US EPA Class VI CO_2 Injection Permit — Requirements and Lessons Learnt from the Wellington, Kansas, Project

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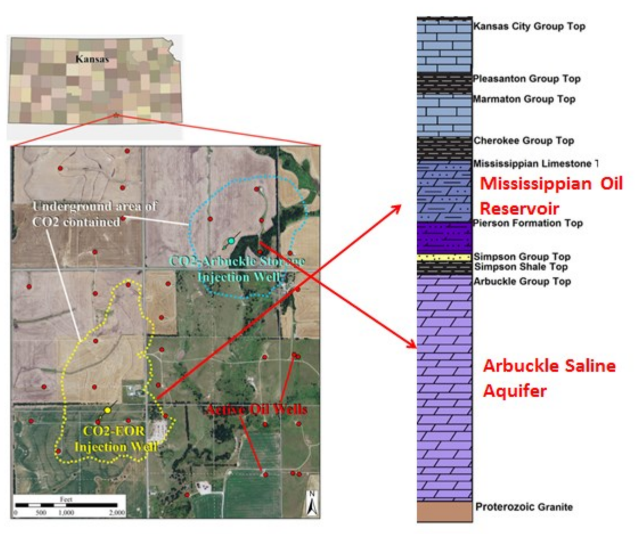
Introduction

The Wellington demonstration project involves injecting 26 KTons of CO_2 in the cambro-ordovician Arbuckle aquifer in central Kansas. A US EPA Class VI injection permit is required for CO2 sequestration in saline aquifers. The primary objectives of the EPA are to protect Underground Sources of Drinking Water (USDW; TDS < 10000 mg/l), and to prevent any injected CO2 from escaping into the atmosphere within the Area of Review (AoR). The AoR is defined as the larger of the maximum extent of a) the CO2 plume, or b) the pressure boundary within which brines from the injection zone can migrate into overlying USDW via abandoned wells, leakage in the injection well, or breach of the confining zone.



