TENASKA TRAILBLAZER PARTNERS, LLC

Report to the

Global CCS Institute

Deep Saline Sequestration Study

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Abstract

The Tenaska Trailblazer Energy Center (Trailblazer or Project), is a nominal 760 MW supercritical pulverized coal electric generating station under development in Nolan County, Texas, United States, approximately 9 miles (14.5 kilometers) east of Sweetwater, Texas.

Trailblazer is expected to be the first new-build coal plant in the United States to incorporate a commercial-scale carbon dioxide (CO_2) capture plant into the initial design. The Project will be designed to capture 85 to 90 percent of the CO_2 that otherwise would be emitted into the atmosphere.

Although the Project intends to sell its CO_2 for use in enhanced oil recovery (EOR), Tenaska believed it was prudent to understand the potential for geologically sequestering CO_2 without concurrent EOR near the Project site as an alternative to the base case. Accordingly, in January 2009, Tenaska contracted with Subsurface Technology Inc. to conduct a basic study on options for CO_2 sequestration without concurrent EOR near the Project site.

This report describes how the Project gathered and analyzed information on CO_2 sequestration in deep saline formations near the Trailblazer site.

This is the sixth in a series of knowledge sharing reports on Carbon Capture and Storage (CCS), developed by Tenaska for the Global CCS Institute.

Deep Saline Sequestration Study Report

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1.0 Introduction

Trailblazer is expected to be the first new-build coal plant in the United States to incorporate a commercial-scale CO_2 capture plant into the initial design. The Project will be designed to capture 85 to 90 percent of the CO_2 that otherwise would be emitted into the atmosphere. The Project plans to sell its captured CO_2 into the Permian Basin CO_2 market in West Texas, where it will be used in EOR and ultimately stored permanently underground.

Although the Project intends to sell its CO_2 for use in EOR, Tenaska believed it was prudent to understand the potential for geologically sequestering CO_2 without concurrent EOR near the Project site as an alternative to the base case. Accordingly, the Project undertook a high-level desktop study of the potential for deep saline injection of CO_2.

2.0 Purpose and Goals

The purpose of this report is to explain the high-level desktop study conducted to evaluate potential CO_2 sequestration options without concurrent EOR available in the area surrounding the Trailblazer site.

A study was performed to evaluate the available formations that could be used to sequester up to 5.75 million tons (5.22 million metric tons) of CO_2 per year. The area around the proposed Trailblazer site was reviewed using available public data. Phase I evaluated oil fields, gas fields, depleted CO_2 reservoirs, non-mineable coal beds, and saline aquifers.

Phase II of the work focused on the Cambrian Sand saline aquifer. As part of this phase, the depth, thickness, porosity and permeability of the Cambrian sand in the area around the Project site to the west as shown in Exhibit 1 was estimated. Also, depleted, abandoned, and currently producing oil and/or gas fields were delineated within the study area. The vertical confinement properties were also characterized.

3.0 Executive Summary

Trailblazer is expected to be the first new-build coal plant in the United States to incorporate a commercial-scale CO_2 capture plant into the initial design. The Project will be designed to capture approximately 5.75 million tons (5.22 million metric tons) of CO_2 annually – about 85 to 90 percent of the CO_2 that otherwise would be emitted into the atmosphere. The Project plans to sell its captured CO_2 into the Permian Basin CO_2 market in West Texas, where it will be used in EOR and ultimately stored permanently underground.

Although the Project intends to sell its CO_2 for use in EOR, Tenaska believed it was prudent to understand the potential for geologically sequestering CO_2 without concurrent EOR near the Project site. Accordingly, the Project undertook a two-phase, high-level desktop study of the potential for deep saline injection of CO_2.

Phase I included a review of a large number of potential options for CO_2 sequestration, including oil fields, gas fields, depleted CO_2 reservoirs, non-minable coal beds, and saline aquifers. Phase II focused on saline aquifers, the most promising of the options reviewed in Phase I.

