COMMERCIAL-SCALE
CO_2 CAPTURE AND SEQUESTRATION
FOR THE CEMENT INDUSTRY

Final Technical Report

Reporting Period: November 16, 2009 – July 28, 2010

Prepared by

Adolfo Garza
Cemex, Inc
920 Memorial City Way, Suite 100
Houston, Texas 77024 USA

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Nelson F. Rekos
USDOE Program Manager

DISCLAIMER

ABSTRACT

On June 8, 2009, DOE issued Funding Opportunity Announcement (FOA) Number DE-FOA-000015 seeking proposals to capture and sequester carbon dioxide from industrial sources. This FOA called for what was essentially a two-tier selection process. A number of projects would receive awards to conduct front-end engineering and design (FEED) studies as Phase I. Those project sponsors selected would be required to apply for Phase II, which would be the full design, construction, and operation of their proposed technology. Over forty proposals were received, and ten were awarded Phase I Cooperative Agreements. One of those proposers was CEMEX. CEMEX proposed to capture and sequester carbon dioxide (CO_2) from one of their existing cement plants and either sequester the CO_2 in a geologic formation or use it for enhanced oil recovery. The project consisted of evaluating their plants to identify the plant best suited for the demonstration, identify the best available capture technology, and prepare a design basis. The project also included evaluation of the storage or sequestration options in the vicinity of the selected plant.

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Executive Summary

This project evaluated the integration of all major carbon capture and sequestration (CCS) components: CO_2 capture transportation/delivery, and sequestration and comprehensive monitoring, verification, and accounting (MVA) for an industrial-scale cement plant.

This project was designed to be executed in 2 phases. Phase I started November 16, 2009, and it was expected to be finished by June 16, 2010 (7 months). In order to be considered for competitive Phase 2 funding, the Recipient was required to prepare and submit to the DOE a detailed Phase 2 Renewal Application by April 16, 2010. Phase II consists of a total of 60 months from the time of acceptance of CEMEX's Renewal Application Form.

CEMEX requested that DOE allow a six-week No Cost extension in Phase I in order to run an optimization analysis and identify the opportunities to reduce both capital and operating cost of the CCS system using both solid sorbent CO_2 capture technologies (RTI Dry Carbonate and CaO Cycle Process). This request was approved by DOE, and the end date of Phase I was moved from June 16 to July 28, 2010.

Previous studies by CEMEX Research Group Switzerland since 2003 have concluded that solid sorbent CO_2 capture technologies are most promising for cement plant application, and a comprehensive technology assessment by CEMEX has shown that both CEMEX's Calcium Looping Process and RTI International's Dry Carbonate CO_2 Capture Process technologies offer significant advantages over competing capture technologies for the cement industry. Dry processes were selected largely because the cement industry has little experience in handling liquid streams. CEMEX USA and RTI engaged in an agreement to work together to develop the most suitable of these capture technologies for application in the cement industry. The major activities of this project included:

- A technical and qualitative evaluation of CEMEX's cement plants in the United States to identify a Phase II host site, resulting in the selection of CEMEX's cement plant in Odessa, TX as having the most promise for installation of a CCS system in the near future.
- Evaluation of CO_2 geologic storage and CO_2 transportation requirements at the chosen cement plant host site and identification of potential off-site sequestration alternatives.
- A preliminary environmental and site permitting study for a commercial-scale CCS demonstration was conducted. An Environmental Information Volume (EIV) was developed identifying the gaps required to be addressed when proceeding with Phase II work.
- Simulation, modeling, and economic evaluations were developed to evaluate the capital investment and operating costs for two CO_2 capture technologies to be installed at the Odessa Plant. CEMEX's CaO Looping technology and RTI's Dry Carbonate Process were selected for a thorough evaluation due to distinct

advantages of both technologies for application within a cement manufacturing facility.

The results of the activities listed above are presented and discussed in this document, as well as conclusions about the incorporation of CCS into a cement plant, particularly the Odessa Plant in western Texas, are included in this Final Technical Report.

1.0 Introduction

It is estimated that the cement industry accounts for about 5% of the global anthropogenic CO_2 emissions. The cement industry has identified measures to reduce its carbon footprint through energy efficiency, reduction of clinker factor, and the use of alternative fuels (including carbon-neutral fuels). However, this industry recognizes that these measures will only go so far in mitigating CO_2 emissions. CO_2 emissions reductions are limited by the very nature of cement production. One of the main reasons for this is that typically only around 40% of emissions are related to combustion of fuels; the rest stems from a chemical reaction in our raw material, the calcination of limestone. Due to the limited potential for conventional means to reduce emissions, CCS is expected to play a significant role if the cement sector is to reduce its absolute emissions at a global scale.

CEMEX, Inc. (CEMEX USA), through Cooperative Agreement DE-FE0002411with the U.S. Department of Energy (DOE) has completed a comprehensive study evaluating the feasibility of conducting a commercial-scale demonstration of CCS, capturing and storing up to 1 million tons of CO_2 emitted from one of CEMEX's cement plants in the United States.

The project was to be executed in two phases with the first phase comprising the selection of a cement plant host site, evaluation of the CO_2 sequestration potential, evaluation of the environmental and public acceptance risks, and selection of a CO_2 capture technology. Phase II was envisioned to include the design, construction, and testing of a commercial-scale integrated CCS system at a CEMEX cement plant.

In Phase II, CEMEX planned to carry out the design and engineering of the selected CO_2 capture technology for cement plant application; environmental permitting to complete documentation required by local, state, and federal agencies; detailed engineering; and procurement of the major components of the commercial-scale CCS demonstration unit. Also included was construction of the CO_2 capture system, CO_2 compression station, CO_2 pipeline (if needed), CO_2 injection station and monitoring, and the MVA system. This was to have been followed by at least 12 months of operation of the commercial-scale CCS demonstration system to determine the real impact on a cement plant's economics, operation, and performance.

This Final Technical Report summarizes progress made, results, and conclusions reached on the project from November 16, 2009, through July 28, 2010.

2.0 Project Goals

The overall objective of this project was to conduct a commercial-scale demonstration of CCS with the sequestration of up to 1 million tons of CO_2 emitted from one of the CEMEX cement plants in the United States. The project included integration of CO_2 capture, transportation/delivery, and sequestration incorporating comprehensive MVA.

This project was designed to be executed in two distinct phases. In Phase I, CEMEX USA proposed to:

- Select a sequestration partner and CCS partner.
- Select the cement plant host site.
- Conduct studies on the sequestration potential at the selected site.
- Select a CO_2 capture technology for commercial-scale demonstration in the cement industry.
- Select the CO_2 sequestration site and determine CO_2 transportation requirements.
- Carry out preliminary environmental and site permitting for the commercial-scale CCS demonstration.
- Prepare the project management plan, including budget, schedule, deliverables, and project team for the commercial-scale CCS demonstration to be conducted in Phase II.

3.0 Project Description

Phase I encompassed work ranging from project definition activities to preliminary design and permitting. Project definition activities included, but were not limited to, development of a project baseline, detailed project management plan, project schedule, project cost estimate, firm host site and financial commitments, and funding plan for the non-DOE share of the project costs. Information was prepared to assist DOE in performing its obligations pursuant to the NEPA process.

Preliminary design activities were carried out, including overall design, development of the process concept (including process flow diagrams with major equipment items and energy and material balances), process chemistry and engineering concepts, technology hardware identification, descriptions of attributes of the devices or modules or major pieces of equipment, principles and engineering or research and development analysis, and data processing to support the design. Capital and operating costs for the project were also determined.

An evaluation and selection of a potential sequestration site around an existing cement plant as well as the evaluation of CO_2 transportation requirements was included.

3.1 Project Team

CEMEX USA was the prime contractor for this proposed project and had the overall obligation of ensuring that the tasks and subtasks of this project management plan (PMP) were performed and delivered on time, on budget, and with scientific integrity. CEMEX USA had primary responsibility for project management activities. CEMEX USA coordinated all interactions with DOE/NETL and all activities of CEMEX staff, project partners, and any consultants, vendors, or suppliers that were utilized in this project.

RTI, an independent, non-profit research organization based in Research Triangle Park, North Carolina, has been developing the Dry Carbonate Process under DOE Cooperative Agreements DE-FC26-00NT40923 and, more recently, DE-FC2607NT43089. RTI's role in this effort was to provide one of the CO_2 capture process technologies, support the process development program, and assist CEMEX USA in the design, integration, and operation of the carbon capture and storage demonstration program.

Schlumberger Carbon Services (SCS) was the sequestration partner. SCS's role was to evaluate and select potential sequestration sites around CEMEX USA plants and assist with the evaluation of CO_2 transportation requirements.

The engineering assessment firm KBR provided process engineering support to the assessment of both CO_2 capture technologies. KBR conducted a comprehensive economic and engineering assessment of the technologies to support an informed decision by CEMEX USA.

AECOM, the environmental consulting firm, conducted environmental, liability, and public acceptance analysis for a set of three candidate cement plants. They also gathered site-specific information to initiate permitting and NEPA analysis for the cement plant host site and prepared the Environmental Impact Volume (EIV) document.

After consultation with several recognized companies, CEMEX selected SCS as the sequestration partner for this project. SCS's role was to evaluate and select potential sequestration sites around CEMEX USA plants and assist with the evaluation of CO_2 transportation requirements. This process included general regional studies around each of CEMEX USA's plants to estimate distance from CO_2 sources, initial estimate of storage capacity, screening for leakage potential, estimated injection depth and pressures, and potential for enhanced oil recovery (EOR). Once a host site was selected, SCS evaluated the site for sequestration options, including the surrounding area for EOR and deep saline aquifers, using available regional data, well data in the surrounding area, and seismic data to help with this evaluation. SCS applied the site data to a 3-D Petrel model and ECLIPSE reservoir simulation to advance the understanding of the site's subsurface properties.

CEMEX USA employed earned value management techniques meeting industry standards for tracking completion of work, keeping activities on schedule, and controlling costs to remain within the projected budget. CEMEX USA implemented, managed, and reported on activities in accordance with the approved PMP. Technical quarterly progress reports were prepared and submitted as required in the Financial Assistance Reporting Requirements Checklist.

3.2 Plant Selection

Sequestration Factors

One primary factor in the selection of the host site was the proximity to good sequestration formations. This evaluation was accomplished in a multi-tiered approach. CEMEX evaluated seven of its production facilities with respect to the availability in the Tier 0.

CEMEX USA and SCS conducted a Tier 0 evaluation of the CO_2 sequestration potential in proximity to seven candidate cement plants identified in CEMEX's proposal. Evaluation was based on distance from the CO_2 source; initial screening of sealing layer and leakage potential; estimated thickness, depth, and pressure of sequestration zones of interest; and the potential for EOR. The evaluation was based on proximity maps of existing wellbores for oil and gas fields, stratigraphic columns of the region, and any other regional data that could be used for a "quick look" analysis.

As a result of this Tier 0 evaluation, three cement plants were identified as sites with relatively good CO_2 sequestration opportunities in their proximity.

In the second part of the suite sequestration analysis, CEMEX USA worked with SCS to conduct a Tier 1 evaluation of the CO_2 sequestration potential in proximity to the three more promising candidate cement plants identified in Tier 0. In order to assure consideration of the main factors contributing to the best selection of the most suitable plant from the sequestration point of view, evaluation criteria were developed with the sequestration partner, and each CEMEX USA location was evaluated. The parameters included in the evaluation were:

- Reservoir Type
- EOR Potential
- Primary Storage Potential
- Secondary Storage Potential
- Number of seals above primary Zone of Injection (ZOI)
- Confidence in Existing Data
- Number of Wells for Leakage Potential
- Public/Political Acceptance
- Land Acreage
- Mineral Ownership
- Tectonics

Upon completion of Tier 1 evaluations, the Odessa Plant was identified as the site with the best sequestration potential with some of its strongest advantages being:

- EOR Potential
- Kinder Morgan CO_2 pipelines actually cross property (see Figure 2)
- Site geology is well-known, large database of subsurface information
- Near a potential "FutureGen" site which was studied in great detail and found to have positive sequestration potential

A view of the Odessa site is presented in Figure 1.