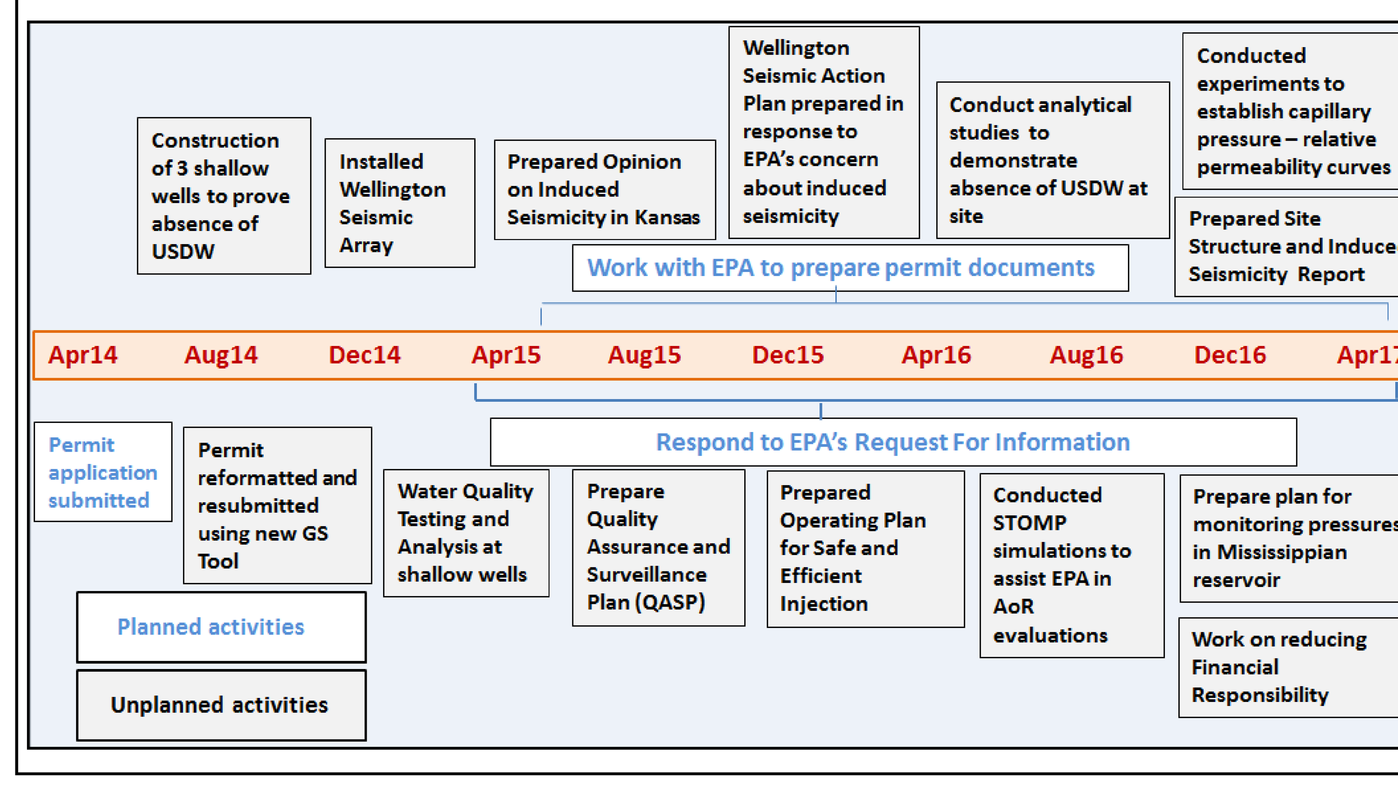
Components of Class VI Permit

The Class VI permit consists of 9 plans, referred to as Attachments. Attachments related to well and infrastructure construction, and operations are relatively easy to prepare. Plans related to AoR, Testing and Monitoring, Post-injection Site Care, Emergency and Remedial Response, and Financial Responsibility can be challenging and potentially expense to prepare.

Plans	Key Challenges
A- Operating Requirements	No key challenges
B– Area of Review and Corrective Action	High resolution characterization of injection and confining zones, addressing uncertainties in formation petrophysical properties, and addressing seismic risk
C—Testing and Monitoring	Region wide (indirect) monitoring of plume and pressure front
D—Well Plugging	No key challenges
E—Post-Injection Site Care	Reducing default monitoring period of 50 years
F— Emergency and Remedial Response	Develop project specific plans to ensure safe and efficient injection, and design/installation of ground-motion sensing equipment
G—Construction Details	No key challenges
H— Financial Assurance	Reducing default obligation of approximately $70 Million
I— Stimulation Program	No key challenges

Permit Timeline

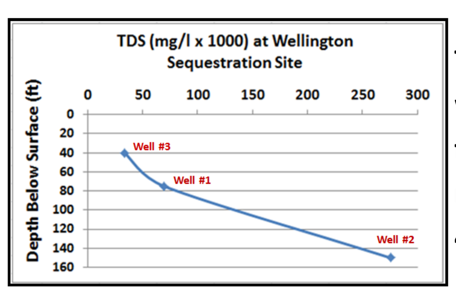
The Wellington permit submittal was the first application for a newly constructed CO2 sequestration well since promulgation of the Class VI Rule in 2011. During the application process, it was realized that were many technical issues for which guidance and precedence was lacking. For example, the Class Rule did not have any formal regulations/guidelines for addressing the subject of induced seismicity. As shown in the permit timeline below, the Wellington team had to expend time and budget on many activities that were unanticipated at commencement of the project. Several of the first-of-a-kind studies conducted in pursuit of the permit and the accompanying reports are expected to serve as a guide and template for future CO2 sequestration projects.