3.1 Phase I Study

The Phase I study included a review of a large number of potential options for CO_2 sequestration, including oil fields, gas fields, depleted CO_2 reservoirs, non-minable coal beds, and saline aquifers. The review was conducted using publicly available data, and **concluded that the Cambrian Sand saline aquifer was the best candidate for CO_2 sequestration, due to its breadth in the region, its excellent reservoir quality and the fact that it has not been extensively drilled.**

3.2 Phase II Study

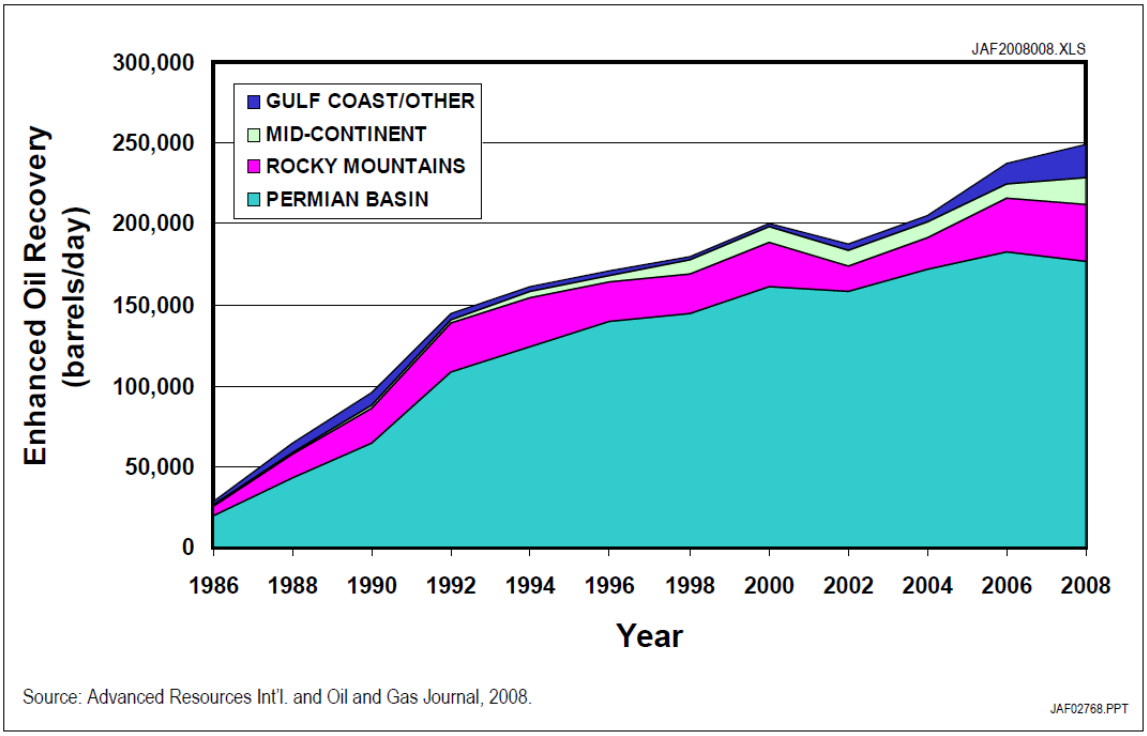
The Phase II study focused on the Cambrian Sand saline aquifer, which was identified in the Phase I study as the best candidate for CO2 sequestration without concurrent EOR. Again using publicly available data, the Phase II study **concluded that it would require between four and 13 wells drilled into the Cambrian Sand aquifer to accommodate the 5.75 million tons (5.22 million metric tons) of CO2 captured annually by Trailblazer for 30 years.**

4.0 Sequestration Options

4.1 Enhanced Oil Recovery Overview

Although EOR opportunities exist on the Gulf Coast and in the Rocky Mountains in the United States, the vast majority of CO_2-based EOR in the United States is conducted in the Permian Basin[1], as shown in Figure 1.1.

FIGURE 1.1 – Growth of CO_2-Based EOR in the United States



EOR has been used in the Permian Basin since the early 1970s.[2] In Texas, rules and regulations are already in place with regard to CO_2 handling and disposal. The addition of CO_2 capture equipment will increase the cost of the Project by about 30 percent and consume an estimated 30 percent of the electricity that otherwise would be available for sale. As a result, Tenaska views a robust CO_2 market as being essential to the Project's success.