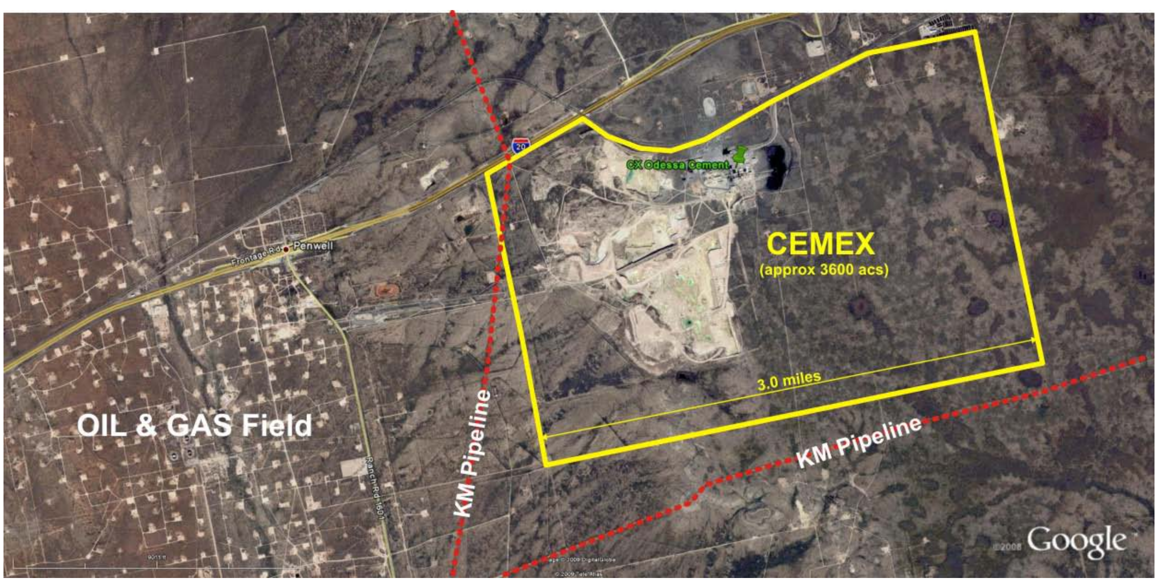

Figure 1. Odessa Site

Process Assessment

The manufacture of cement consists of four major functions as depicted in Figure 2 and described as follows:

1. *Mining*: The raw materials used to prepare cement are primarily limestone, clay, shale, and silica sand. These materials are quarried, crushed, and transported to a nearby cement plant.
2. *Kiln feed preparation*: Raw materials are proportioned to the correct chemical composition and ground to a fine consistency. Hot gases from the pyroprocessing system (kiln) are used to dry the raw materials before they are fed into the kiln.
3. *Clinker production*: The finely ground raw meal is fed into large rotary kilns where it is heated to about 1,500°C (2,700°F). The flame in the hottest part of the kiln can reach up to 1,870^{o}C (3,400^{o}F). This high temperature causes the raw meal to react and form complex mineral compounds which exit the kiln as small, dark gray nodules called "clinker."
4. *Cement milling of clinker*: The clinker is cooled and ground with approximately 5%wt. of gypsum and other additives to produce cement.

Process components of a cement plant important to identify differences between the three candidate plants are: 1) kiln technology, 2) raw mill technology and configuration, 3) fuel firing systems, and 4) waste heat utilization.

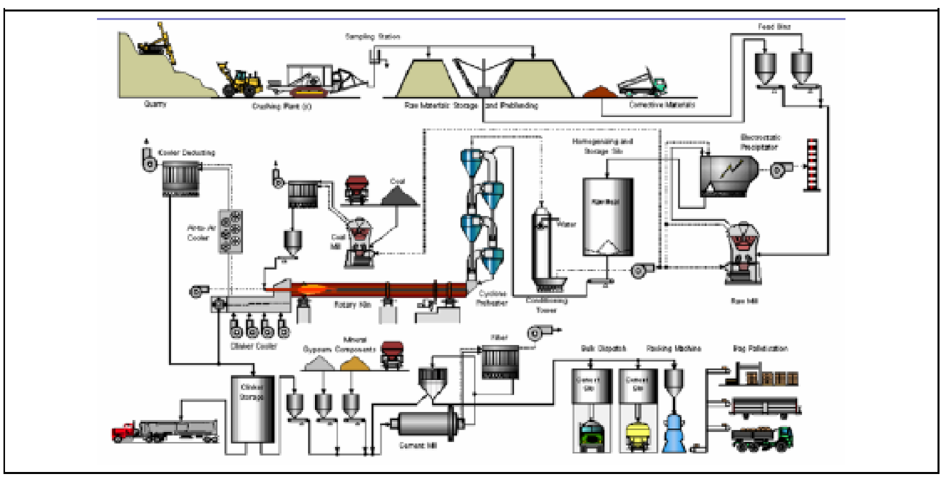

Figure 2. Illustration of the cement manufacturing process

Plant operating conditions of three cement plants, selected in a preliminary evaluation were compared in order to select one candidate cement plant. The process assessment of the three candidate cement plants (Plants A, B, and C) was conducted through review of plant data records of process flow diagrams, operating conditions (clinker rate, fuel use, excess oxygen [O_2], gas temperature, and compositions) and flue gas characteristics of the Odessa Plant (Plant A), Plant B, and Plant C. This process assessment provided insights on kiln configuration and operating conditions to determine kiln suitability to retrofit CCS technology. These three cement plants have different kiln technology and process configuration.

The Odessa plant operates two kiln lines: a long-dry kiln and a 4-stage preheater kiln. Production line #1 is the long-dry kiln system. Although it has a relatively simple kiln configuration, the type and age of kiln technology and design of auxiliary equipment are major drawbacks to retrofit CCS technology on this kiln. Production line #2, the 4-stage preheater kiln, also has a relatively simple kiln configuration. It does not integrate the operation of either the raw mill or coal mill with kiln flue gases.

Plants B and C operate a preheater-precalciner kiln. This kiln configuration is more complex because it uses kiln flue gases to dry raw materials and fuels to maximize the overall energy efficiency. In this regard, three factors may hinder the successful retrofit of a first generation CO_2 capture system in these cement plants:

- Flue gases may experience significant variation in flow rate, gas temperature, and gas composition, as a function of the operational condition of dual fuel firing (kiln and calciner), raw meal, and flue grinding systems.
- Extensive equipment modification would be required, such as adapting the raw and fuel grinding systems to operate with another source of heat if a CO_2 capture technology such as CEMEX's calcium process were going to be designed to pull the total of flue gases off the preheater tower exit. By design, these raw and fuel grinding systems may or may not include small back-up air heaters for mill start-up and will not likely be able to sustain continuous operations at full production capacities.
- Cement production cost will considerably be impacted if additional fuel consumption, likely natural gas, is required to independently operate the raw meal and fuel grinding systems.

Plant C configuration is even more integrated, because it also uses the clinker cooler exhaust, along with the kiln flue gas, to dry raw materials and fuels.

Typical operating conditions of these three cement plants were also evaluated. Two sets of operating conditions are identified for the cement plants highly integrated (Plant B and C), raw mill ON and raw mill OFF.

Given the configuration of a cement kiln, operating conditions fluctuate as a result of:

- Changes in kiln operation due to variations in kiln feed chemistry, kiln feed rate, fuel firing regime, excess air, etc.
- Changes in cooler operation due to variations in hot clinker flow pattern into cooler, air-to-clinker ratio, specific air loading, under-grate pressures, etc.

- Changes in raw mill operation due to variations in raw mix chemistry, raw mix moisture content, etc.
- Changes in fuel mill operation due to variations in fuel type, fuel hardness, fuel moisture content, etc.

Stack flue gases may experience variability in flow, temperature, and gas composition as operating conditions vary due to one of the listed factors, particularly for kiln systems highly integrated such as those in Plants B and C. Solid sorbent CO_2 capture technologies—RTI's dry carbonate process and CEMEX's calcium process—are thermodynamically dependent for CO_2 adsorption. A fluctuation in flue gas temperature of 20-60ºF can severely impact kinetic performance. Plants B and C would require a robust and reliable process temperature control ahead of the CO_2 capture units.

In order to assure a long-term successful commercial demonstration of CO_2 capture in cement kilns, CEMEX USA believes that Odessa production line #2 is the most suitable kiln to retrofit a CO_2 capture technology. Simplicity of kiln configuration, flue gas stability, small scale-up factor, availability of waste heat, and easy gas conditioning make it an excellent candidate for this project. Some European CO_2 capture projects using the Calcium Looping Technology have reached successful laboratory experimentation (<0.5TPD CO_2) and are transitioning to proof of concept units (5to 25 TPD CO_2). Given the emphasis of most of these projects is the power industry, starting with a small scale-up factor, the lower end of the proof-of-concept units, ~5TPD CO_2, is recommended because some significant design challenges still need to be proved at the lowest scale possible. CEMEX USA considers that the combination of these criteria is needed to minimize the risk of implementing a CO_2 capture technology in a cement plant.

Process Audit of the Odessa Site

Recent process data was gathered as baseline information for detailed engineering and economic analyses of CO_2 capture technologies on the Odessa production line.

A process audit of the viable cement plant (Odessa plant) consisted of field measurements of gas and solids streams following CEMEX standards for cement kiln process evaluation. Before starting this process audit, the kiln was operated at, or close to, its nominal capacity under stable operating conditions. Upon reaching stable operating conditions, solid measurements were taken to determine flow rates of return dust and clinker. Return dust is the kiln feed dust picked up by preheater exit gases. This dust is collected in the main baghouse and sent back to the homogenization silo. Kiln feed rate was calculated by using a kiln feed-to-clinker ratio of 1.67 determined by clinker weigh tests. Quality analyses were also run on all the solid samples. Various gas measurements and samples were taken around the system including at the following points:

- Kiln exit
- Preheater exit
- Exit of each preheater cyclone

- Cooler vents
- Discharges of cooler air fans
- Fuel conveying air line
- Main stack
- Before and after the main baghouse

Process boundaries for the mass and energy balance are depicted in Figure 3. Stream identification is presented in Table 1.

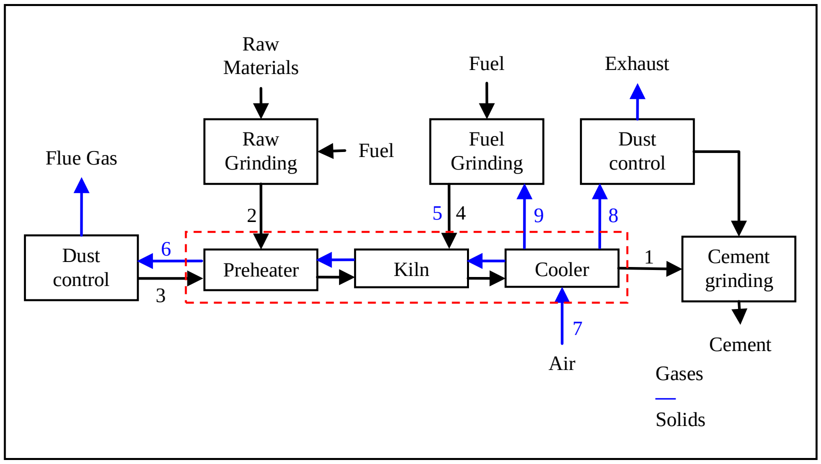

Figure 3. CEMEX Odessa Plant – Production Line #2

Table 1. Stream Identification – Odessa Plant Kiln #2

Stream #	***Name***	***Flow Rate (TPH)***	***Temperature (oC)***
1	Clinker	32.7	116
2	Kiln feed	52.6	77
3	Return dust	5.84	77
4	Fuel	4.75	86
5	Fuel conveying air	16.5	86
6	Kiln / Preheater exit gases	96.2	330
7	Cooling air	109.8	77
8	Cooler exhaust	56.3	326
9	Cooler coal-mill air take off	4.4	529

Historic clinker production rates were reviewed to determine the level of operation at which process audit measurements were taken on this kiln. It was concluded that process measurements during this audit can represent the future average operating conditions of this kiln, and they are suitable for process engineering and design.

Measured CO_2 emissions were estimated at 250,292 metric tons per year, and a 75% capture efficiency gives us 187,719 metric tons of CO_2 per year. The specific CO_2 emissions for Kiln #2 were calculated at 888 kg CO_2 per metric ton of cement.