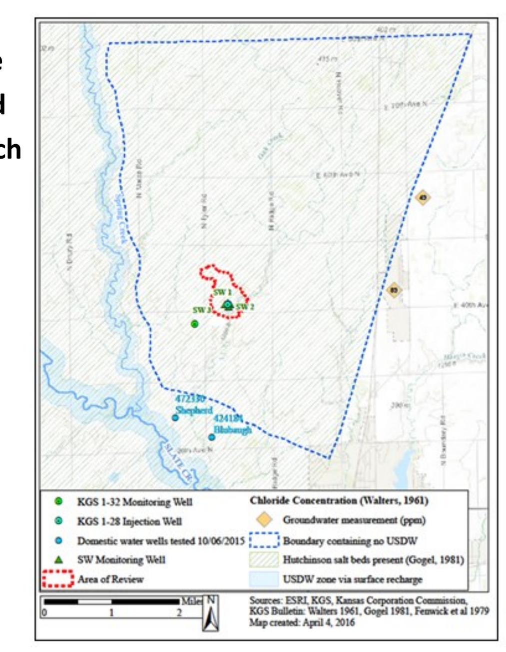
Plan H - Financial Responsibility

Project Task	EPA Cost
Corrective Action	$0
Well Plugging	$0.22M
Post-Injection Site Care	$0.29M
Site Closure	$1.01M
Emergency Response	$68.48M
Total	$70.01M

EPA assessed the financial obligation of the Wellington project at $70.01 million (M), which translates to an estimated annual cost of approximately $2M (3% of face value) as premium for an insurance policy or deprived interest to finance a trust fund. Further compounding matters was the (default) 50 year post-injection monitoring period, resulting in prohibitive costs. The challenge therefore was to reduce the financial obligation, most of which was associated with protecting any USDW at the site.



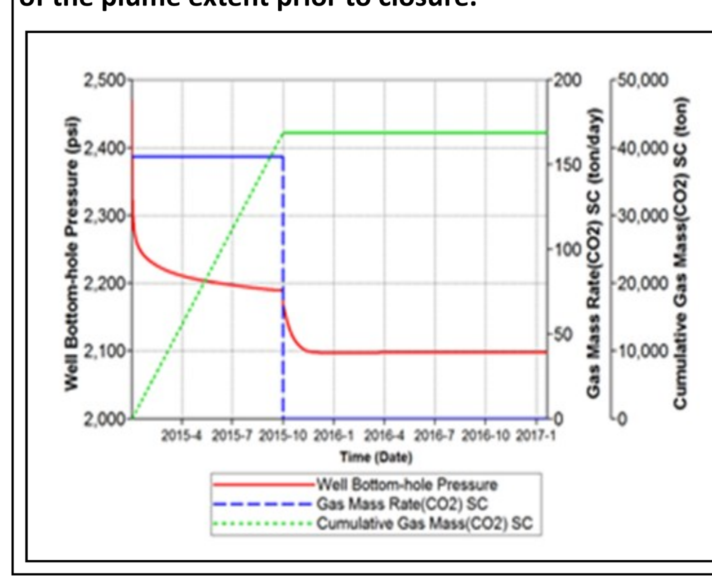
To demonstrate the absence of any USDW at the site, KGS constructed 3 new wells, conduct region wide water quality sampling/testing and geologic research. The water levels in the new wells were monitored for a period of 6 months, and the data was utilized to estimated the formation hydraulic properties, which revealed aquiclude like conditions in any potential USDW. The TDS in the new wells were in excess of 40,000 mg/l.

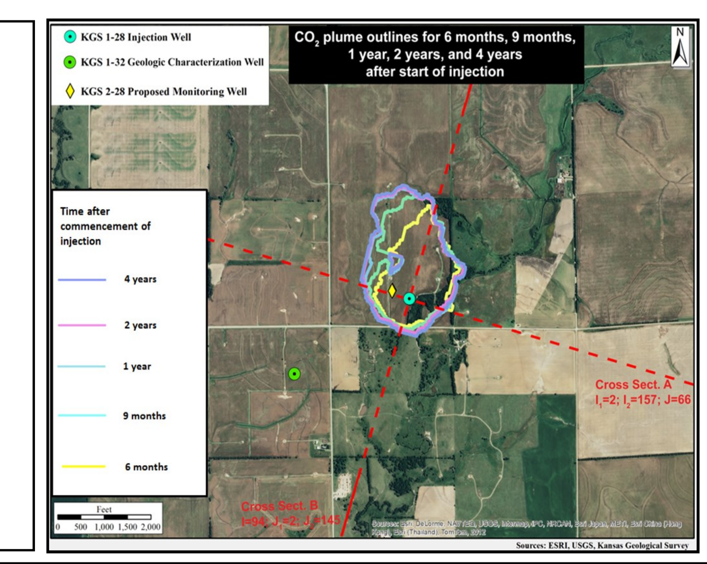


The regional water quality information collected for the study was carefully analyzed in order to develop a verifiable conceptualization of the hydrogeology, and to delineate the boundaries of brackish water with TDS greater than 10,000 mg/l. The finding were documented in 5 separate report published for the EPA , which successfully demonstrated the absence of a USDW at the site, resulting in lowering of the financial obligation to $6.1M from $70.01M. Approximately 12 human-months were to expended to achieve the results.