A 2006 study conducted by the Advanced Resources Institute for the United States Department of Energy (DOE) estimated that there are up to 20.8 billion additional barrels of oil in the Permian Basin that could be produced using EOR.[3] The same report estimates that applying EOR to the Permian Basin's oil reservoirs would enable 2.5 billion tons (2.27 billion metric tons) of CO_2 emissions to be stored.[4] It also found that the overall market for purchased CO_2 in the Permian Basin could be up to 49.0 trillion cubic feet[5] (1.39 trillion cubic meters).

Tenaska's preliminary discussions with major oil producers and mid-tier companies in the Permian Basin about purchasing the Project's CO_2 indicate that there is ample

appetite for the approximately 5.75 million tons (5.22 million metric tons) of CO_2 that the Project will produce annually. It is Tenaska's intention to enter into a long-term contract with a credit-worthy counterparty or counterparties for the sale of the CO_2 captured by the Project.

4.2 Geological Sequestration

Although the Project intends to sell its CO_2 for use in EOR, Tenaska believed it was prudent to understand the potential for geologically storing CO_2 without concurrent EOR near the Project site.

Accordingly, the Project undertook a high-level desktop study of the potential for geologic storage CO_2 without concurrent EOR.

When evaluating potential geologic sequestration sites, there are several parameters to be considered, including:

- Location. The site should be as close to the CO_2 production as possible. It also should avoid major population centers which can complicate the process.
- Geology. Both porosity (how much space there is between grains or within cracks or cavities in the rock) and permeability (how easily a substance such as CO_2 or water can move through a porous rock) are important geologic factors to be considered. The ideal geology is a deep, thick formation of porous and permeable rock that can handle large volumes of CO_2 over extended periods with a minimal number of injection wells. Faulting and thickness of the cap rock also should be evaluated.
- Water. Major ground or surface water sources should be avoided.
- Integrity of the formation. It is desirable to locate near a sealing formation (the formation above the target formation that keeps the CO_2 from migrating) that has not been extensively drilled and does not have faults or fractures

4.3 Project Economics

Revenue from CO_2 sales will be a critical component in making the Project financially viable, unless Federal policies evolve in such a way that significant government incentives are available for geological sequestration of captured CO_2. Accordingly, a strategic decision was made at the Project's inception to locate in West Texas, near one of the oldest and most robust CO_2 markets in the world.

The desktop study undertaken by the Project did not attempt to quantify the costs associated with geologic sequestration, since the Project's business strategy is to sell its CO_2 into the Permian Basin CO_2 market. No quantification was required, given that geologic sequestration has never been part of the Project's business plan.

5.0 Trailblazer Sequestration Study

5.1 Study Overview

The Project engaged Subsurface Technology Inc. (Subsurface) to conduct the desktop study, using publicly available data. Subsurface completed its work in two phases.

5.1.1 Subsurface Technology Inc.

Subsurface is a Houston, Texas-based firm that is a major underground injection consulting and engineering firm. Subsurface is actively engaged in projects ranging from underground injection and storage well systems, to complex subsurface investigations and remediation for the oil and gas, chemical, mining, utility and other industries.

5.1.2 Publicly Available Data

With the extensive drilling conducted by the oil and gas industry in Texas, large volumes of data are available. The Bureau of Economic Geology at the University of Texas at Austin maintains an extensive core library, as well as drilling records, field reports, maps, and research documents that were used in the study. In addition, many areas of the state have field reports, production history, and published studies that were used.

5.2 Phase I Scope of Work

Subsurface reviewed the potential reservoirs for CO_2 sequestration around the Trailblazer site. The effort had a primary study area and secondary study area if the primary area was found to have limited potential. The reservoir review included evaluation of available public data on geologic formations in the area. The reservoir study targeted saline aquifer formations, abandoned oil fields, oil fields where CO_2 sequestration would enhance oil recovery, gas fields, and non-minable coal beds. Based on this data, a list of candidate formations for CO_2 sequestration was identified. Using available public data, the deepest fresh water reservoir was identified as well as known faults and mines in the area. The resulting data was used to identify target formations for review in Phase II.

5.3 Phase II Scope of Work

Phase II focused on the Cambrian Sand saline aquifer identified in Phase I. The goal of this phase of work was to map the formation and cap rock. The work product would allow Tenaska to identify a suitable sequestration field location.