Kiln energy efficiency was determined after conducting mass and energy balance calculations on production line #2. The ratio of total energy input (fuel use) to total clinker output is named specific heat consumption (SHC). SHC serves as guidance during process audits to identify opportunities for process improvement in terms of energy consumption. SHC calculated for production line #2 is 1008 kcal/kg of clinker (3.63 million British thermal units (MMBTU)/short ton of clinker). This number can provide a baseline to evaluate full impact of the CO_2 capture technology on operation, economics, and performance of this production line.

Opportunities for process improvement identified during this audit that can have a positive impact in retrofitting CCS technology are:

- Minimization of air in-leakage along preheater tower would yield a higher CO_2 concentration in the kiln flue gas.
- Increase in cooler recuperation efficiency would yield reduced fuel consumption, therefore less fuel-derived CO_2 emissions.
- Optimization (or replacement) of direct firing system would yield reduced fuel consumption, therefore less fuel-derived CO_2 emissions.

Gas and solids flows at different points in these systems are determined. The volumetric gas flow of kiln exit gases, 49,510 Nm^3/h, contains a combination of combustion products, excess air and CO_2 from limestone calcination inside the kiln. Gas flow at the preheater exit, 68,799 Nm^3/h, contains the kiln exit gas, CO_2 from partial limestone calcination, and air in-leakage along the preheater tower. The measured stack gas flow, 187,374 Nm^3/h, contains the sum of preheater gases and air used for gas quenching. The stack gas flow is over 2.5 times the volume of the preheater exit gas flow. If gas quenching were to be done by other cooling mechanisms, it would be possible to achieve a smaller stack gas flow rate. A smaller volume of stack gas would be very beneficial for the CO_2 capture equipment designs (smaller CO_2 adsorption reactors would likely be required). Air infiltration in the form of in-leakage and quenching also has a significant impact on the CO_2 concentration. While the CO_2 concentration at the kiln inlet is ~19% vol. and 23.5% vol. at preheater exit, it is only 8.6% vol. at the main stack. Likewise, the concentrations of O_2, H_2O, and N_2 are impacted. In order to retrofit this plant with a CO_2 capture technology as per DOE's desired 10%vol. target, minimization of the amount of air in-leakage is a must.

As previously discussed, CO_2 concentration of production line #2 at the stack was measured lower than expected. An internal analysis was conducted to evaluate water injection at the exit of the preheater tower exit. Plants B and C are configured with gas conditioning towers to quench gases prior to the main baghouse any time the raw mill is shut down. This practice is common across the cement industry and would not pose any adverse effect to flue gas characteristics. Before considering the installation of a gas conditioning tower for the Odessa plant, the use of water injection with spray nozzles to quench the Odessa flue gas was analyzed. This analysis indicates that water injection may be feasible and will achieve a higher CO_2 concentration, up to 21.7% vol. from 8.6% vol., at the stack of this production line. One drawback is that this practice does limit the ability to recover heat from the gas stream. Calculations show that quenching gases from

330^{o}C to 220^{o}C would require approximately 22GPM of water. In practice, gas temperatures may need to be slightly above 200^{o}C to avoid water condensation and corrosion (due to presence of SO_3) in the baghouse unit.

A computational fluid dynamics (CFD) model was set up to predict the behavior of gas quenching using water injection at the exit duct of the preheater tower of production line #2. Duct dimensions and nozzle specifications were determined.

Using a set of historic stack data and flue gas measurements, the stack gas and preheater gas baseline data were defined for process engineering and design of RTI's Dry Carbonate Process and CEMEX's Calcium Looping Process.

CEMEX USA believes that the Odessa plant, production line #2, can be retrofitted to operate at commercial scale a proposed CO_2 capture technology to capture >75% of CO_2 from the cement kiln flue gas comprised of about 20%vol. CO_2 for a total capture amount in the range of 160,000 to 180,000 metric tons of CO_2 per year.

<u>Permitting Environment and Public Acceptance of Candidate Plants</u>

The objective of this work was to review the environmental liability and public acceptance of three potential sites for a commercial-scale CCS demonstration project. The three CEMEX sites were Plant A (Odessa), Plant B, and Plant C.

In order to evaluate these three sites, the CEMEX contractor, AECOM, visited each site and met with the site environmental staff, researched and evaluated the current permitting environment in each state, and also researched the current trends in the local and regional environment regarding the acceptance of CCS. Based on the review of available information, all three sites could serve as the demonstration project site. However, Plant A and Plant B appear to have the greatest degree of public acceptance, and the Plant A site would likely have the least cumbersome level of permitting requirements. As a result, the overall ranking for the three sites is as follows:

1. Plant A (Odessa, Texas)
2. Plant B
3. Plant C

Based on the above analysis, it was determined that CEMEX's Odessa, TX Plant was the most viable host site for this industrial CO_2 capture demonstration.

<u>Other Site-Specific Factors</u>

An assessment of the three candidate cement plants previously identified was conducted using site surveys to determine associated factors required to retrofit a CO_2 capture technology in an existing cement plant facility. Questions were designed to obtain qualitative assessments related to the proposed CCS technologies in the areas of:

- Space availability
- Water availability
- Fuel and power supply
- Transportation networks
- Waste disposal
- Flexibility of process equipment
- Site-specific risks

A number of sources, including plant plots, site construction records, plant operating permits, environmental permits, etc., were consulted. A ranking per criterion was given to the three candidate plants, having 1 for highest potential and 3 lowest potential. The lowest total number of all criteria together yields the cement plant site with the highest combined potential to assimilate the retrofit. It is important to mention that, in practice, some criteria and different factors within a criterion may have greater weight than others. However, due to the purely qualitative assessment of site suitability aspects to retrofit CCS technology at this point, equal grading was given to each one.

Space availability and difficulty for construction in available areas is a critical factor in the final cost of engineering and construction. Sufficient area is available for additional process equipment at these three cement plant sites. However, some plant layout challenges were identified for the Plants B and C due to the distribution and current use of these available areas.

Water availability for CO_2 capture process demands was assessed at these three cement plant sites. The location of Plants B and C favor them in terms of water availability. Plant A (Odessa plant) may need additional water sources if more process water is required.

Fuel supply is a key factor for a cement plant to be able to retrofit a CO_2 capture technology. Natural gas is available at these three cement plant sites for additional process purposes. Although procuring additional kiln fuel (coal, petcoke) for these sites is not of concern, the limiting factor relies on the ability of the sites to process (pulverize) this fuel. It was found that Plants B and C are operating their coal mill systems at their maximum capacities and certainly will not be able to process additional fuel without modifications to the overall milling systems. On the other hand, Plant A (Odessa plant) has about 35% readily available capacity to supply pulverized fuel if needed. However, modifications to the firing system (from direct to indirect) are required for the Odessa plant to use that available coal mill capacity.

The retrofit of CO_2 capture technology in a cement plant will definitively impact the level of power consumption by the plant because additional process equipment will require power (e.g. additional fans, conveyors, compressors, etc). Under this criterion, power needs to be managed depending on the solid sorbent CO_2 capture technology of choice. RTI's Dry Carbonate Process will consume power to operate process equipment, while

CEMEX's Calcium Looping Process, although it is also a power-intensive process, will likely generate power that can either be consumed to operate process equipment or be exported back to the utility grid. According to results of this site assessment, Plants B and C have readily available substation capacity. The Odessa plant is close to its substation capacity and will likely require additional equipment.

The logistics to bring additional fuels and/or materials onsite for CO_2 capture technologies does not seem to be a constraint for any of the three cement plant sites. CO_2 pipeline transportation networks are only available at the Odessa plant.

Any process modification, including re-routing ducting, building new equipment, etc, requires construction and potential-of-significant-deterioration (PSD) permits at these sites.

Plant A (Odessa cement plant) is located approximately 10 miles away from residential developments, while Plants B and C are within 1 mile. This fact brings certain implications to the local permitting due to their proximity to urban areas.

This site assessment of the three candidate cement plants identified the Odessa plant as best-suited for a successful CCS commercial demonstration.

3.3 Process Selection

The results of an initial comparison of various process types conducted by CEMEX are presented in Table 2. CEMEX ultimately decided that dry processes are best suited for the cement industry and focused on two such processes for this project—RTI's Dry Carbonate Process and CEMEX's Calcium Looping Process.

Table 2. Qualitative Comparison of General CO_2 Capture Technologies for the Cement Industry

Parameter	Post-combustion			Oxy-combustion
	Solid-based (CaO Looping, RTI's dry carbonate)	Solvent-based (ex. Amines)	Membranes	
Energy Demand	Intensive to regenerate sorbent	Intensive to regenerate solvent	Intensive to pressurize gases	Intensive to operate air separation unit
Equipment Materials Processes	In development	Well-developed	In development	Conceptual retrofit on cement kilns
Flue Gas Conditioning	Extensive to avoid sorbent contamination	Extensive to avoid solvent contamination	Extensive gas to avoid membrane deterioration	Removal of other gas constituents from CO_2 product
Other Gases (O_2, CO, NOx, $H_2O_{(v)}$)	Insensitive	Need inhibitors to avoid degradation	May interfere with CO_2 separation rate	Need to assure CO_2 purity

Acid Gas Control (SO_2, HCl)	May be required	Required	May not be required	May be required
Hazardous Toxic Corrosive	No	Yes	No	No

Bench Scale Studies

The main objectives of this work were to complete an evaluation of RTI's Dry Carbonate Process under simulated cement kiln flue gas conditions and to evaluate various properties of CEMEX's calcium sorbents under simulated cement kiln flue gas conditions using RTI's lab-scale reactor systems and analytical tools.

RTI's lab-scale packed-bed, multi-cycle test reactor was used to achieve the main objective of this subtask. A simplified process flow diagram of the packed-bed reactor system is provided in Figure 4. This system consists of four main sections:

- Flue gas generation
- Packed-bed reactor
- Gas switching valves
- Gas analysis equipment

This arrangement allows for the generation of a wide range of simulated flue gas compositions including neat (CO_2-H_2O-N_2) to more realistic (CO_2-H_2O-SO_2-O_2-N_2) flue gas mixtures. High temperature thermo-gravimetric analyses (TGA) were also used to evaluate CEMEX's calcium sorbents and RTI's Na-based sorbent.

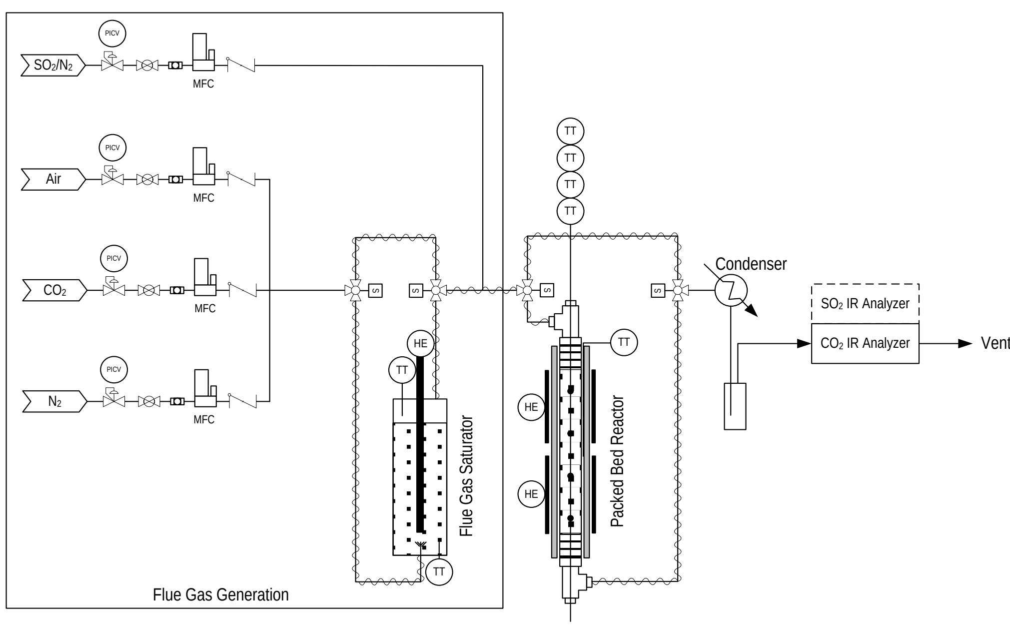

Figure 4. Simplified Process Flow Diagram of Packed-Bed Reactor System for Multi-cycle Testing

Additional TGA were conducted using CEMEX's calcium sorbent. TGA work performed during this reporting period was done on RTI's atmospheric pressure TA Instruments Q500 Thermogravimetric Analyzer. The Q500 is a research-grade TGA that measures weight changes in a material as a function of temperature and/or time under a controlled gaseous atmosphere to allow for a determination of a material's thermal stability and composition. It includes a vertical, dual range microbalance (i.e. can be set for mass loadings of 0–200 mg and 0–1 g) with automated gas switching. RTI has established a flexible gas feed system to allow for the controlled delivery and mixing of a wide variety of gases to the TGA from a resource of gas cylinders. This gas feed arrangement allows for the generation of a wide range of gas compositions that the CaO Looping technology would potentially experience, including inert (Argon or Helium), simulated flue gas (CO_2-H_2O-N_2), and regeneration gas mixtures (Air or CO_2-H_2O-O_2).

