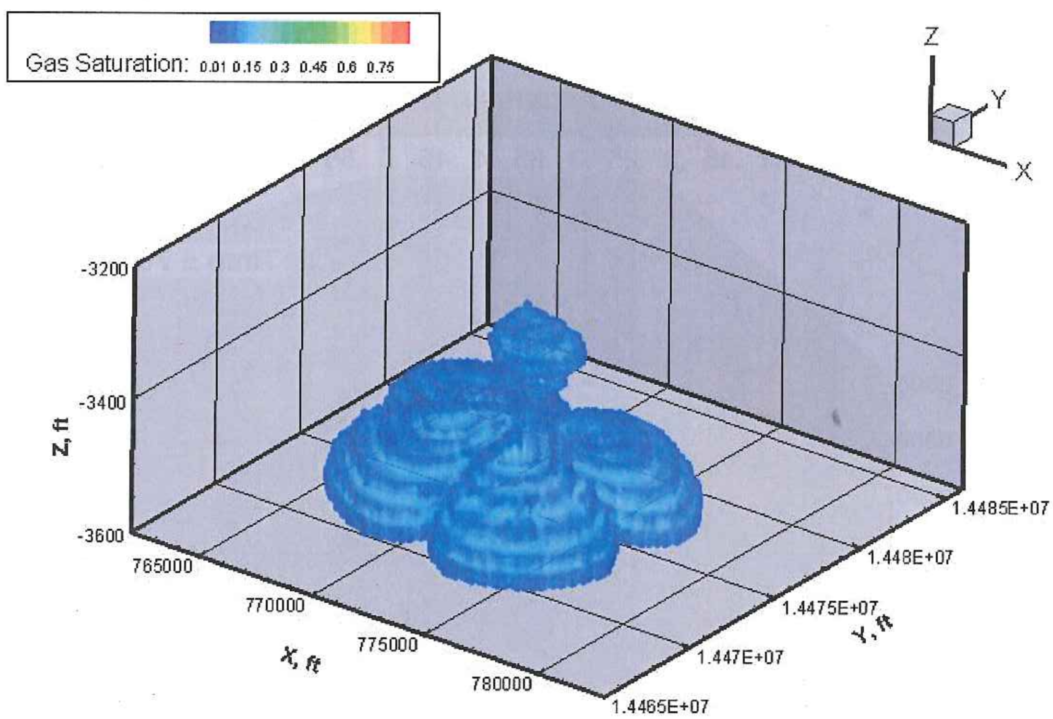



**Figure 17.** (Contd)

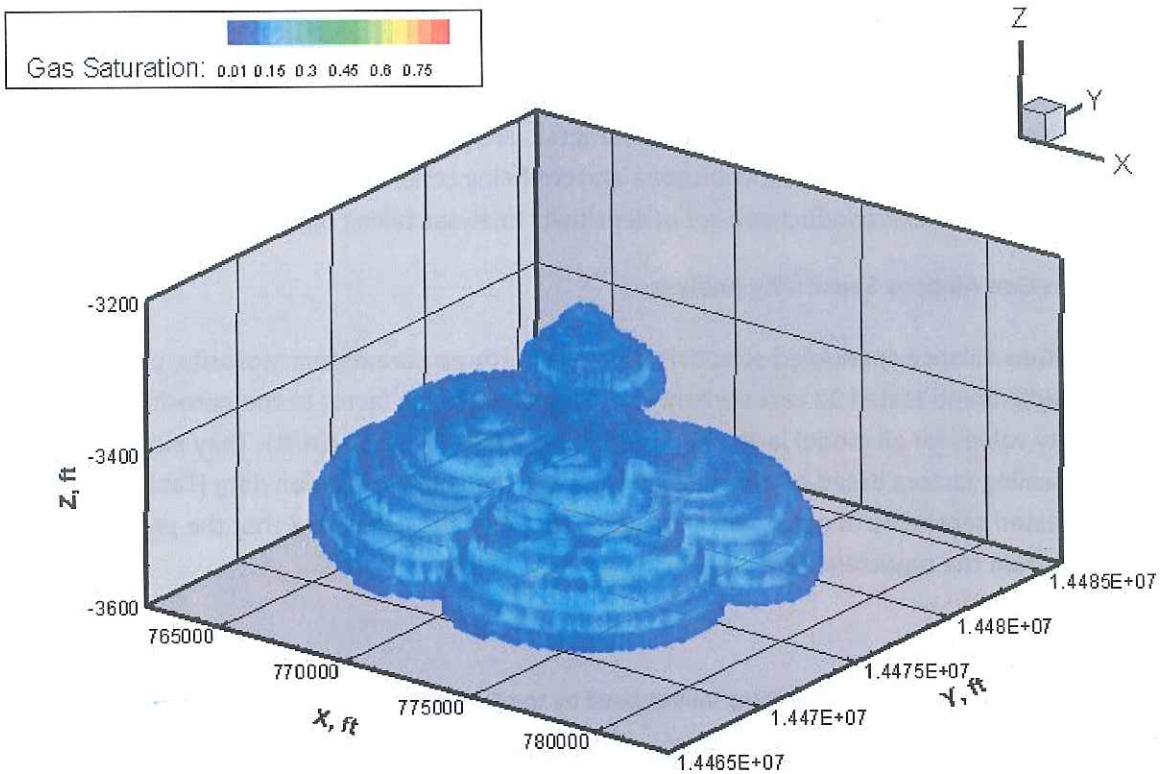



Time=5 yr

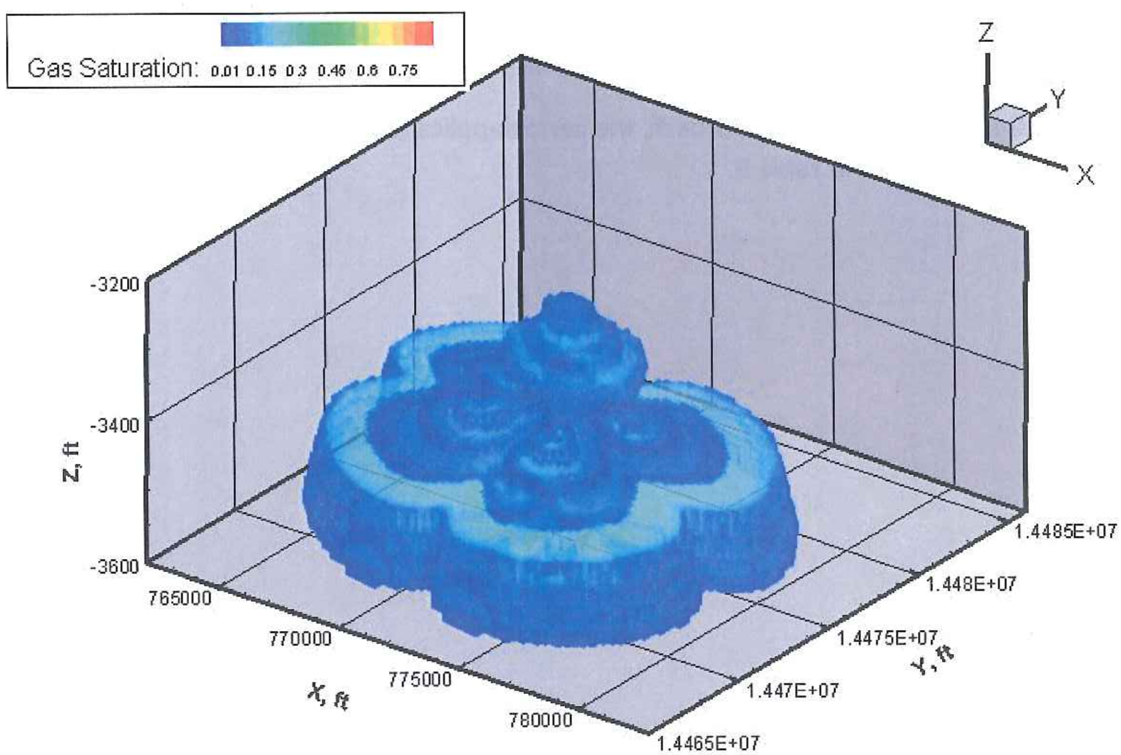



Time=10 yr

**Figure 18. $CO_2$-Rich Phase Saturation Shown at Selected Times (5 Years, 10 Years, 20 Years, and 70 Years), Generated by the Independent Assessment Model**




Time=20 yr




Time=70 yr

**Figure 18.** (Contd)

### 2.6 Sensitivity Analyses

Modeling underground $CO_2$ storage involves many conceptual and quantitative uncertainties. Additionally, limited site characterization data at the project site increases input parameter uncertainties. The principal uncertain input parameters are permeability, porosity, fracture gradient and residual water saturation of the injection zone and confining zone. To address these uncertainties, the permit applicant and EPA conducted a set of sensitivity analyses taking different approaches.