Phase II of the work was centered on the Cambrian Sand saline aquifer located under and around the Trailblazer site. As part of this phase, the depth, thickness, porosity and permeability of the Cambrian sand in a 15-mile radius around the plant was estimated. Also, depleted, abandoned, and currently producing oil and/or gas fields were delineated within the 15-mile radius of the plant. The vertical confinement properties were characterized. The potential injection capacity of the formation was determined. A base case design of the CO_2

injection wells was created. This work included estimating a base case, high case, and a low case well performance. In addition, known wells that penetrate the Cambrian Sand and vertical confinement were mapped.

Subsurface's work products included:

- Core analysis of Cambrian Sand from publicly available core samples;
- Map showing faults, wells that penetrate the Cambrian Sand and overlying confining layers, depleted, abandoned, and currently producing oil and/or gas fields, and known mine shafts in the area around and west of the Project site;
- North-South and East-West cross sections around the plant showing injection zones, vertical confinement thicknesses and the lowest fresh water reservoir; and
- Preliminary modeling.

6.0 Study Results

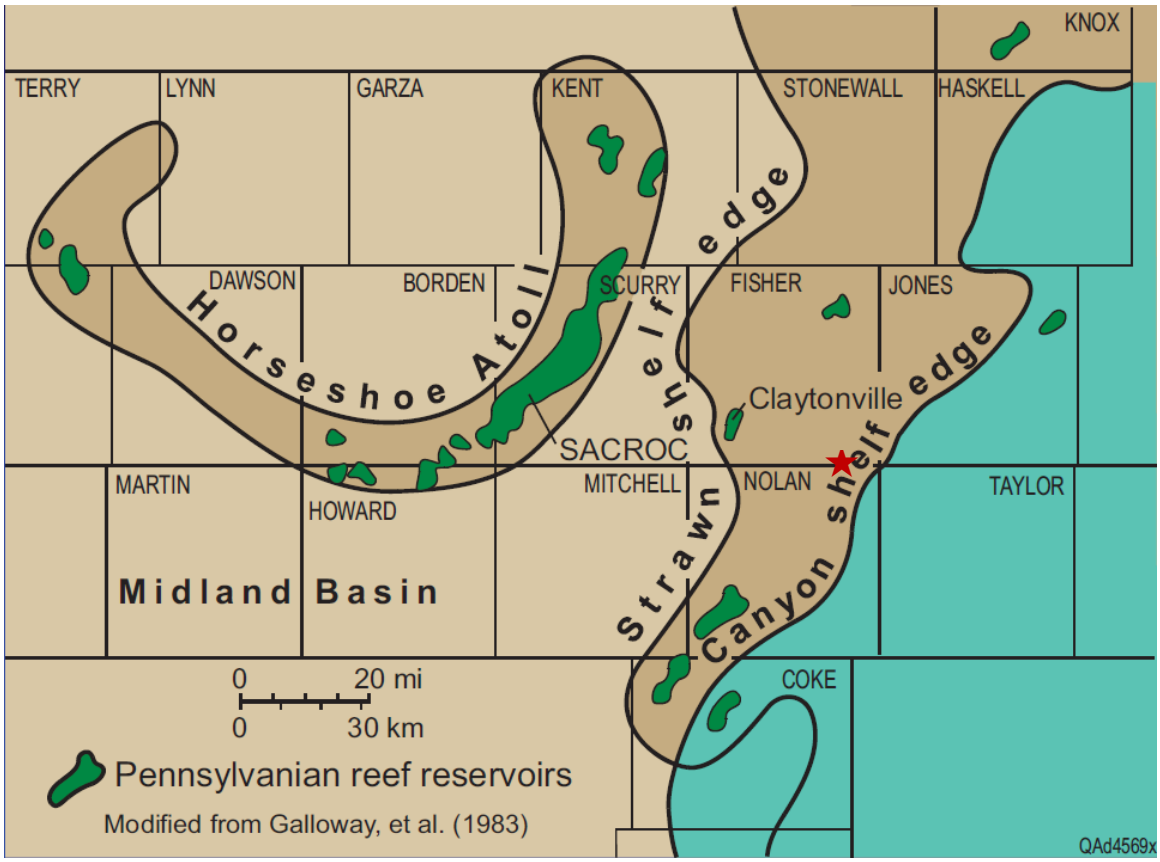
6.1 Phase I

6.1.1 Regional Geology

The Trailblazer site is located on the Eastern Shelf of the Midland Basin. Numerous oil fields are present in the immediate region of the Trailblazer site. These produce from the Cambrian Sand/Hickory Formation through the Pennsylvanian Cisco Formation.