Results using RTI's engineered sodium carbonate sorbent showed that the most favorable cement plant process conditions would require flue gases with high CO_2 (~20%vol.) and H_2O (>15%vol.) concentrations. Figure 5 shows that the performance of the Dry Carbonate sorbent is highly tied to the water content of the flue gas, and the process requires operating at a regeneration temperature of ~140^{o}C.

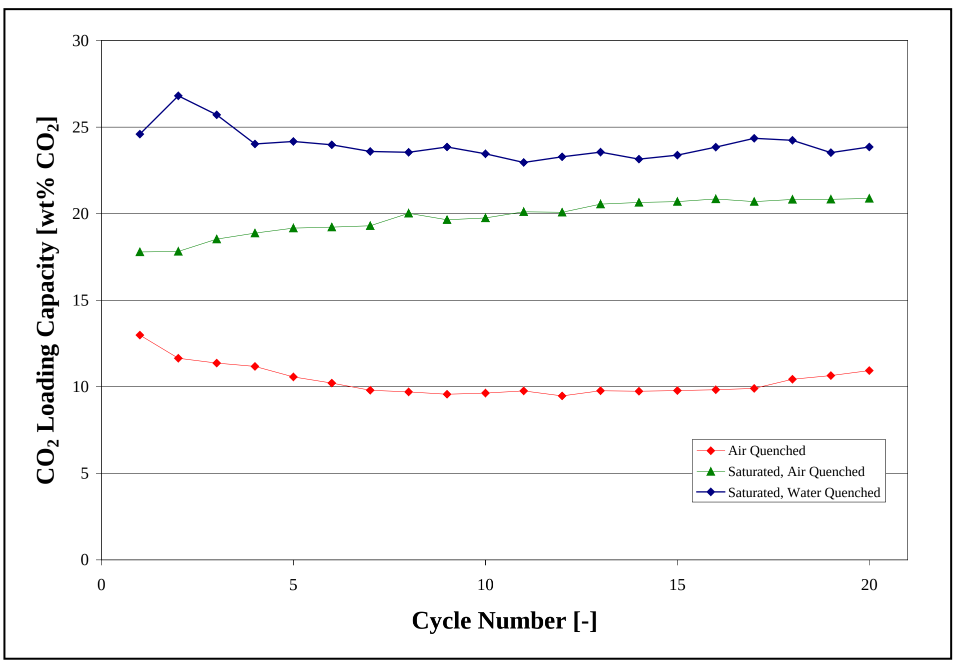

Figure 5. Effect of Flue Gas Composition on CO_2 Loading Capacity

CO_2 loading capacities of RTI's engineered sodium carbonate sorbent for the best test conditions are shown in Figure 6. This graph shows a stable CO_2 loading capacity of 23-24%wt. over 10 cycles. Detrimental conditions on this sorbent are related to attrition and/or sulfur contamination contained in the flue gas. However, testing of either of these conditions was not possible due to the limitations of the reactor systems used to evaluate the sorbent. Based on past experience and learning on other DOE-funded projects, it is expected that the dry carbonate sorbent will require a continuous sorbent make-up to the process due to losses from attrition and contamination. Cement plant flue gases could be conditioned as currently practiced in power plant applications; thus, losses to attrition and contamination are expected to be manageable for cement industry applications.

Results using CEMEX's calcium sorbent showed that the most favorable process conditions would require regeneration temperature near 850^{o}C along with a diluted regeneration gas to avoid a significant drop in the CO_2 loading capacity. CO_2 loading capacities of CEMEX's calcium sorbent for the best test conditions are also shown in Figure 6. This graph shows a decay of CO_2 loading capacity between the 1st and 5th cycle, before leveling off to ~17%wt. over 10 cycles.

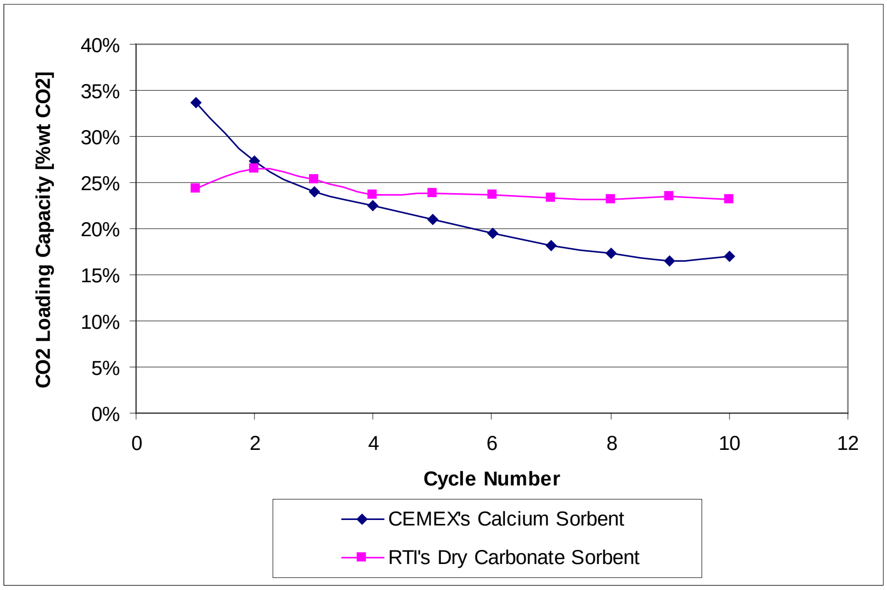

Figure 6. Multi-Cycle Testing of CEMEX and RTI's Sorbents

Comparing these two CO_2 loading capacity trends, it is clear that RTI's engineered sodium carbonate sorbent performs better than CEMEX's calcium sorbent over time. The engineered sorbent's characteristics (particle size distribution, surface area, pore distribution and structure, etc.) allow for a large number of cycles that ultimately would result in low sorbent make-up and purge sorbent. In fact, the sorbent was designed to withstand long operating periods to minimize the operating cost due to sorbent replacement and/or disposal. RTI's Dry Carbonate Process does require careful process design considerations in terms of installing the proper flue gas conditioning systems, absorber fluid dynamics, and sorbent handling to avoid sorbent deterioration.

CEMEX's calcium sorbent is not an engineered material and is not expected to withstand the same cycling that is required of RTI's sorbent. This calcium-based sorbent is used to capture CO_2 but also can be used as raw material for clinker production. The decay of CO_2 loading capacity can be offset by higher make-up and purge rates and transfer to the cement plant's kiln. Finding an optimal balance between these make-up and purge sorbent rates and the clinker production capacity of a kiln system is the key to operating CEMEX's calcium process at higher CO_2 loading capacities. However, the ability to use the spent calcium sorbent in the cement process is a cost advantage over the RTI sorbent which must be reprocessed or disposed.

Design Basis

The main objective of this subtask was to develop the preliminary engineering and design packages for RTI's Dry Carbonate CO_2 capture technology and CEMEX's Calcium Cycle Process integrated into the second kiln line (Kiln #2) of CEMEX's Odessa, TX cement plant.

A conceptual design basis for CEMEX's Calcium Cycle Process and RTI's Dry Carbonate Technology was developed. This design basis for process engineering and design was established to set a comparative baseline for both technologies. More details of this design basis are shown in Figure 7 and Table 3. In addition, two per-ton CO_2 bases were defined to determine technology costs:

1. $CO_{2\_avoided} = CO_{2\_captured\ in\ flue\ gas} - CO_{2\_emitted\ through\ stack\ after\ capture}$
2. $CO_{2\_compressed} = CO_{2\_avoided} + CO_{2\_generated\ by\ capture\ system}$

Parameter	***Value***
Capture rates	>75% CO_2 in kiln flue gas 100% CO_2 generated by capture system
Fuel for capture system	Petcoke
Kiln flue gas flow rate (Nm^3/h)	74,569
Temperature (^oC)	220
CO_2 (% vol.)	21.7
O_2 (% vol.)	5.1
H_2O (% vol.)	14.2
N_2 (% vol.)	58.8

Figure 7. Design Basis for Engineering and Economic Analysis (including flue gas conditions from cement plant)

ASPEN process simulation was conducted to prepare detailed mass and energy balances of both technologies as per the specified design basis. Stack gas measurements at the Odessa plant kiln 2 were conducted by Clean Air. The aim of these gas measurements was to validate stack gas values used for the preparation of conceptual design basis and engineering packages for RTI's Dry Carbonate CO_2 capture technology and CEMEX's Calcium Cycle Process.

Basic block flow diagrams for the integration of these technologies at the Odessa kiln #2 were prepared and are shown in Figures 8 and 9. They show that extensive retrofit is required for both technologies to capture CO_2 at the Odessa plant. Including the capture block, seven new process blocks are needed for full integration. Preliminary engineering and design of equipment in all of these process blocks was completed by CEMEX and RTI. KBR provided feedback on various process units based on its own experience.

Equipment lists, including equipment sizing, materials of construction, specifications, etc., were completed for the economic analyses carried out as part of this effort.

Fuel grinding and air separation are essential blocks to supply fuel and oxygen for sorbent regeneration in CEMEX's calcium process. Waste heat power generation is also very important to take advantage of the high operating temperatures to generate power to offset power demand. The CO_2 purification and compression block is necessary to meet CO_2 storage specifications (pressure, temperature, gas composition, etc.). In contrast, steam generation and flue gas conditioning are very important process blocks for RTI's Dry Carbonate process because these supply the necessary steam for sorbent regeneration and treat the flue gas before contacting the sorbent material. Also, the CO_2 purification and compression block is needed to meet CO_2 storage specifications.