#### 2.6.1 FutureGen Alliance Sensitivity Analyses

The FutureGen Alliance conducted sensitivity analysis for three parameters: porosity, permeability, and fracture gradient and tested 32 cases where they applied a scaling factor to the porosity and permeability values for all model layers and to fracture gradient (0.585 psi/ft). They picked the bounding values for scaling factors based on the evaluation of the site characterization data (Table 8). The permit applicant tested sensitivity of results to selected parameters and concluded that the predicted plume area varied from the representative case by about 80 to 120%.

**Table 8. Scaling Factors Bounding Values Used by the FutureGen Alliance for Sensitivity Analysis**

| Parameter | Minimum | Representative Case | Maximum |
|---|---|---|---|
| Porosity | 0.75 | 1 | 1.25 |
| Permeability | 0.75 | 1 | 1.25 |
| Fracture Gradient | 0.88 | 1 | 1.10 |

Using a quasi-Monte Carlo (QMC) approach, the permit applicant developed 32 cases for sensitivity analyses which are shown in Table 9.

**Table 9. The Scaling Factor for Porosity, Permeability, and Fracture Gradient for 32 Cases**

| Case | Porosity | Permeability | Fracture |
|---|---|---|---|
| 1 | 1.2439 | 1.1327 | 0.9262 |
| 2 | 0.7521 | 0.9805 | 1.0086 |
| 3 | 0.9187 | 1.1471 | 1.0819 |
| 4 | 1.0854 | 0.8138 | 0.9352 |
| 5 | 0.8076 | 1.2027 | 0.8863 |
| 6 | 0.9743 | 0.8694 | 0.9597 |
| 7 | 1.1410 | 1.0360 | 1.0330 |
| 8 | 0.8632 | 0.7582 | 1.0575 |
| 9 | 1.0299 | 0.9249 | 0.9108 |
| 10 | 1.1965 | 1.0916 | 0.9841 |
| 11 | 0.7706 | 1.1101 | 1.0412 |
| 12 | 0.9373 | 0.7768 | 0.8945 |
| 13 | 1.1039 | 0.9434 | 0.9678 |
| 14 | 0.8262 | 0.8323 | 0.9923 |
| 15 | 0.9928 | 0.9990 | 1.0656 |
| 16 | 1.1595 | 1.1657 | 0.9189 |
| 17 | 0.8817 | 1.0546 | 0.9434 |
| 18 | 1.0484 | 1.2212 | 1.0167 |
| 19 | 1.2150 | 0.8879 | 1.0900 |
| 20 | 0.7891 | 0.9064 | 0.9271 |
| 21 | 0.9558 | 1.0731 | 1.0004 |
| 22 | 1.1225 | 1.2397 | 1.0738 |
| 23 | 0.8447 | 0.9620 | 1.0982 |
| 24 | 1.0113 | 1.1286 | 0.9515 |
| 25 | 1.1780 | 0.7953 | 1.0248 |
| 26 | 0.9002 | 1.1842 | 0.9760 |
| 27 | 1.0669 | 0.8508 | 1.0493 |
| 28 | 1.2336 | 1.0175 | 0.9026 |
| 29 | 0.7582 | 1.1533 | 0.9298 |
| 30 | 0.9249 | 0.8200 | 1.0031 |
| 31 | 1.0916 | 0.9867 | 1.0765 |
| 32 | 0.8138 | 0.8755 | 1.0276 |

### 2.6.2 EPA Independent Assessment Sensitivity Analyses

EPA conducted additional simulations to evaluate the effects of using different values for specific parameters (i.e., for porosity, permeability, residual water saturation and fracture pressure) on the AoR calculation and the total mass of $CO_2$ injected.