Plan E—Post-injection Site Care and Closure Plan

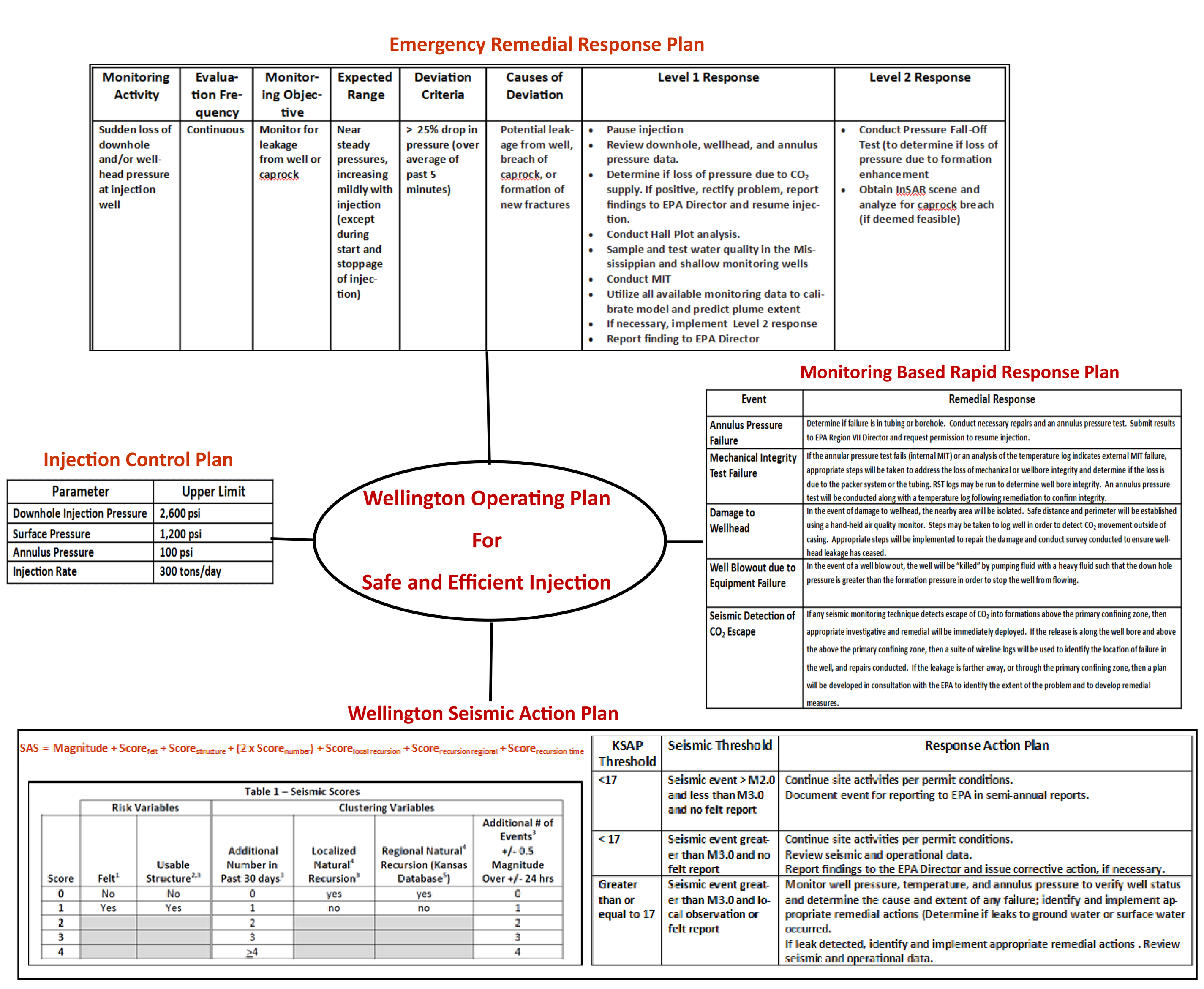
In order to reduce the default post-injection monitoring period of 50 years, KGS conducted sensitivity studies with various formation parameters (temperature, dispersivity, etc) and constitutive relations to demonstrate stabilization of the plume and injection pressure in a shorter time frame. Laboratory based experiments were also conducted in order to establish capillary pressure and relatively permeability relationships of the formation material. Analytical approaches were developed and applied to populate the derived properties within the model domain. Field based criteria for plume and pressure stabilization were developed and incorporated in the permit as conditions to allow site closure. 2D and 3D seismic surveys are to be conducted for verification of the plume extent prior to closure.