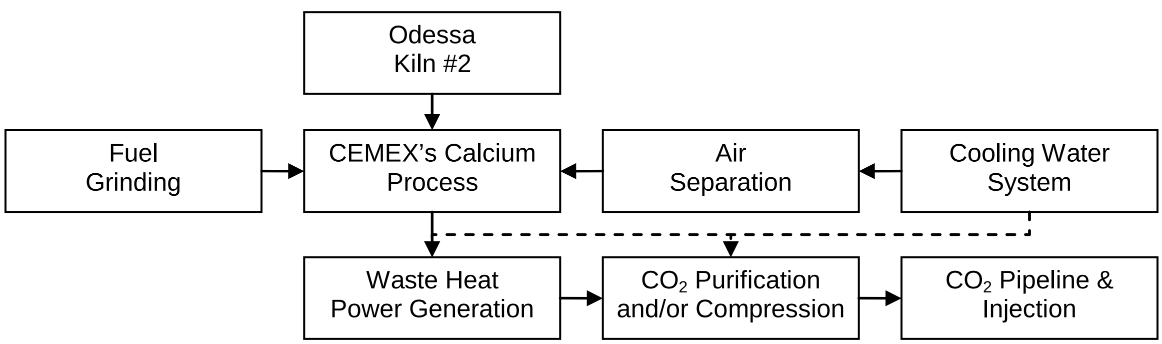

Figure 8. CEMEX's Calcium Process Integrated at Odessa Kiln #2

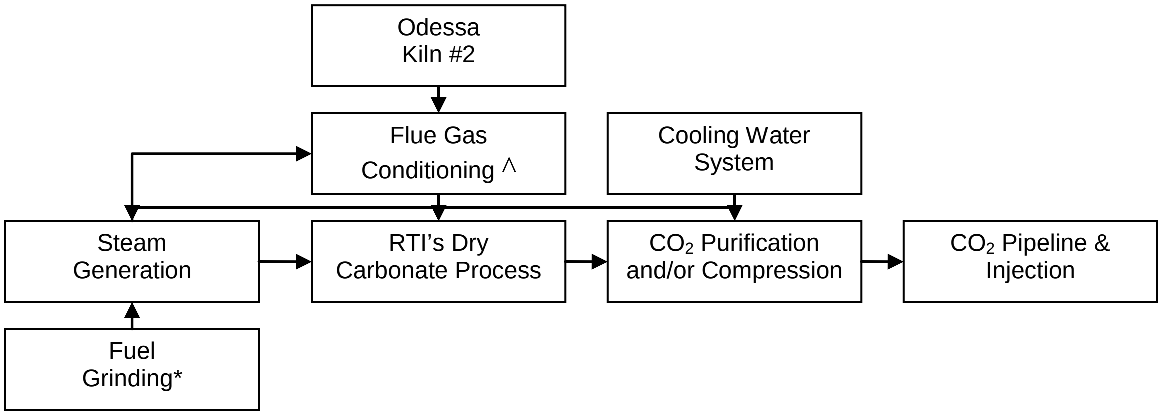

Figure 9. RTI's Dry Carbonate Process Integrated at Odessa Kiln #2

* Not needed if natural gas is used.
^ Not very significant in natural gas case

During the economic and engineering work, it was found that the CO_2 purification block significantly increases the cost and complexity of this technology integration. A CO_2 penalty was also identified when inert gas constituents in the CO_2 product stream are removed by chilled distillation. RTI's regeneration unit seems to be favorable to avoid CO_2 purification if positive pressure operation is properly designed. On the other hand, sorbent regeneration under direct contact with product of combustion in CEMEX's regeneration unit creates a level of uncertainty to whether CO_2 purification is avoidable for this capture process. Research and development is advisable to determine the impact of traces of other gas constituents in CO_2 product streams for geological storage and/or enhanced oil recovery operations. A standard set of CO_2 sequestration conditions and a better understanding of the concentration limits for sequestration and EOR are needed.

Another process block of relevance to the integration of these technologies at the Odessa plant is the cooling water block. It was concluded that the Odessa plant would likely require municipal/industrial district water supply due to onsite water shortage. Both capture processes need to generate steam for heating and power generation purposes. Unavoidable water losses related to steam generation and water cooling for the steam cycles and air separation unit(s) makes the water component of this technology integration a challenge for this plant. However, this water issue may not be as significant at other cement plant sites around the U.S.

Baseline process conditions for both capture technologies were determined using the design basis, engineering considerations for process equipment, and Aspen modeling tools. The absolute CO_2 emissions of Odessa kiln #2 was estimated to ~250,000 metric tons per year. Capturing over 75% of all the CO_2 generated by the integrated system (kiln and capture system) would result in 160,000 to 180,000 metric tons per year of CO_2 avoided for these technologies. Higher avoided CO_2 emissions can be achieved if the CO_2 penalty by the CO_2 purification unit is eliminated. Compressed CO_2 for injection is between 250,000 and 375,000 metric tons per year. Results of baseline process conditions also showed that utilities are increased. If the utility consumption of the Odessa plant (all cement plant equipment) is used as reference for comparison, the retrofit of either of these technologies on Odessa kiln #2 would double the power and fuel demand of the plant. Water demand would increase up to 7 times more than the normal consumption for this plant. Further sensitivity analyses were conducted to identify opportunities to mitigate such increases in plant utilities.

4.0 Economics

The main objective of this effort was to conduct an economic and engineering assessment for RTI's Dry Carbonate Process and CEMEX's Calcium Cycle Process integrated into CEMEX Odessa plant, kiln 2.

Basic process engineering and design of both capture technologies were submitted to KBR for the economic assessment resulting in:

- Order of magnitude, non-binding, indicative capital cost estimates intended only for economic comparisons
- Estimate accuracy: +/- 40% only for total cost
- Historical cost ratios applied to equipment costs developed from sized equipment lists to determine the total installed cost (TIC)
- U.S. gulf coast basis

Exclusions: Capital and operating expenses for additional equipment and utilities required for start-up and shutdown operations are expected to be within the +/- 40% accuracy of the estimate. These costs are presented in Table 3.

Table 3. Baseline Capital and Operating Costs

	CaO Looping Technology	RTI's Dry Carbonate Technology
Capital Cost (Millions USD)	282.8	177.3
Operating Costs* (USD/ton CO_2 avoided & injected)	234.0	232.0

* Includes Annualized Capital Cost

Sensitivity analyses were conducted to identify the opportunities to reduce both capital and operating cost of the CCS system using either solid sorbent CO_2 capture technologies for the Odessa plant case, based on capital and operating costs provided by KBR. In order to perform these analyses, CEMEX requested and received a six-week no-cost extension to Phase I. A summary of these cases is shown in Table 4. Process and equipment descriptions of both capture technologies submitted to KBR were used for the engineering assessment.

Table 4. Basis for Sensitivity Analyses

Case	***CEMEX's Calcium Cycle***	***RTI's Dry Carbonate***
Base	Kiln CO_2 rate: ~250,000 TPY Fuel: Petcoke Waste Heat Power Generation: Yes	Kiln CO_2 rate: ~250,000 TPY Fuel: Petcoke Waste Heat Power Generation: No

	CO_2 Purification: Yes	CO_2 Purification: Yes
1	Base case without CO_2 Purification	Base case without CO_2 Purification
2	Case 1 using Natural Gas	Case 1 using Natural Gas
3	Case 1 with Maximum Waste Heat Power Generation	- - - - -
4	Case 3 with 1MM TPY Kiln CO_2 rate	Case 2 with 1MM TPY Kiln CO_2 rate

Case 2 represents the optimum scenario for RTI's Dry Carbonate technology and Case 4 represents the optimum scenario for CaO Calcium Cycle technology. Optimized Capital and Operating costs for these optimized scenarios are reported in Table 5.

Table 5. Optimized Capital and Operating Costs

	CaO Looping Technology	RTI's Dry Carbonate Technology
Capital Cost (Millions USD)	244.5	99.8
Operating Costs* (Usd/ton CO_2 avoided)	139.0	100.6
Operating Costs only (Usd/ton CO_2 avoided)	21.0	44.0

* Includes Annualized Capital Cost

Furthermore, it is estimated that a 20% capital cost reduction ($/ton CO_2 avoided) can be achieved by scaling up the Odessa case to a one-million-tons-CO_2/yr project, with optimum annualized costs of these technologies ranging between $80 USD to $140 USD per ton of CO_2 avoided, including CO_2 capture, purification, compression, transportation, and sequestration costs (for the whole CCS process).

Cost estimates were submitted by KBR and reviewed by CEMEX and RTI. The capital cost of these technologies for the optimum cases ranged between $100 (MMUSD) and $240 MMUSD, including the sequestration component (well preparation, drilling, monitoring, etc).

The following three process modules (without considering the CO_2 injection module) account for ~75% of the total capital cost for CEMEX's calcium process: 1) CO_2 purification and compression, 2) waste heat power generation, and 3) CO_2 capture. As described in subtask 3.2, CO_2 purification has its own cost and recovery penalties that increase the total capital cost. Alternatives to avoid the use of CO_2 purification for this technology need to be investigated. Waste heat power generation is capital intensive due to heat recovery from multiple sources of waste heat available in this capture process. Dimensions of vessels, the amount of refractory needed and structural support make the CO_2 capture component expensive. Air separation is also a process block that in some way contributes to the total capital cost of this technology.

The economic assessment of RTI's Dry Carbonate process for baseline conditions resulted in similar contributions by CO_2 purification and compression, steam generation and CO_2 capture to the total capital cost. However, proportions are significantly different, particularly for the CO_2 capture block due to inexpensive materials of construction used in low-temperature operations. The steam generation component accounts for ~25% of the total capital cost due to design basis considerations (CO_2 capture from steam boiler exhaust with petcoke as main fuel and low SO_2 emissions in boiler flue gas).

Optimum annualized costs (for the whole CCS process) of these technologies range between $80 USD and $140 USD per ton CO_2 avoided, including CO_2 capture, purification, compression, transportation, and sequestration costs. These total process costs include the amortization of the capital expenditure at 7% interest rate and a 20-yr project life. A breakdown of these cost metrics showed cost allocations on a per-ton-of-CO_2-avoided basis of ~30% and ~70% for operating and annualized capital costs of the CEMEX's calcium process. This high capital cost component is attributed to the reasons explained above. The cost allocation for RTI's Dry Carbonate process on the same basis was about 55%/45% for operating and annualized capital costs. Natural gas, power, and sorbent consumptions are the reasons for this cost split. This cost breakdown shows that CEMEX's calcium process is more capital intensive, while RTI's Dry Carbonate is more operating intensive. Regardless of the capture technology, the cost of CO_2 capture and sequestration for this cement plant is very high. Further cost optimization is required.

The sensitivity analysis completed in this subtask showed that:

- Eliminating CO_2 purification (Base vs. Case 1) may reduce the cost of CO_2 avoided up to 30% for these technologies.
- Switching to natural gas fuel (Case 1 vs. Case 2) yields the largest cost reduction to RTI's Dry Carbonate process, up to 35%.
- Maximizing waste heat power generation (Case 1 vs. Case 3) to offset power demand by the CO_2 capture and compression process yields the largest cost reduction to CEMEX's calcium process, up to 30%.
- The economy of scale (Case 1 vs. Case 4), 1MM TPY CO_2 kiln emission rate, yields up to 20% cost reduction for these technologies.

It can be concluded from this sensitivity analysis that CEMEX's calcium process is best set for the Odessa kiln #2 with petcoke firing, maximum waste heat power generation without (or with minimum) CO_2 purification; while RTI's Dry Carbonate process is best set for the Odessa kiln #2 with natural gas firing without (or with minimum) CO_2 purification. For these cases, the cost breakdown between capital and operating cost on a per-ton-of-CO_2-avoided basis became ~15% and ~85% for operating and annualized capital costs of the CEMEX's calcium process, while remained relatively unchanged (about 55%/45%) for RTI's Dry Carbonate Process.

The breakdown between capital and operating costs should be considered when deciding to operate a cement plant with CCS under these conditions . Fuel prices, particularly natural gas prices, will likely increase as demand for lower carbon fuels increases due to potential CO_2 regulations in the future. Similarly, power prices will increase over time as utilities figure out ways to reduce CO_2 emissions (i.e., by switching to natural gas or capturing CO_2) and translate the final abatement cost to industrial consumers. These factors together can challenge the attainment of low operating costs attributable to fuel and power use of a cement plant with CCS. CEMEX's calcium process's ability to generate power to offset power demand and to use inexpensive fuels is attractive for the cement industry. Opportunities to lower capital cost need to be investigated, particularly for CO_2 purification, compression, and waste heat power generation. Additionally, it is recommended to conduct further studies of the dry carbonate system using petcoke or coal and SO_2 scrubbers to make the balance of operating and capital cost for the Dry Carbonate Process a little more in the favor of capital costs. It is also recommended that an optimal heat integration study be performed for the dry carbonate technology.

An engineering comparison completed in this activity showed that:

- Both solid sorbent capture technologies need pilot testing to better define reactor and system designs, identify actual auxiliary equipment needed for the optimum operating conditions and test the long-term sorbent's performance under actual cement kiln flue gas conditions.
- A better synergy with the cement plant exists for CEMEX's calcium process due to beneficial use of resources (i.e., spent sorbent used for clinker production onsite and/or offsite and waste heat used for power generation).
- RTI's Dry Carbonate process has a lower overall annualized cost than CEMEX's calcium technology.
- Both solid sorbent capture technologies can be integrated into this kiln. However, as previously described, extensive retrofit of auxiliary equipment is required.
- The best set of conditions for each technology suggests that CEMEX's calcium process offers flexibility in the use of different fuels (coal, petcoke, natural gas, or alternative fuels like biomass) and perhaps in the use of different sorbents (i.e., onsite or offsite limestone).
- CEMEX's calcium process has an inherent advantage in the cost of raw materials used for CO_2 capture. The calcium process uses natural limestone, an abundant material throughout the world, which is found at the cement plant site and is already used as the main raw material component in the cement manufacturing process. RTI's Dry Carbonate process uses a sorbent which is inherently more expensive, because of manufacturing costs and because it is not currently used by the cement manufacturing process.
- Both solid sorbent technologies require careful design considerations to minimize the impact on the plant's air and water emissions.