Residual water saturation values used in the FutureGen AoR model ranged from 0.0597 to 0.0810. However, residual water saturation values found in the literature for the Mt. Simon Sandstone range from approximately 0.2 to 0.4 (Zhou et al. 2010; Bandilla et al., 2012b; Krevor et al., 2012). Thus, EPA evaluated the sensitivity of the results to this parameter. Using the same scaling factor as the permit applicant for porosity, permeability, and fracture gradient and values of 0.2 and 0.4 for residual water saturation, 14 cases were tested (Table 10-a, -b, and -c). The sensitivity of selected output variables, including the mass of injected $CO_2$ (Total $CO_2$, dissolved $CO_2$, $CO_2$-rich phase, trapped $CO_2$), maximum pressure differential relative to initial formation pressure at the injection well, maximum injection pressure among the four wells, and the acreage of plume area, were analyzed and are presented in Table 11-a, -b, and -c.

**Table 10-a. Sensitivity Analysis Cases for Porosity and Permeability**

| Case | Scaling Factor | | Distribution |
|---|---|---|---|
| | Porosity | Permeability | |
| 1 | 0.75 | 0.75 | Assigned to all model layers |
| 2 | 1.25 | 1.25 | |
| 3 | 1.25 | 0.75 | |
| 4 | 0.75 | 1.25 | |
| 5 | 0.75 | 0.75 | Assigned to all model layer in the injection zone (Mt. Simon and Elmhurst) |
| 6 | 0.75 | 1.25 | |
| 7 | 0.75 | 0.75 | Assigned to all model layer above the injection zone (Lombard, Proviso, Ironton, Franconia) |
| 8 | 1.25 | 1.25 | |
| 9 | 1.25 | 0.75 | |
| 10 | 0.75 | 1.25 | |

**Table 10-b. Sensitivity Analysis Cases for Fracture Pressure**

| Case | Scaling Factor-Fracture Pressure (maximum injection pressure) |
|---|---|
| 11 | 0.88 |
| 12 | 1.1 |

**Table 10-c. Sensitivity Analysis Cases for Fracture Pressure**

| Case | Residual water saturation for all model layers |
|---|---|
| 13 | 0.2 |
| 14 | 0.4 |

**Table 11-a. Output Results of Sensitivity Analysis for Porosity ( $\phi$ ) and Permeability ($k$) for Important Cases**

| Output Parameters | Case1 -25% $\phi$ -25% $K$ All layers | Case2 +25% $\phi$ +25% $K$ All layers | Case3 +25% $\phi$ -25% $K$ All layers | Case4 -25% $\phi$ +25% $K$ All layers | Case5 -25% $\phi$ -25% $K$ Inj. layers | Case6 -25% $\phi$ +25% $K$ Inj. layers | Case7 -25% $\phi$ -25% $K$ Top layers | Case8 +25% $\phi$ +25% $K$ Top layers | Case9 +25% $\phi$ -25% $K$ Top layers | Case10 -25% $\phi$ +25% $K$ Top layers | Base |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Injected $CO_2$ (MMT) | 18.3 | 21.6 | 18.9 | 21.6 | 19.2 | 21.6 | 21.6 | 21.6 | 21.6 | 21.6 | 21.6 |
| Tot. Dissolved $CO_2$ (MMT) | 3.2 | 4.0 | 3.7 | 3.6 | 3.4 | 3.6 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 |
| Tot. $CO_2$-rich Phase (MMT) | 15.1 | 17.6 | 15.2 | 18 | 15.8 | 18.0 | 17.7 | 17.7 | 17.7 | 17.7 | 17.7 |
| Tot. Trapped $CO_2$ (MMT) | 1.8 | 2.2 | 2.2 | 1.8 | 1.8 | 1.8 | 2.1 | 2.2 | 2.2 | 2.1 | 2.2 |
| Max. Pressure Diff. (PSI) | 484 | 370 | 475 | 381 | 475 | 390 | 474 | 465 | 465 | 437 | 450 |
| Max. Injection Pressure (PSI) | 2250 [i] | 2130 | 2250 [i] | 2140 | 2250 [i] | 2150 | 2240 | 2230 | 2230 | 2210 | 2220 |
| Plume Area ($Mi^2$)[ii] | 8.56 | | | | 8.35 | | | | | | 5.56 |

i. Maximum allowable injection pressure=2252.3 psi
ii. Plume area for critical cases are shown