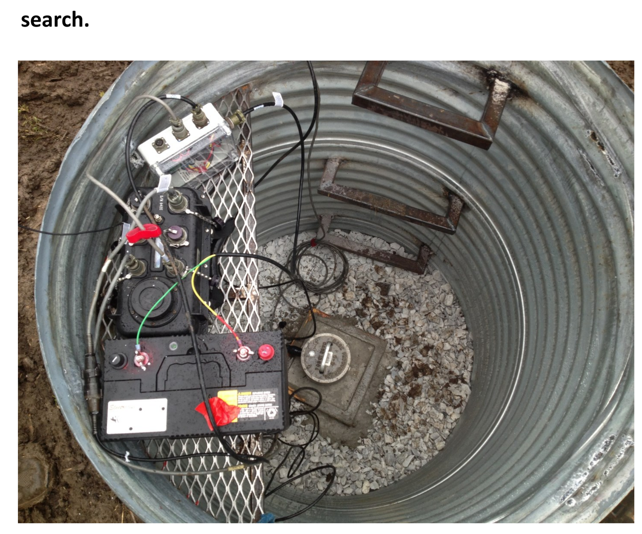
Plan F—Emergency and Remedial Response

In order to ensure safety and to mitigate the impacts of catastrophic events, the Wellington Plan for Safe and Efficient Injection was developed. This first-of-a-kind plan is likely to serve as a template for future CO sequestration projects, and consists of 4 sub-plans: Monitoring Based Rapid Response Plan, Wellington Seismic Action Plan, Emergency Remedial Response Plan, and the Injection Control Plan.



Emergency Scenarios
Well Integrity Failure
Equipment Failure
Water Quality Changes
Migration of CO_2 out of Injection Zone
Release of CO_2 to Surface
Natural Disaster
Induced Seismicity Event

A network of 15 seismometers was installed to provide early warning of deteriorating conditions. Corrective actions are to be implemented at pre-set thresholds as specified in the Wellington Seismic Action Plan. Collectively, these measures will ensure safe injection at the site. The seismometers have been monitoring ground motion since 2015 and assist in seismic research.