Figure 6.1.1 shows Nolan County's location among geologic fields in West Texas. The red star indicates the approximate location of the Trailblazer site.

FIGURE 6.1.1 – West Texas Geologic Fields



6.1.2 Producing Fields – Potential for EOR

The Canyon Reef fields associated with the Horseshoe Atoll (SACROC) have been undergoing CO_2 injection for EOR for more than 30 years. The DOE has designated several analogous Strawn and Canyon Reef oil fields near the Trailblazer site as candidates for CO_2 sequestration with associated potential for "value-added" EOR. These include Jameson, Nena Lucia, Round Top, and Claytonville. A pilot CO_2 injection program was initiated at the Claytonville Field in the spring of 2007. At this time, the results of this program are unknown.

Additional producing fields in the area may prove to be conducive to CO_2 injection. These include Canyon Sand fields, such as Lake Trammell.

6.1.3 Depleted Oil Fields

In the immediate vicinity of the site, the Lake Sweetwater and Neill, South Fields have produced 5,970,762 barrels and 8,221,716 barrels of oil, respectively, from the Odom Lime (Strawn). Very few wells are still producing and these fields are essentially depleted. The DOE has designated the Odom Lime at the Fort Chadbourne Field, located to the south in Coke County, as being "amenable" to CO_2 injection.

A field paper indicated that the Odom Lime formation would be good as a confining zone, but not as an injection zone. In addition, the formation is very small.

6.1.4 Saline Aquifers

Formations containing saltwater in the vicinity of the site include the Coleman Junction (2500 feet (762 meters)), Wolfcamp/Cisco Lime (3500 feet (1067 meters)) and the Cambrian Sand (6350 feet (1935 meters)). These are considered potential candidates for sequestration.

6.1.4.1 Coleman Junction

The Coleman Junction is laterally extensive throughout the Eastern Shelf. In the area of the site it is over 100 feet (30.5 meters) thick and possesses porosities raging between 19 percent - 25 percent. Tests indicate the permeability is excellent. The Coleman Junction does not produce hydrocarbons in the area.

6.1.4.2 Wolfcamp/Cisco

The top of the sequence of the Wolfcamp/Cisco Limestone section is considered to be Wolfcampian (Early Permian, 290 Ma) in age, while the middle to lower portion of the sequence (Cisco) is commonly referred to as the Breckenridge. It is laterally extensive, beginning just east of Sweetwater and continuing to the White Flat Field located 4 miles (6.5 kilometers) east of the Project site where the basal portion is utilized for oil field saltwater disposal. The basal portion is also utilized by other saltwater disposal wells in the area.

6.1.4.3 Cambrian Sand

The Cambrian Sand is regionally extensive and was deposited upon the Precambrian basement during a long period of marine transgression. It is oil productive 4 miles (6.5 kilometers) to the east of the Project site in the White Flat Field. At the White Flat Field, the Cambrian Sand is only productive along the Fort Chadbourne Fault System.

At the White Flat Field, the Cambrian Sand averages 150 feet (46 meters) in thickness and is present as several lenses separated by tight sand or dolomite. Core analysis and drill-stem tests indicate the presence of excellent reservoir quality.

Very few wells drilled to the west of the Fort Chadbourne Fault System were drilled to the Cambrian Sand because it was recognized very early that it was only productive along the fault zone. However, a well adjacent to the site was drilled to the upper portion of the Cambrian Sand. It logged 51 feet (15.5 meters) of permeable (microlog) Cambrian Sand in the uppermost section. A drill-stem test recovered 5050 feet (1539 meters) of saltwater with flowing pressures of 570 pounds per square inch (psi) – 2475 psi (39 bar – 171 bar), with a 15-minute shut-in pressure of 2640 psi (182 bar). This indicates that excellent reservoir quality is present in the Cambrian Sand at the site and that it is non-productive of hydrocarbons. Unfortunately, no core data is available to calculate average rock porosity and permeability. Only general estimates can be made off of the drill-stem test.