**Table 11-b. Output Results of Sensitivity Analysis for Fracture Gradient**

| Output Parameters | Case11 -12% | Case12 +10% | Base |
|---|---|---|---|
| Total Injected $CO_2$ (MMT) | 11.5 | 21.6 | 21.6 |
| Tot. Dissolved $CO_2$ (MMT) | 2.2 | 3.9 | 3.9 |
| Tot. $CO_2$-rich Phase (MMT) | 9.3 | 17.7 | 17.7 |
| Tot. Trapped $CO_2$ (MMT) | 1.3 | 2.1 | 2.2 |
| Max. Pressure Diff. (PSI) | 243 | 449 | 450 |
| Max. Injection Pressure (PSI) | 1980 [i] | 2220 | 2220 |
| Plume Area ($Mi^2$) [ii] | 7.12 | | 5.56 |

i. Maximum allowable injection pressure=2252.3 psi
ii. Plume area for critical cases are shown

**Table 11-c. Output Results of Sensitivity Analysis for Residual Water Saturation ($S_{Lr}$)**

| Output Parameters | Case13 $S_{Lr}$=0.2 | Case14 $S_{Lr}$=0.4 | Base |
|---|---|---|---|
| Total Injected $CO_2$ (MMT) | 21.6 | 20.1 | 21.6 |
| Tot. Dissolved $CO_2$ (MMT) | 4.2 | 4.4 | 3.9 |
| Tot. $CO_2$-rich Phase (MMT) | 17.4 | 15.7 | 17.7 |
| Tot. Trapped $CO_2$ (MMT) | 2.1 | 2 | 2.2 |
| Max. Pressure Diff (PSI) | 463 | 456 | 450 |
| Max. Injection Pressure (PSI) | 2240 | 2250 | 2220 |
| Plume Area ($Mi^2$) [i] | | 6.96 | 5.56 |

i. Plume area for critical cases are shown

For cases where less than 100 percent of the $CO_2$ mass was injected, the projected acreage of the plume is calculated by providing a normalization of the plume area for direct comparison across cases.

The plume area at the end of the 20-year injection period, as calculated by the permit applicant and the independent assessment model were 6.35 $mi^2$ and 5.56 $mi^2$, respectively. The plume area calculated by

the permit applicant is slightly larger and, thus, more conservative. Also, both values are much smaller than the 25 $mi^2$ area FutureGen evaluated for all penetrations through the confining Zone.
The results of sensitivity analyses for porosity, permeability, fracture gradient, and residual water saturation, Cases 1-14, indicate that:

- Injectivity (i.e., the total mass of injected $CO_2$) is very sensitive to the permeability;
- Injectivity is lower in low permeable cases because formation pressure reaches the maximum allowable pressure of 2252 psi and therefore model prevents additional injection to keep the pressure less than the maximum allowable pressure;
- Decreasing both permeability and porosity values produces a larger plume area;
- Changing the parameters of porosity, permeability, fracture gradient, and residual water saturation, only in the confining layers (top layers) has a negligible impact on injectivity and plume area;
- The predicted plume area increases by about 150% from the base case in the largest plume-size scenario, (Case 1: Figures 10-a and 11-a), but it is still much smaller than 25 $mi^2$ evaluated by the permit applicant during project siting/site characterization;
- Increasing the value of residual water saturation produces a larger plume area and reduces injectivity.

## 3. AOR PRESSURE FRONT DELINEATION

To delineate the AoR, a permit applicant must use computational modeling that accounts for the physical and chemical properties of all phases of the injected carbon dioxide stream and may choose from a number of methodologies for calculating the critical pressure which is the pressure great enough to mobilize fluids up an open conduit (i.e., an artificial penetration, fault or fracture) from the injection zone into the overlying USDW.