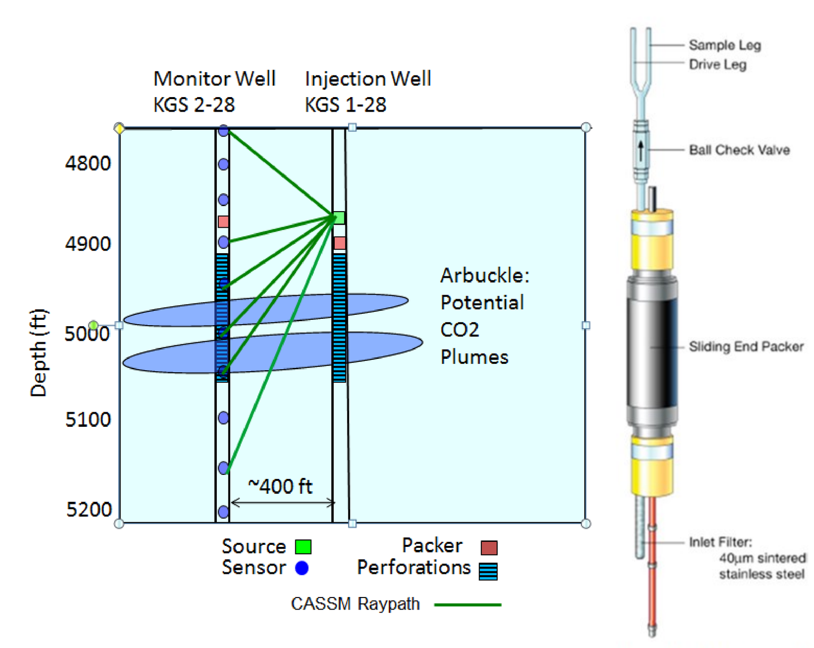


Plan C—Testing and Monitoring

The goals of the Wellington Testing and Monitoring Plan are to ensure safe injection, track the plume and pressure fronts, and to provide early warning of deteriorating conditions. The plan is closely linked with the Wellington Plan for Safe and Efficient Injection which is to be executed if predefined safety thresholds are to be exceeded. A unique feature of the plan is to monitor for Sulfur Hexafluoride (SF_6) which is to be injected as a tracer in order to distinguish the CO2 source on account of CO2 based Enhanced Oil Recovery activities in the overlying Mississippian reservoir at the site. The pressures in the Mississippian reservoir are also to monitored in order to assist in induced seismicity evaluations. A 169-page Quality Assurance protocol was developed for the project to ensure validity of the monitored data and to derive statistically defensible conclusions.

Monitored Fluid Chemical Parameters

Arbuckle, Mississippian, and Wellington Formation	Cations: Al, Ba, Mn, As, Cd, Cr, Cu, Pb, Sb Se, and Tl , Ca, Fe, K, Mg, Na, Si Anions: Br, Cl, F, NO_3, SO_4 Dissolved CO_2 ,TDS, Alkalinity , pH, Specific conductance , Temperature , Oxidation-reduction potential , Sulfur hexafluoride , Hydrogen sulfide , Acetaldehyde
CO2 Stream	O_2, CO_2, H_2S, As, S, Se, Hg, Water vapor



Injection Zone monitoring

	Direct	Indirect
Plume	U-Tube	2D and 3D Seismic Surveys, Continuous Active Source, Crosswell Seismic
Pressure	Downhole Pressure & temperature	Passive Seismic, InSAR and cGPS

Well Testing and Monitoring

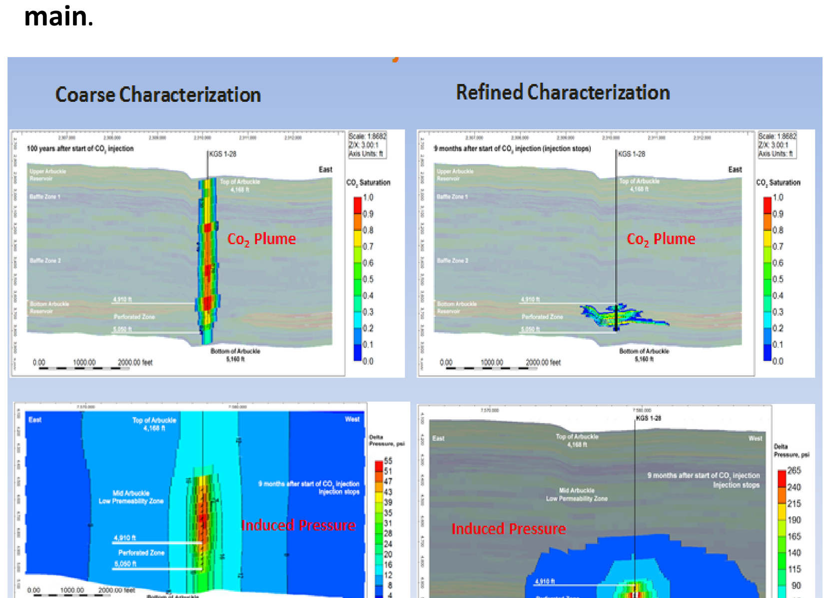
Well Integrity	Temperature log, annulus pressure, pressure fall-off, corrosion coupon
Wellhead	Injection rate and volume (flow meter), pressure, temperature
Annulus	Annular pressure, fluid volume

Plan B—Area of Review and Corrective Action

Modeling

As per Class VI rules, the Area of Review is to be derived from modeling results. Sensitivity studies indicated that due to the buoyant nature of the injectate, the plume and the pressure fronts are highly influenced by the scale of the modeling and the resolution of the petrophysical properties derived from geophysical logs, laboratory measurements, and field tests.