Results of this engineering assessment suggest that both CO_2 capture technologies have distinct advantages and disadvantages in operability and cost. Given the advantages discussed regarding the calcium process and CEMEX's own intimate knowledge of this process, CEMEX would like to pursue the development of this technology further through pilot application. Significant research and development work is needed to optimize the technology design, plant integration, and capital cost.

5.0 Sequestration Analysis

Evaluation of CO_2 Sequestration MVA

CEMEX USA and SCS evaluated current techniques used for MVA in projects around the world. The outcome of this evaluation narrowed the techniques based on prior experience, technical merit, and applicability to the potential storage sites. A full MVA design was not carried out because CEMEX decided to forego Phase II.

Regional Geology and Evaluation of Potential Storage Reservoirs

As part of the three-part evaluation, CEMEX USA and SCS settled on Odessa as the primary host site for the second evaluation. Because of the CCS history within the western Texas area, the regulatory and public environments for the Odessa plant (site) were believed to provide substantial benefits to the successful implementation and execution of the project. The second portion of the evaluation commenced after the site was selected. This investigation included a thorough examination of the regional and site-specific geologic setting. That information was used to identify potential geologic formations for CO_2 storage reservoirs. Information and data from this portion of the study was used to develop the simulation model parameters and the simulation storage capacity models for the potential storage reservoirs.

Geologic Setting and Site Description

The site is located in south central Ector County, Texas. The geologic setting of the site is the Permian Basin, a seismically stable sedimentary basin that extends from western Texas into south-eastern New Mexico. The basin formed during the pre-Permian and continued developing into the Permian's thick layers of sedimentary rock were deposited into the semi-restricted sea that filled the basin. The base of the Permian sediments is separated from earlier Pennsylvanian sedimentary rock by the major Permian/Pennsylvanian unconformity that is found throughout the region. The greater Permian Basin is comprised of the Northwest Shelf, Delaware Basin, Central Basin Platform, and Midland Basin (Figure 8).

The site lies atop the Central Basin Platform located between the Delaware Basin to the west and the Midland Basin to the east. Geologic evidence suggests that the Central Basin Platform formed during the pre-Permian, when a carbonate platform underwent a period of major uplift as a result of block faulting (Figure 9). Fault trends are observed to be largely northwest to southeast in direction, confined to the pre-Permian, and believed to be controlled by lines of pre-existing Proterozoic weakness.

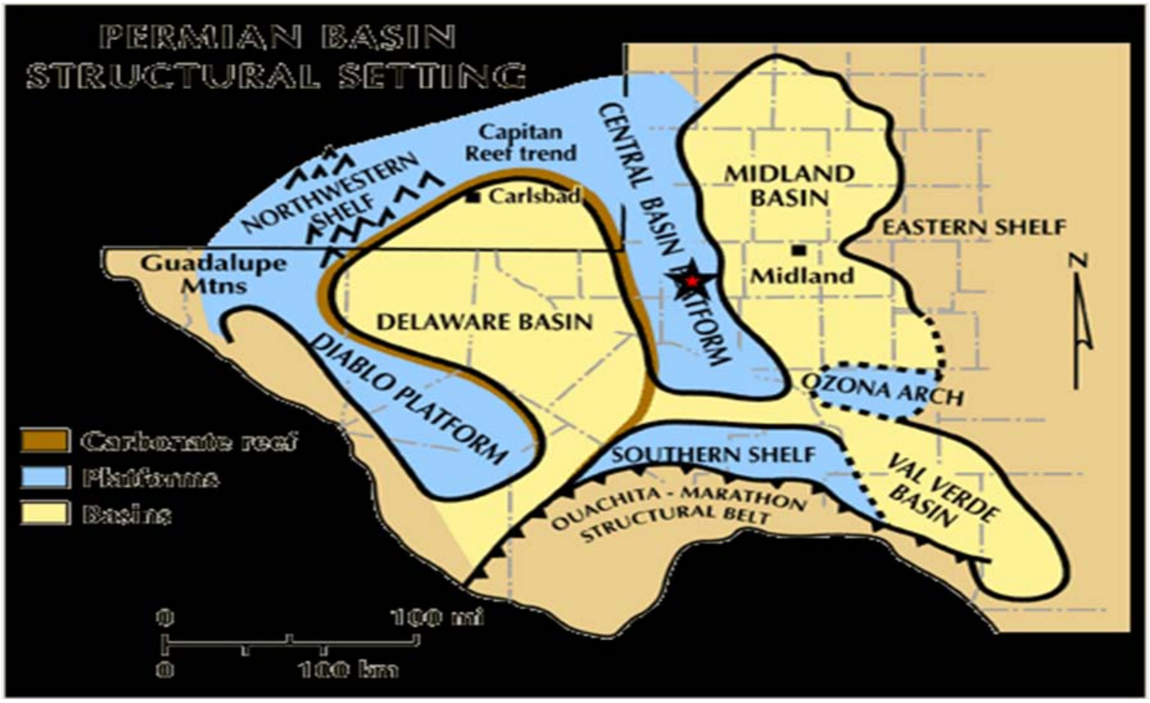

Figure 10. CEMEX Geologic Setting

(**http://www.beg.utexas.edu/techrvw/presentations/posters/wtgs-dutton/graphics/c7964-a1a.gif**).

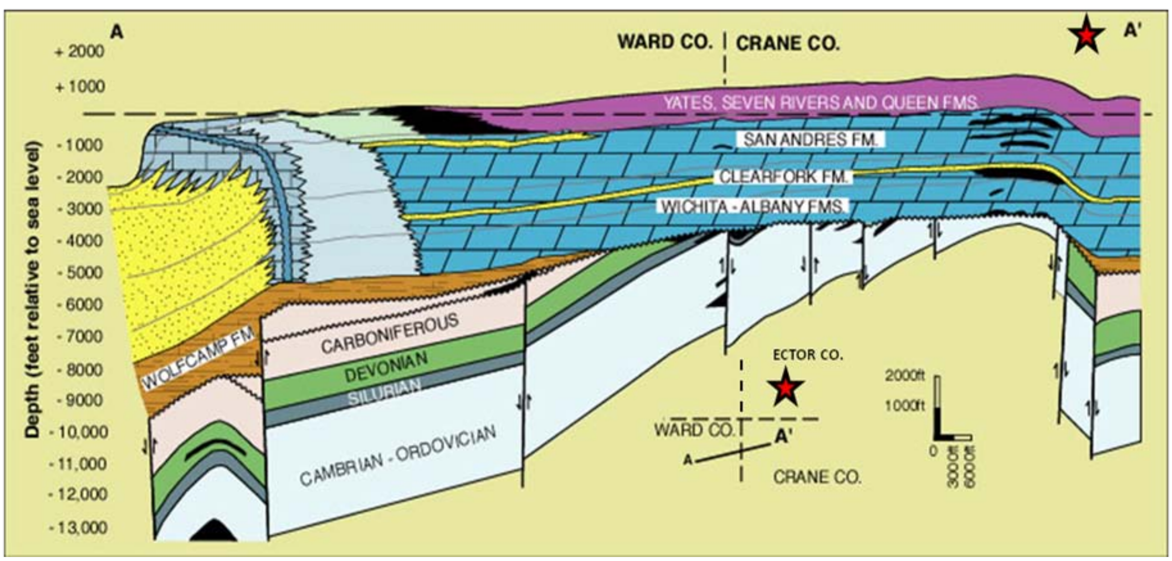

Figure 11. Central Basin Platform Cross-Section

(**http://geoinfo.nmt.edu/staff/scholle/graphics/permdiagr/CentBasinPlat.html**)

Following completion of the uplift, a series of Permian-aged clastic, evaporate, and carbonate sediments filled the newly created Delaware and Midland basins, overlapping on the structural high of the Central Basin Platform. Permian rocks are approximately one mile thick in the Central Basin Platform and thicken eastward and westward toward the Delaware and Midland Basins respectively. Up to an additional half mile of Triassic rocks overlie the Permian and are, in turn, overlain by several hundred feet of Cenozoic rocks. A strategraphic column summarizing the formations and ages is provided as Table 4.

The site lies within a region of historic and currently active hydrocarbon exploration and production. The most prolific productive unit is the Lower Guadalupian aged San Andres formation. Regional production also exists in mixed carbonate and siliciclastic deposits ranging from the Yates in the Middle Permian to the Ellenburger dolomites in the Lower Ordovician. Immediately beyond the western property boundary is the Penwell Field. South Cowden Field is located just east of the property. Harper Field is north of the property, and Jordan Field is south (Figure 10).

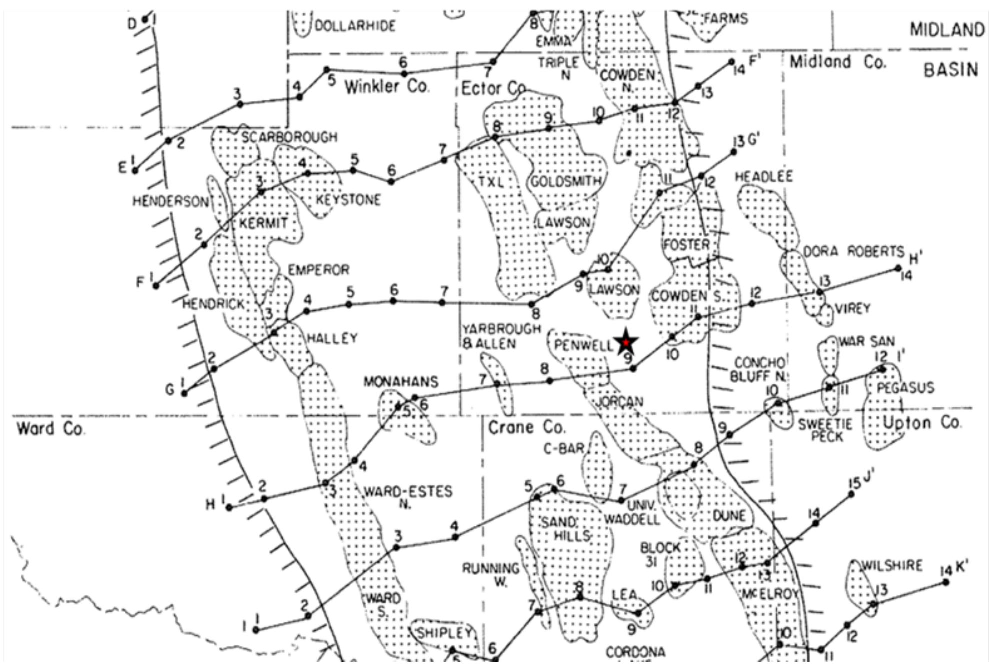

Figure 12. CEMEX Odessa Site, Area Oil Production
(Regional Cross Sections, Central Basin Platform, western Texas, Bebout, and Meador, 1985)

Potential Geologic Formations For CO_2 Storage

Two potential injector well locations were chosen using publically available and acquired private well data and 2-D seismic lines Schlumberger Carbon Services used the data to construct a geologic subsurface model to identify suitable formations for storage of an estimated 300,000 tons per year of CO_2 for a three-year injection period.

Four potential storage zones were identified on or near the site. All potential reservoir intervals directly beneath the property consist of carbonate rocks. The formation and units that make up these zones are identified on the stratigraphic column presented as Table 6.