EPA did not specify the appropriate approach or equation for determining the critical pressure and instead presented several options and equations in the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance.* EPA further acknowledged the limitations of the approaches in certain geologic settings and indicated that such geologic settings would require additional consideration and an alternative approach to defining the AoR to include both the plume and area of elevated pressure. The Agency, in the AoR Guidance at the time of finalization in 2013, anticipated that new methodologies to address over-pressured/over-pressurized scenarios (i.e., where the current/pre-injection pressure in the injection zone is already sufficient to force fluids up an artificial conduit into an overlying USDW if such a conduit existed), would be investigated, researched and published in the future as such geologic settings are given more consideration (e.g., by Nicot, Birkholzer and others).

The FutureGen Alliance's project is proposed to be sited in an overpressured geologic setting (i.e., the Mount Simon currently is at a pressure high enough to force fluids through an artificial conduit into the overlying St. Peter Sandstone-USDW). The FutureGen Alliance, in consultation with EPA, assessed a range of options that might allow them to define the "pressure footprint of their project" –including evaluating available numerical solutions and a recently developed analytical solution.

### 3.1 Analytical Solutions

FutureGen applied an analytical solution developed by Lawrence Berkeley National Laboratory (Cihan et al., 2011; 2013) which allows a prediction of pressure at various depths and an associated leakage rate resulting in an indirect determination of a pressure front. However, FutureGen applied non-conservative assumptions, including thief zones (intervening permeable formations), when employing this analytical solution the results of which yielded the conclusion of a "plume-sized AoR".

### 3.2 Numerical Solutions

In consultation with EPA, FutureGen considered the applicability of and evaluated the project using a range of numerical solutions (i.e., the calculation of a critical pressure that is then evaluated using computational modeling to indicate the pressure footprint). Methods evaluated are identified in Table 12.

**Table 12. Pressure Front Delineation Methods Evaluated**

| Approach | Results |
|---|---|
| AoR Guidance Equation 1 | Not applicable |
| Nicot (2008) | 13.76 psi |
| Birkholzer (2011) | 9.65 psi |
| LBNL Non-Conservative: Assuming thief zones | Plume-sized AoR |
| LBNL Conservative: Assuming no thief zones | Large AoR (Similar to the AoR predicted by Nicot (2008)) |

### 3.3 Analysis

EPA considered the results of all methods evaluated by the permit applicant and the results of independent assessments to inform a final determination of the AoR delineation resulting from the area of elevated pressure. Acknowledging that each approach is an approximation with a set of assumptions, that there are applicable components of a number of the approaches considered, and with a focus on adopting a conservative, protective approach for the pressure-delineated AoR, EPA considered the following:

- The critical pressure of 10 psi at 70 years (the end of the 50-year PISC period)
- The maximum extent of the 10 psi contour during the life of the project life (60 years).

In consultation with the permit applicant, EPA determined it most appropriate to use the maximum extent of the 10 psi contour during the life of the project as the AoR boundary while also acknowledging that future site characterization and operational data and advances in research and methodologies for determining the critical pressure at projects with over-pressured conditions, may be cause for re-evaluation of the Area of Review in the future.

## 4. CORRECTIVE ACTION

The FutureGen Alliance evaluated and provided information to EPA regarding the location and depth of wells within the AoR as defined by both the plume and pressure front. The permit applicant has confirmed that no wells (with the exception of the FutureGen stratigraphic test well[1]) have been identified that require corrective action. EPA has independently evaluated the well information submitted by the permit applicant and concluded that no wells within the delineated AoR require corrective action.

## 5. CONCLUSIONS

The FutureGen Alliance applied a computational modeling tool, STOMP, to delineate the AoR based on the $CO_2$ plume (and the associated pressure front). The result of their model for the representative-base case indicated a plume area of 6.35 $mi^2$ at the end of injection (20 years) and a maximum plume extent of 6.46 $mi^2$ at 22 years. Additionally, their pressure front is conservatively defined for regulatory purposes by the maximum extent of the 10 psi contour at 60 years covering an area of 1,814 $mi^2$.

EPA conducted an independent assessment model using STOMP to confirm these results and conducted sensitivity analyses for selected output parameters to address uncertainties in input parameters. EPA confirms that the pressure front as conservatively defined for regulatory purposes by the maximum extent of the 10 psi contour at 60 years and which is inclusive of the modeled plume area is appropriate for this project (Figure 19) .