Utilizing current practices of constructing a layered-cake model can provide misleading results. Consequently, a high level of effort was expended to characterize the injection and confining zones at high resolution, and develop methodologies to extrapolate the hydrogeologic properties throughout the model domain.

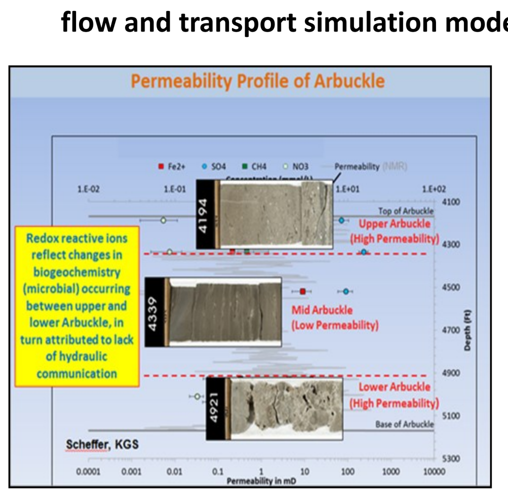


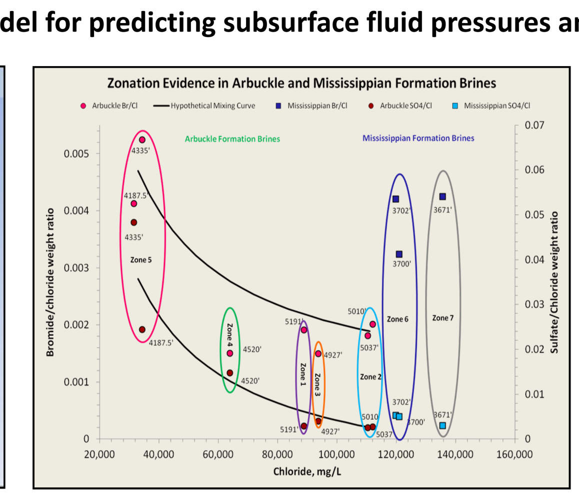
Hydrogeologic Characterization of the Injection and Confining Zones

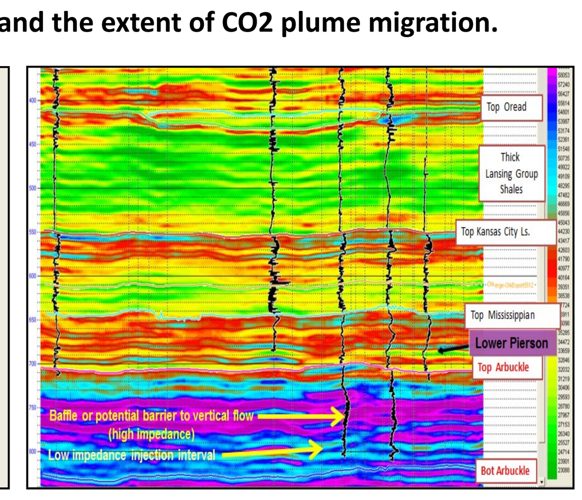
Two 5,000+ feet wells were drilled into basement to derive an extensive suite of geophysical logs, obtain core and swab samples, and conduct hydraulic tests. The geochemistry data, including ion composition, molar ratios, biogeochemistry, and isotopic characterization were used to estimate the competence of the caprock and hydraulic stratification within the injection zone. The biomass concentrations and microbial diversity/counts confirmed the existence of a highly stratified Arbuckle reservoir. X-Ray Diffraction and Spectral Gamma Ray Analyses (specifically the Rhomma-Umma analysis) were utilized for mineralogical characterization of the injection and confining zone, which was necessary to develop the reaction kinetics for conducting geochemical simulations in order to predict the sequestration potential in the mineralogical phase and for estimating the change in formation properties such as permeability and porosity due to precipitation of minerals. Helical computerized tomography scans were used to inspect the texture of the rocks and to inspect for the presence of very minute fractures.