Additionally, to the west a well was drilled into the upper portion of the Cambrian Sand and recovered 5370 feet (1631 meters) of salty sulfur water from 6540 - 6575 feet (1993 – 2004 meters). Although it was not logged through the Cambrian, the drilling report from the well indicates sand was present at the total depth of 6675 feet (2035 meters).

Generally, 15 - 20 feet (4.5 – 6 meters) of tight dolomite separates the Cambrian Sand from the basal portion of the Ellenburger Dolomite. However, log analysis of wells drilled into the Ellenburger in northwest Nolan County, indicates the Ellenburger to be thicker and tighter, therefore, providing a thicker seal over the Cambrian Sand.

Furthermore, in the southeast corner of Scurry County, 5 miles (8 kilometers) to the northwest of Nolan County, a well was drilled to the top of the Cambrian Sand at 7990 feet (2435 meters) and microlog analysis indicates 6 feet (1.8 meters) of permeability at the top of the sand. In addition, the mud log indicates glauconitic quartz sand is present. The well was not drilled deeper than the top of the Cambrian Sand at 7990 feet (2435 meters). Therefore, the total sand thickness of the Cambrian is unknown at this location. However, this confirms the presence of Cambrian Sand further to the west of Nolan County.

Estimated total dissolved solids in the Cambrian sand ranges from 40,000 to 70,000 parts per million (ppm) along the Eastern Shelf. The dissolved solids are well above the 10,000 ppm requirement for total dissolved solids under United States Environmental Protection Agency underground injection requirements.

From the evidence cited above in regards to the Cambrian Sand, it appears to be laterally extensive in the region surrounding the site and possesses excellent reservoir quality. Since very few wells penetrate the Cambrian, it is considered to be the best candidate for CO_2 sequestration.

6.1.4.4 Non-mineable Coal Beds

Although coal beds are present in the subsurface in the Eastern Shelf, they are not considered potential candidates for CO_2 sequestration because they are very thin and would not have the required storage capacity.

6.2 Phase II

A structural map of the top of the Cambrian Sand was completed around the Project site, as shown in Exhibit 1.

The depth of the Cambrian Sand around the Fort Chadbourne Fault System is estimated at 4,100 feet (1250 meters) below sea level. Moving west the formation deepens to 5,600 feet (1707 meters) below sea level approximately 30 miles (48 kilometers) west of the Fort Chadbourne Fault System. The general gradient of the top of the formation shallows to the east at 50 feet per mile (9.45 meters per kilometer). The mapping did show some minor structural features in the formation. The map also illustrated the numerous wells that have been drilled in the area. The large number of wells present that may penetrate the cap rock were determined to be the biggest risk for CO_2 migration.

Information from various oil wells in the area was used to create detailed major cross sections around the plant showing injection zones, vertical confinement thicknesses and the lowest fresh water reservoir. The cross sections showed the Cambrian Sand running from Fort Chadbourne Fault System approximately 35 mile (56 kilometers) west. Some wells on the western edge of the study area show the Cambrian Sand is not present. Due to limited wells drilled through the Cambrian Sand a definitive thickness could not be determined. However a thickness was estimated at 150 feet (45 meters) in the center area of the formation. Based on rock properties, the Odom Lime would be the cap rock used that would confine the CO_2. The Caddo Lime and the Ellenburger formation don't have the properties to be considered a true cap rock, as they are relatively thin and may not have the low porosity to fully contain the CO_2, and so would be treated as an arrestment interval where no injection would take place, but where CO_2 could migrate. The Cambrian Sand formation would be the best formation to use as an injection interval.

A core of the Cambrian Sand was found in the Texas Bureau of Economic Geology core library. A section of the core was analyzed by STIM-LAB in Duncan, Oklahoma in order to better understand the qualities of that formation. Two plugs were removed from the core samples. STIM-LAB preformed routine core analysis, X-Ray diffraction and thin section analysis on each plug. The mineralogy of the samples showed the sandstone was mostly quartz with some dolomite and glauconite. The presence of glauconite in the samples suggests the sand was deposited in a marine environment.