[1] The FutureGen stratigraphic test well will be converted to a Single-Level In-Reservoir monitoring well for the project.

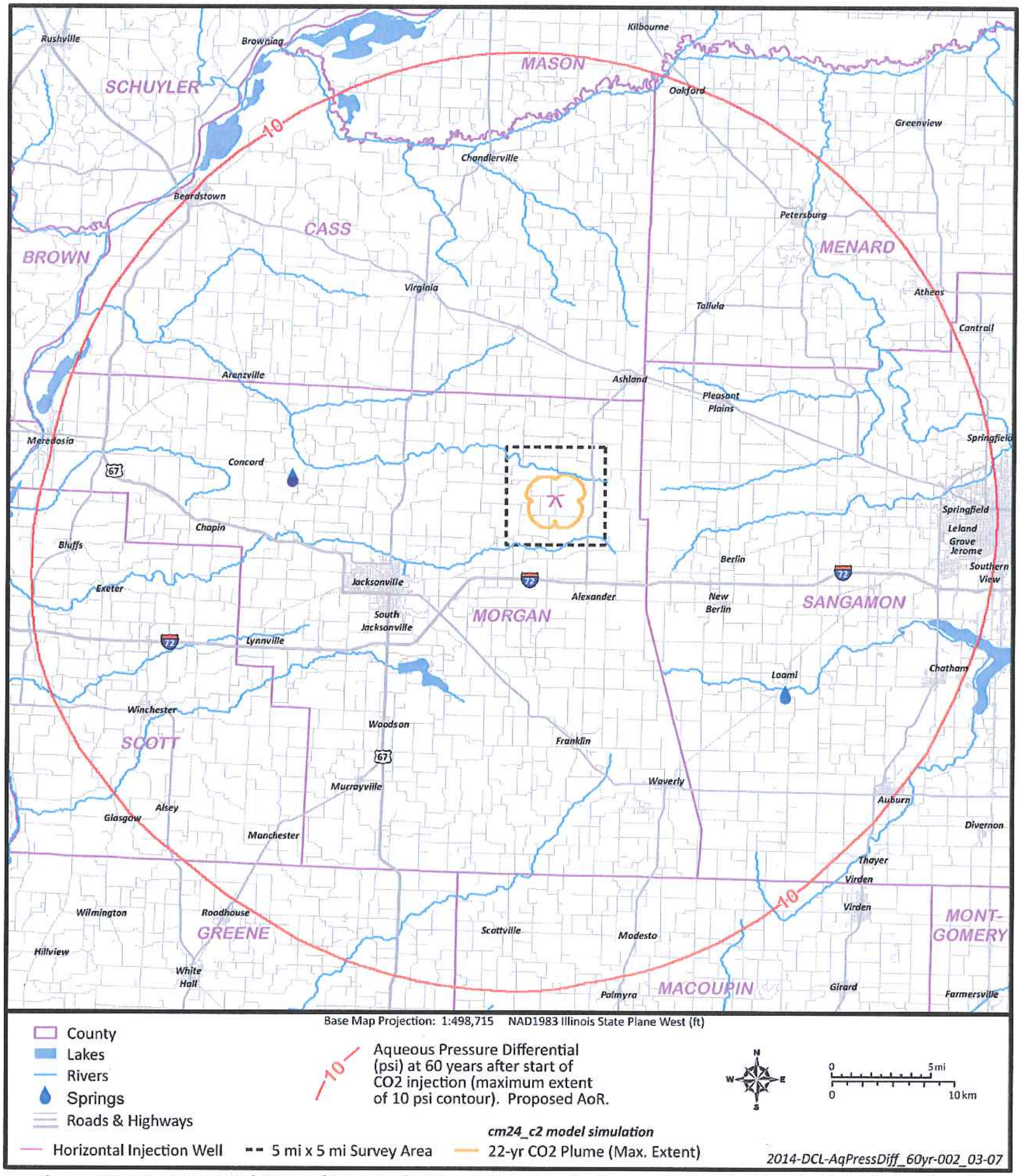



**Figure 19. EPA Approved Area of Review for the FutureGen Project as Delineated by the Permit Applicant Accounting for Both the Plume and Pressure Front**

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