The initial formations identified as potential reservoirs consist primarily of limestone sequences identified as the Strawn, Canyon, and Cisco units of Pennsylvanian age (Table 6). A deeper formation consisting of Devonian carbonates was also identified as a possible storage reservoir. The depth for the deeper unit ranges from 10,500 ft.. to 9,000 ft.. total vertical depth (TVD). The primary seal overlying these potential storage intervals is interpreted as the major Pennsylvanian/Permian unconformity separating the two geologic systems across the central United States. Add to this seal capacity the overlying Wolfcamp Shale and two internal shale intervals dividing the reservoir into multiple stages and these deeper storage targets possess more than adequate vertical seal potential. The lower inter-interval shales are interpreted as from the Bend unit or possibly the lowermost shale being the Devonian Woodford Shale. Regional correlations are difficult within the fault block underlying the site and will warrant additional regional study to verify their exact age relationships.

Log data from wells near and on the site penetrating to the Ellenburger were analyzed for suitable porosities and permeabilities for CO_2 injection. A reservoir model was constructed for identified reservoir intervals ranging from the Pennsylvanian Cisco limestone at roughly 8,200 ft. TVD to Pennsylvanian Bend shale at roughly 10,500 ft. TVD. Simulation results suggest that these intervals are capable of sequestering projected CO_2 injection volumes for the initial injection period proposed by CEMEX.

Table 6. Permian Basin Stratigraphic Column (Regional Cross Sections, Central Basin Platform, western Texas, Bebout, and Meador, 1985).

System	Series	Group or Formation				
		Delaware Basin	Shelf Margin	Shelf	Midland Basin	
Quaternary						
Tertiary		Ogallala				
Cretaceous						
Triassic		Dockum				
Permian	Ochoa	Dewey Lake Rustler Salado Castile	Dewey Lake Rustler Salado			
	Guadalupe	Bell Canyon	Capitan	Tansill Yates (Y) Seven Rivers (SR)		
		Cherry Canyon	Goat Seep	Queen (Q) Grayburg (GB)		3
		Brushy Canyon	4 San Andres (SA)			3
	Leonard	Bone Spring	Glorieta (GL)/San Angelo (SAn) Upper Clear Fork (CF) Tubb (TUBB) Lower Clear Fork Wichita-Abo		Spraberry (SPR) Dean	2
	Wolfcamp (WC)	Wolfcamp				
Pennsylvanian (PENN)	Cisco (CIS) Canyon (CAN) Strawn (STR) Bend (BEND) Atoka/Morrow					1
Mississippian (MISS)	Chester Meramec Osage Kinderhook				Barnett	
Devonian (DEV)		Woodford				
Silurian (SIL)		Fusselman (FUSS)				
Ordovician (ORD)	Upper	Montoya				
	Middle	Simpson				
	Lower	Ellenburger (E)				
Cambrian	Upper	Hickory/Bliss				

The second potential storage unit was identified as the Clear Fork to Glorieta group, which are likely lower Permian, Leonardian in age (Table 6). These units occur above the unconformity at depths from 7,000 ft. to 5,000 ft. TVD. Suitable porosities and permeabilities were noted in log data from wells north of the site. Correlations to logs closer to the site were difficult to make due to lack of appropriate data. A shale unit divides this secondary interval from the overlying San Andres formation and would be the primary vertical seal for this interval. The lack of adequate correlateable information for this interval within or near the site identifies the need for additional investigation to better characterize and model this unit.

Analysis of log data from a small number of wells north of the site suggests that a suitable reservoir interval may exist beneath the productive Permian-aged San Andres interval, but above the Pennsylvanian Cisco, Canyon, and Strawn intervals. Porosities and permeability estimates resulting from this initial analysis are promising. However, a lack of suitable data nearer to the site has prevented more thorough modeling.

The third potential reservoir interval is within the middle Permian Guadalupian series and is associated with hydrocarbon bearing units in the area (Table 6). This interval comprises the San Andreas and Shallower Grayburg units ranging in depth from 4,500ft. to 3,500 ft. TVD. The highest porosities and permeabilities found at the site are associated with these units. These Permian carbonates are prolific hydrocarbon producers to the west in the Penwell Field, to the east in the South Cowden Field, and to the north in the Moss Field. This production provides additional evidence that these intervals have porosity and permeabilities that could be utilized for storage of CO_2. Simulation results suggest that these intervals are capable of sequestering projected CO_2 injection volumes for the initial injection period proposed by CEMEX.

The fourth potential storage opportunity may exist to the southeast of the site within the Brushy Canyon units, previously identified in the studies associated with a potential FutureGen storage site on the southern side of the platform. This option may present a significant opportunity for CO_2 storage with close proximity to the site, but was not within the scope of this preliminary Phase I evaluation.

The Brushy Canyon interval grades into siliciclastic rocks to the southeast as it progresses off of the platform into the Midland Basin. Porosities and permeabilities measured in the productive Brushy Canyon sands are more than adequate for CO_2 storage. Such targets could be made accessible to the CEMEX site through a pipeline of 5 to 50 miles in length. It is recommended that data acquisition, modeling, and simulations be carried in the future to characterize this as a potential CO_2 reservoir.

As discussed, the West Texas Permian Basin has abundant well penetrations, wireline data, core, production information, and seismic from years of hydrocarbon exploration and extraction. However, only limited penetrations were associated with the site, and while those showed promising potential for CO_2 storage within several intervals, the data was not adequate to make a definitive statement about the storage limits on the property. Because so much information in the general vicinity of the site indicates multiple storage interval options, researchers in this preliminary investigation suggest that sufficient encouragement on the storage capacity of the site warrants additional investigation of strata directly under the site.

Modeling and Characterization of Potential CO_2 Storage Formations

In order to determine if the formations identified as potential storage reservoirs were suitable, the study created models and ran simulations to predict the fate and transport of the CO_2 during and after injection into the reservoir. This evaluation was carried out by CEMEX's sequestration partner, SCS. The following section summarizes the effort to create and run these predictive models.

Discussion of Modeling Methods

Sequestering CO_2 in deep saline reservoirs occurs through four mechanisms: 1) structural trapping, 2) aqueous dissolution, 3) hydraulic trapping, and 4) mineralization. The principal objective of CO_2 fate and transport analysis is to predict the migration, dissolution, entrapment, chemical reaction, and ultimate disposition of CO_2 in the reservoir formation. Because of the complexity of these processes, these predictive analyses are typically conducted using numerical simulation, which is commonly referred to as "reservoir modelling." The following sections describe numerical simulation of CO_2 injections into the potential reservoirs. The simulations were balanced in terms of discretization, resolution, and execution speed. The simulations involve injecting supercritical CO_2 into selected reservoir formations and modelling the fate and transport of the CO_2.

The geologic analysis provided the data for the geocellular flow simulation model construction. In order to accurately integrate this data, a model-centric approach is taken that allows the geologic and geophysical data to be constructed into a 3D model of the storage and sealing intervals being investigated. SCS utilizes the Petrel workflow to achieve this integration.

The reservoir model is used to estimate the spatial extent of the CO_2 plume during and after the planned injection period. These tasks are done in an iterative manner. An ECLIPSE dynamic model was used to simulate the fluid flow in the reservoir formation. The reservoir simulation work in this study has been conducted with the ECLIPSE 300® simulator. The ECLIPSE simulator is widely used in the petroleum industry for modelling the reservoir flow in oil and gas fields. The compositional finite difference simulator determines fluid flow as a result of injection and/or production activities that act as boundary conditions. The CO2STORE option used in this work was specifically designed for carbon storage projects and was added to the simulator in the 2006 commercial release. It allows the fluids in the pore space to be modelled in two phases: a CO_2-rich phase (labelled "gas phase") and an H_2O-rich phase (labelled "liquid phase"). The development of the plume throughout and beyond the planned injection period is highly dependent on the distribution of reservoir properties, such as porosity and permeability in the Petrel Model.

Model Input Parameters and Execution

Only two of the four potential reservoirs were modelled: the San Andreas between 4,000 ft. to 4,500 ft.) and the deep Pennsylvanian carbonates between 9,700 ft. and 10,500 ft.. The remaining two potential reservoirs, the Brushy Canyon unit and the Clear Fork to Glorieta group, were not modelled due to insufficient data. A schematic representation of the intervals of interest and their associated seals is depicted in Figure 13, and the Petrel interval layer model for the simulation runs is included as Figure 14.

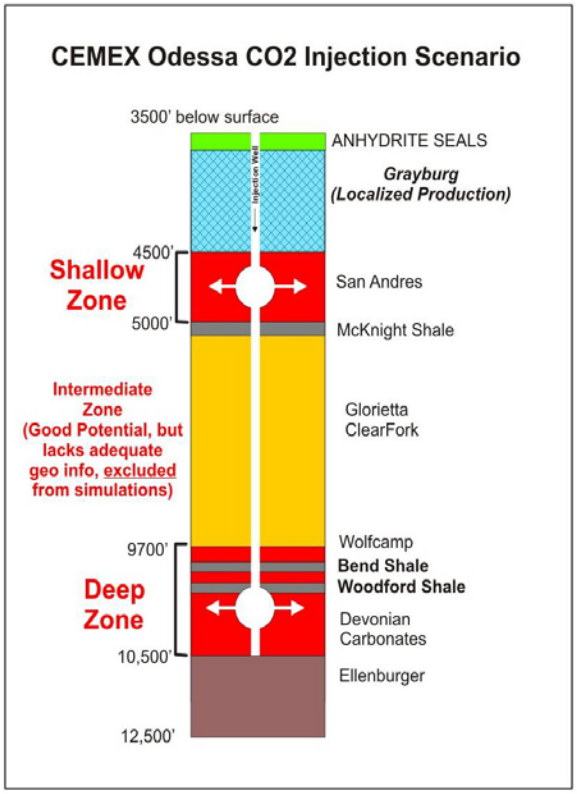

Figure 13. Primary Intervals of Interest and their Associated Seals

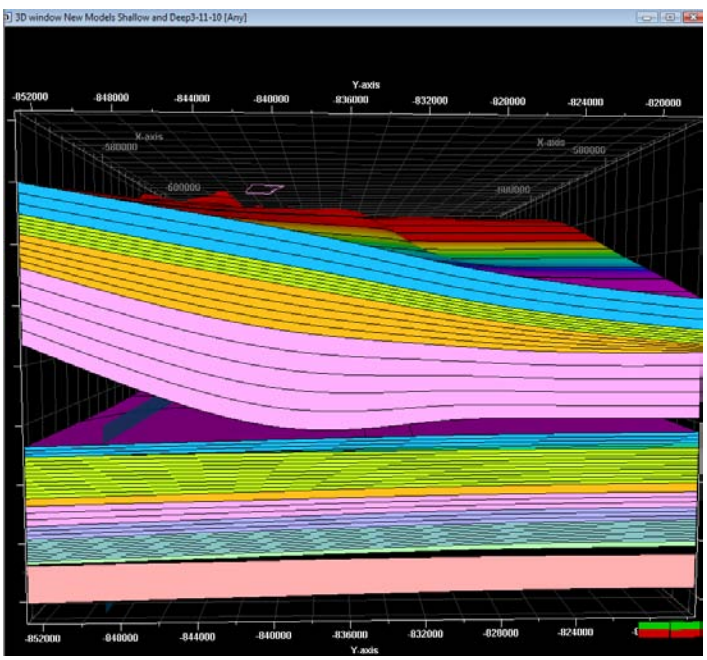

Figure 14. Shallow and Deep Storage Intervals Used in the Simulations

SCS Petrel Model, 2010

Of the two primary formations under consideration for CO_2 injection, the deep interval has poorer overall characteristics, but is further from existing oilfield activities. The shallow interval has better characteristics, but may be too shallow (3,500 to 5,500 ft.) for effective injectivity of CO_2. Both intervals show significant and extensive sealing characteristics that are expected to maintain CO_2 within the geologic formations in which it is injected.

Value ranges for porosity, permeability, pressure, temperature, amount injected, injection duration, injection rate, and plume migration duration for the shallow and deep intervals were input into the model (Table 7).