Estimated rock properties were loaded into a reservoir model. Five different models were run using one, three, four, seven and 13 CO_2 injection wells. A base injection pressure of 1800 psi (124 bar) and an initial formation pressure of 3530 psi (243 bar) were used in the model. The model showed the minimum number of wells required to accommodate 5.75 million tons (5.22 million metric tons) of CO_2 a year was four, assuming extremely favorable rock properties. With rock properties in the mid-range of expectations, seven-wells would be required to accommodate Trailblazer's CO_2 output. Thus, the seven well case would be considered the base case. Thirteen wells would be required if the rock properties fell below the base case.

6.3 Additional Work

The next step in developing a deep saline sequestration field would be to complete a detailed site characterization study. The first step would be to acquire existing seismic data to refine the location of the injection field. The injection field location would be selected based on lack of faulting, minimal existing wells, and the thickness of the target formation and cap rock. Once the site was selected, 2-D and 3-D seismic surveys would be completed in conjunction with a stratigraphic test well. The results from the seismic survey and test well would be used in a detailed reservoir model. When the model was complete, the site would be ready to apply for a permit probably under the EPA's Underground Injection Control Program Class VI rules (Safe Drinking Water Act).

7.0 Relevance to Carbon Capture and Storage

Although Trailblazer plans to sell its captured CO_2 into the Permian Basin EOR market, it is instructive to understand the potential for geologic storage without concurrent EOR in the area surrounding the site. An understanding of the desktop study conducted by Subsurface for Tenaska could assist other CCS projects in determining at a high level the suitability of various formations for sequestration.

8.0 Conclusions

Trailblazer was located in West Texas in order to ensure that the CO_2 captured by the Project would be a source of revenue rather than a liability. Although it is Tenaska's intention to sell the Project's captured CO_2 into the robust Permian Basin CO_2 market, the company believed it was prudent to at least conduct a high-level review of the potential for saline sequestration in the area around the Project.

The study revealed that the Cambrian Sand formation that is part of the Eastern Shelf of the Midland Basin is a viable saline reservoir for sequestering CO_2. It is estimated four to 13 wells would be required to inject the 5.75 million tons (5.22 million metric tons) a year of CO_2 projected to be captured by the Project for 30 years. The biggest technical risk of developing a sequestration project in the formation is the numerous wells that have been drilled into the cap rock above the target formation. This could be mitigated by examining plugging records to ensure that the wells were plugged properly, and to correctly plug any wells that had been plugged incorrectly.

9.0 Acronyms and Citations

9.1 Acronyms

Acronym/Abbreviation/Frequently Used Term	**Definition**
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DOE	United States Department of Energy
EOR	Enhanced Oil Recovery
EPC	Engineering, Procurement and Construction
FEED	Front-End Engineering Design
Fluor	Fluor Enterprises, presumptive EPC contractor
MOU	Memorandum of Understanding
Project	Tenaska Trailblazer Energy Center
ppm	Parts per million
psi	Pounds per square inch
Subsurface	Subsurface Technology Inc.
Tenaska	Tenaska, Inc., developer of the Trailblazer Energy Center, and Tenaska Trailblazer Partners, LLC, owner of the Trailblazer Energy Center
Trailblazer	Tenaska Trailblazer Energy Center

9.2 Citations

[1] *Storing CO_2 and Producing Domestic Crude Oil with Next Generation CO_2-EOR Technology: An Update*, U.S. Department of Energy, DOE/NETL-2010/1417, April 30, 2010, p. 13.

[2] *Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Permian Basin*, Advanced Resources International for the U.S. Department of Energy, February 2006, p. 2-3.

[3] *Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Permian Basin*, Advanced Resources International for the U.S. Department of Energy, February 2006, p. 1-7.

[4] *Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Permian Basin*, Advanced Resources International for the U.S. Department of Energy, February 2006, p. 1-8.

[5] *Basin Oriented Strategies for CO_2 Enhanced Oil Recovery: Permian Basin*, Advanced Resources International for the U.S. Department of Energy, February 2006, p. 1-7.

Exhibit 1

Structural Map of the Top of the Cambrian Sand