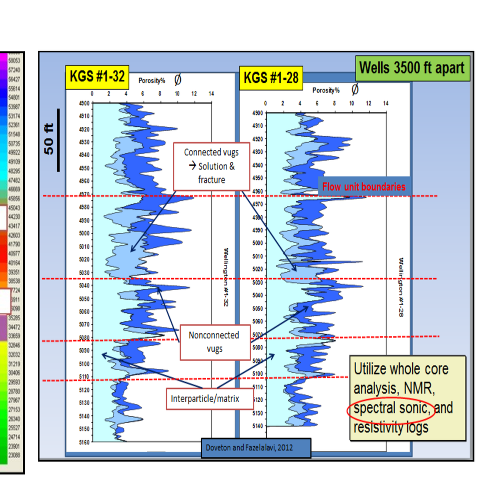
Nuclear Magnetic Resonance (NMR) and sonic logs were used to estimate the matrix and vuggy porosities. The T2 distribution data from the NMR logs was used to estimate the pore throat radius (as a function of capillary pressure) in order to calculate the entry pressure of the caprock. The Flow Zone Interval and residual saturation information was used to develop a new technique for estimating hydraulic conductivity profile, which compared favorably with core based estimates of this property.

The characterized data was the combined with 3D multi-component seismic volume in a geocellular model which was used to develop a multiphase flow and transport simulation model for predicting subsurface fluid pressures and the extent of CO2 plume migration.



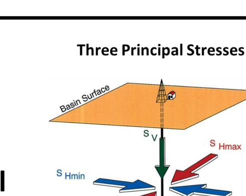




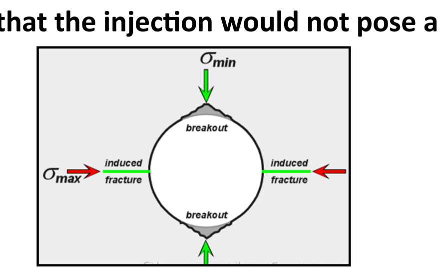


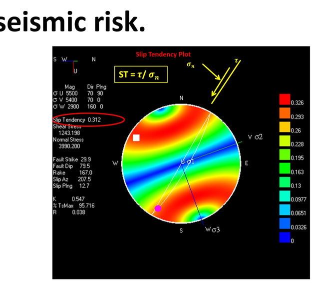
Seismic Investigations

The discovery of an 8,000 feet long fault immediately west of the proposed injection well complicated the permitting process with EPA.

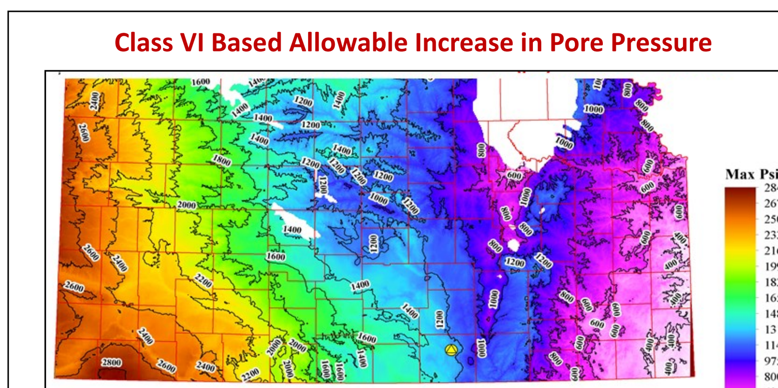


Extensive (and unplanned) research was conducted to establish the regional stress field utilizing drilling induced fractures and step rate test data, which was combined with analytical techniques to establish the fault Slip Tendencies. Several publications were prepared over a period of 18 months to satisfactorily demonstrate to EPA that the injection would not pose a seismic risk.





Class VI Based Allowable Increase in Pore Pressure



Class VI pressure limitations may restrict commercial scale CO_2 sequestration to western half of the state