Table 7. Model Input Parameters for Simulation. SCS Petrel Model, 2010

Parameter	Shallow Reservoir	Deep Reservoir
Injection Depth Interval	3,660 to 5,570 ft.	9,740 to 10,450 ft.
Injection Interval	710 ft.	1,690 ft.
Initial Pressure	1,691 psi at 3,906 ft. depth	4,226 psi at 9,761 ft. depth
Maximum Pressure	6,589 psi at 3,906 ft. depth	6,589 psi at 9,761 ft. depth
Temperature (from nearby logs)	104^o F	170^o F
Porosity Range	?	?
Permeability Range	?	?
Injection Rate	300,000 tons/year	300,000 tons/year
Injection Amount Total	?	?
Injection Duration	1 year or 3 years	1 year or 3 years
Total Duration of Plume Observation	5 years	5 years

Porosity and permeability distributions are usually characterized by well logs and core samples taken at the subject site. This was not possible at the site, so high and low cases for porosity and permeability were selected in an effort to bind the actual values. Further, plume size is expected to be largest when porosity is low and permeability is high (LoPhiHiK), and smallest when porosity is high and permeability is low (HiPhiLoK). To define upper and lower limits for plume size, these two permeability and porosity conditions were used in the simulation.

The injection rate and duration was varied in the study for a period of one year or three years. The maximum injection rate used reflected the expected injection rate of 300,000 tons of CO_2 per year. Most of the runs were made at this injection rate. An additional set of runs was made to test the maximum injectivity of the formations by specifying a very high rate, 1 million tons of CO_2 per year. In all cases, the well was shut after the injection period ended, but the simulation continued for two more years to model the additional growth and drift of the plume during this observation period.

In addition to the input variables, the following assumptions were used for the model simulation runs:

- The salts (NaCl, $CaCl_2$, and/or $CaCO_3$) are assumed to stay in the liquid phase.
- The gas density is obtained by an accurately tuned cubic equation of state.
- The brine density is first approximated by the pure water density (Kell, 1975) and then corrected for salt and CO_2 effects by Zaytsev (1993).
- The CO_2 gas viscosity is calculated from Zaytsev (1993) and Fenghour (1999).

In the simulations, CO_2 was injected into a single well located near the center of the site. Injection Well #1 injects in the deep interval, and Injection Well #2 injects in the shallow interval. Significant uncertainties can impact the size and position of the resulting CO_2 plume in the reservoir. A set of model runs was defined that estimate the plume characteristics for a range of these uncertainties. Sixteen simulations were run with different input parameters to reflect different possible conditions that might be encountered during actual injection.

The result of the sixteen simulations provided two cases that best represent the expected outcome from injection into both the deep and shallow formations. The first case simulated injecting 1 million tons of CO_2 per year into the deep formation, and the second simulated injection of 300,000 tons per year into the shallow formation. Both injections were through a single well located onsite to minimize facility costs and model complexity. Based on the simulation results that follow, injection into the Deep interval alone will store the expected volume of CO_2 within the boundary of the CEMEX Odessa site.

Figure 15 shows the aerial extent of the injected CO_2 plume at 1 year (left) and 5 years (right) for the selected shallow case (named CEMEX_S_LOPHIHIK_I3O2). The site property boundary is provided for reference, and the single injection well is located at the center of the plume. The plume is seen to remain well within the property boundary in the first year, but extends beyond the boundary in the narrow north/south dimension by year 5.

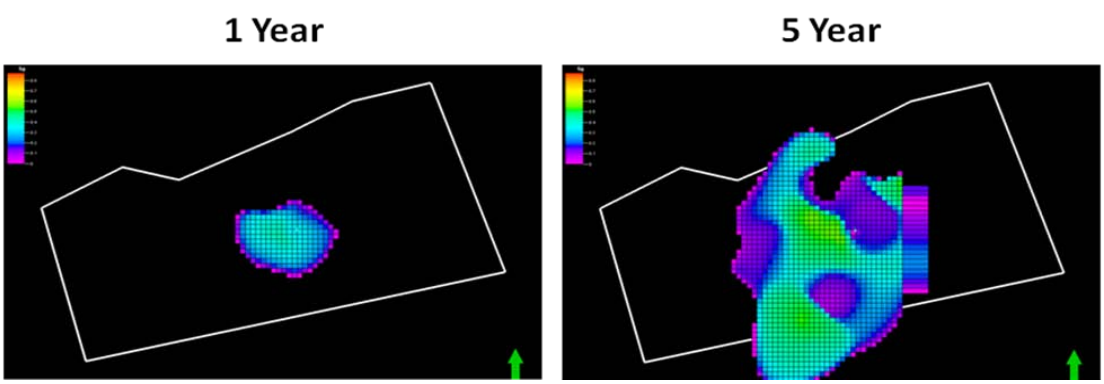

Figure 15. Aerial View of Injected CO_2 plume at 1 Year and 5 Years for Shallow Interval Case - CEMEX_S_LOPHIHIK_I302

In order to understand the maximum capacity of a storage facility, cases injecting 1 million tons of CO_2 per year were also included to explore this upper limit of the site. The selected deep simulation run (named CEMEX_D_LOPHIHIK_I3O2_1MM) shows the aerial plume extent at 1 year and 5 years (Figure 16). At 5 years, the plume edges are just outside the site. This suggests that slightly less than 3 years of injection at this rate (equivalent to less than 3 million tons of CO_2) represents the deep formation storage capacity at the site for this time frame.

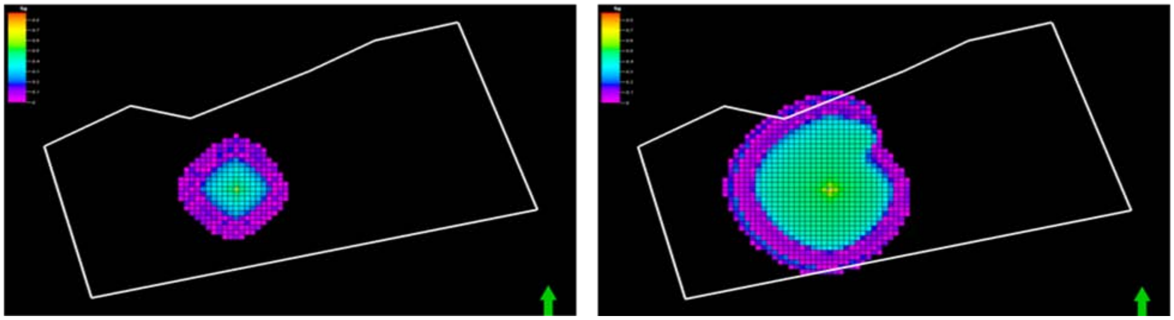

Figure 16. Aerial View of Injected CO_2 Plume at 1 Year and 5 Years for Deep Interval Case - CEMEX_D_LOPHIHIK_I302_1MM

The expected and maximum operational cases shown above are all for the LoPhiHiK condition. This case has the least storage density and the highest permeability, allowing for the largest aerial extent of plume migration. This is a more pessimistic case when trying to keep the plume within a limited area around the injection well. It should be noted that the spatial distribution of the actual plume will vary from the model results due to variations in reservoir properties and geologic conditions.

Summary and Conclusions

The primary uncertainty when modeling plume area is the distribution of porosity and permeability. In this study, upper and lower bounds have sought to capture this range of uncertainty. However, these properties will always cause uncertainty in until a well is drilled on the site and thoroughly tested. Porosity values influence the storage capacity of the site, while permeability values influence the injectivity and drift. Bounds used in this study cannot truly be certain upper and lower bounds, but the results suggest that the deep interval is a viable CO_2 storage facility for the expected 900,000 tons of CO_2 to be injected during a three- year period.

Additional modelling is expected to be performed as part of the next phase to finalize detailed modelling and evaluation of the sequestration site and the four potential reservoirs. The next phase should make progress towards full understanding of storage capacities, permeability, risk factors, and other feasibility factors of the selected sequestration site.

The evaluation and selection of an MVA technique, the preliminary design, engineering and planning for sequestration site, and the preliminary design, engineering, and planning for a CO_2 transportation network were not executed because Phase II for the construction and operation of an industrial-scale demonstration project was not pursued.

6.0 Conclusions

The Odessa plant was selected as the host site for a CCS demonstration facility based on the results of a comprehensive study which included an analysis of the geology and the Environmental Liability and Public Acceptance review and a detailed assessment of the existing equipment, retrofit requirements, and the potential interface needs with the CO_2 capture system. The Odessa site showed the highest sequestration and EOR potential with a CO_2 pipeline actually crossing the property. It also appears to have the greatest degree of public acceptance and has the least cumbersome level of permitting requirements.

This study suggests capturing CO_2 only from kiln 2 at Odessa Plant. In order to assure a long-term successful commercial demonstration of CO_2 capture in cement kilns, CEMEX USA believes that kiln 2 is the most suitable to retrofit a CO_2 capture technology for the first time in the cement industry. Simplicity of kiln configuration, flue gas stability, small scale-up factor, availability of waste heat and easy gas conditioning make it an excellent candidate for this project and will minimize the risk of implementing a CO_2 capture technology. Kiln 2 could be retrofitted to operate at commercial scale to capture >75% of CO_2 from the cement kiln flue gas comprised of about 20%vol. CO_2 for a total capture amount in the range of 160,000 to 180,000 metric tons per year of CO_2 avoided (not emitted to the atmosphere) for these technologies. The Kiln #2 line at the Odessa plant gave the project the highest probability of success given the state of development of the two capture technologies, and the EOR potential in the Permian Basin. Two other plants (Plants B and C) were identified as good candidates for CCS, as well.

A comprehensive geological assessment of the Odessa cement plant was conducted, and multiple intervals or zones for potential CO_2 injection onsite were identified. Geologic evaluation is positive, according to the models developed for deep sequestration. Results suggest that the deep zone is a viable CO_2 storage reservoir for 900,000 tons of CO_2 to be injected during a three-year period, and potential onsite CO_2 storage capacity for the deep zone is ~3 million tons. Other CO_2 storage options are available for this cement plant. EOR remains a viable alternative because of its proximity to a CO_2 pipeline and the oil wells, and research from this study also indicates a strong likelihood of nearby (5-25 miles) storage potential. This is the sandstone reservoir studied for the FutureGen project in this region.

Preliminary equipment design and specifications of the majority of primary equipment for solid sorbent technologies, RTI's dry carbonate sorbent and CEMEX's calcium looping process were obtained. The results of the technological assessment of both solid sorbent options indicate that they are not currently mature enough for the scale of development expected by DOE, and additional pilot testing is needed to mitigate risks. Technological risks exist but can be overcome through continued development of these novel technologies.

A detailed engineering assessment and capital and operating costs for both CO_2 capture technologies and the overall CCS system were estimated. CCS was identified as very costly for a retrofit to a Cement Plant. A sensitivity analysis was conducted to identify the opportunities to reduce both capital and operating cost of the CCS system. Optimum operating costs (for the whole CCS process) of these technologies (RTI's Dry Carbonate Sorbent and CEMEX's Calcium Looping Process) range between $80 USD and $140 USD per ton of CO_2 avoided, including CO_2 capture, purification, compression, transportation, and sequestration. These total process costs include the amortization of the capital expenditure

RTI's Dry Carbonate Process has its own advantages and disadvantages, and additional research is needed to prove the merit of this technology. If CEMEX were going to choose a CO_2 capture technology, this study suggests that CEMEX's Calcium Process may offer better opportunities to retrofit a cement plant with CCS because of CEMEX's own intimate knowledge of this process and the natural synergies with the cement manufacturing process. However, additional research and development work is needed to optimize the technology design, plant integration, and capital cost. A pilot-scale unit of ~5 TPD CO_2 for experimentation is a must before it is fully implemented at commercial-scale in a cement plant.

Based on these conclusions, CEMEX realized that careful project considerations must be taken to mitigate the technological risk and high capital cost of CCS in a cement plant identified with this study. Given the time restrictions of this DOE program, it was decided not to pursue Phase II for the construction and operation of an industrial-scale demonstration project, and the no-action alternative for Phase II was selected and communicated to DOE.

7.0 Acronyms and Abbreviations

CCS	carbon capture and sequestration
CO_2	carbon dioxide
EOR	enhanced oil recovery
FOA	Funding Opportunity Announcement
FEED	front-end engineering and design
MVA	monitoring, verification, and accounting
DOE	U.S. Department of Energy
GPM	gallons per minute
H_2O	water
kcal/kg	kilocalories per kilogram
MMBTU	million British thermal units
N_2	nitrogen
NETL	National Energy Technology Laboratory
Nm^3/h	normal cubic meters per hour
O_2	oxygen
SCS	Schlumberger Carbon Services
SHC	specific heat consumption, heat input per mass of clinker
TGA	thermogravimetric analyses

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