Expansion of Michigan EOR Operations
Using Advanced Amine technology at a 600 MW Project
WOLVERINE CARBON CAPTURE AND STORAGE PROJECT

FINAL TECHNICAL REPORT

REPORT # DOE/FE/0002477

Project Period:

November 16, 2009 to June 15, 2010

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July 13, 2010

DOE Award # DE-FE0002477

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Abstract

Wolverine Power Supply Cooperative Inc, a member owned cooperative utility based in Cadillac Michigan, proposes to demonstrate the capture, beneficial utilization and storage of CO_2 in the expansion of existing Enhanced Oil Recovery operations. This project is being proposed in response to the US Department of Energy Solicitation DE-FOA-0000015 Section III D, "Large Scale Industrial CCS projects from Industrial Sources" Technology Area 1. The project will remove 1,000 metric tons per day of CO_2 from the Wolverine Clean Energy Venture 600 MW CFB power plant owned and operated by WPC. CO_2 from the flue gas will be captured using Hitachi's CO_2 capture system and advanced amine technology. The capture system with the advanced amine-based solvent supplied by Hitachi is expected to significantly reduce the cost and energy requirements of CO_2 capture compared to current technologies. The captured CO_2 will be compressed and transported for Enhanced Oil Recovery and CO_2 storage purposes. Enhanced Oil Recovery is a proven concept, widely used to recover otherwise inaccessible petroleum reserves. While post-combustion CO_2 capture technologies have been tested at the pilot scale on coal power plant flue gas, they have not yet been demonstrated at a commercial scale and integrated with EOR and storage operations.

Amine-based CO_2 capture is the leading technology expected to be available commercially within this decade to enable CCS for utility and industrial facilities firing coal and waste fuels such as petroleum coke. However, traditional CO_2 capture process utilizing commercial amine solvents is very energy intensive for regeneration and is also susceptible to solvent degradation by oxygen as well as SOx and NO_2 in the flue gas, resulting in large operating costs. The large volume of combustion flue gas with its low CO_2 concentration requires large equipment sizes, which together with the highly corrosive nature of the typical amine-based separation process leads to high plant capital investment. According to recent DOE-NETL studies, MEA-based CCS will increase the cost of electricity of a new pulverized coal plant by 80-85% and reduce the net plant efficiency by about 30%. Non-power industrial facilities will incur similar production output and efficiency penalties when implementing conventional carbon capture systems.

The proposed large scale demonstration project combining advanced amine CO_2 capture integrated with commercial EOR operations significantly advances post-combustion technology development toward the DOE objectives of reducing the cost of energy production and improving the efficiency of CO_2 Capture technologies. WPC has assembled a strong multidisciplinary team to meet the objectives of this project. WPC will provide the host site and Hitachi will provide the carbon capture technology and advanced solvent. Burns and Roe bring expertise in overall engineering integration and plant design to the team. Core Energy, an active EOR producer/operator in the State of Michigan, is committed to support the detailed design, construction and operation of the CO_2 pipeline and storage component of the project. This team has developed a Front End Engineering Design and Cost Estimate as part of Phase 1 of DOE Award # DE-FE0002477.

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1 EXECUTIVE SUMMARY

The Wolverine Carbon Capture and Storage (WCCS) Project aims to demonstrate advanced technologies that capture and sequester carbon dioxide (CO_2) emissions from stationary sources into underground formations. During Phase 1 of the project, the project team completed preliminary process design and engineering and a cost estimate for the CCS project. This information along with a cost share application was submitted to the Department of Energy for Phase 2 that would comprise of Detailed Design, Procurement, Construction and Operational Period of the Demonstration Project.

The WCCS Project is sized to capture 1,000 metric tons per day of CO_2 for compression, transportation and injection for EOR operations and/or storage into geologic formations. The CO_2 capture system will utilize Hitachi's advanced amine-based solvent technology to capture about 90% of the CO_2 from the treated flue gas stream. The WCCS project will remove 300,000 metric tons per year of CO_2 from the flue gas from Unit 1 (300 MW CFB Boiler) of the Wolverine Clean Energy Venture (WCEV). This concept will be the first ever CO_2 capture process integrated with low emission Circulated Fluidized Bed technology.

The Wolverine Power Supply Cooperative Inc. (Wolverine) has assembled a team of experts in the field of Carbon Capture and Storage (CCS). The team consists of Burns and Roe Enterprises Inc. (BREI), the Program Manager and Project Engineer; Hitachi Power Systems America, Ltd. (Hitachi), the supplier of the CO_2 Capture Technology and advanced amine solvent; Core Energy LLC (CE), provider of storage and EOR for the Project; Western Michigan University (WMU), performing Geological Study for storage and EOR operations; and Fishbeck, Thompson, Carr and Huber (FTCH), the environmental consultant who has completed the Environmental Information Volume (EIV) for the project.

The host WCEV project is a 600 MW clean coal plant to be located near Rogers City, Michigan. It comprises of two (2) subcritical 300 MW CFB boilers that feed two (2) corresponding 300 MW steam turbines. Situated within the limits of an active limestone quarry southeast of Rogers City in Presque Isle County, the WCEV plant is designed as a low emissions base load plant to serve the energy demand in Michigan.

The Hitachi post-combustion CO_2 capture concept is designed to achieve 90% capture with large cost savings and efficiency improvement over current amine scrubbing technologies. Capture system steam consumption is improved by roughly 30% when operated with the Hitachi solvent as compared to commercial solvents. When operated with the advanced solvent, it is estimated that the energy required to capture and compress CO_2 will improve by roughly 2.8 MW or 15% as compared to the energy required to capture and compress 1,000 metric tons of CO_2 using conventional commercial solvents. A testing plan has been developed to confirm this performance improvement and associated reduction in operational costs during the demonstration period of the project.

CO_2 storage will be performed at sites owned by Core Energy. Core Energy currently owns and operates a significant infrastructure for CO_2 EOR in the vicinity of the project site. This infrastructure provides a great deal of flexibility as to where the CO_2 can be delivered for the primary near term purpose of EOR, and the secondary longer term purpose of deep saline aquifer storage. CO_2 storage capacities and recoverable oil reserves have been quantified by Western Michigan University to document the geological potential for expanded storage in the project area. Since the project period is constrained by the timeline set forth in the Recovery Act (All funds must be expended by September 2015), the demonstration period is scheduled to conclude slightly over one year of operation. Due to the small volume of CO_2 that will be injected during the project period, the primary destination for CO_2 will be Enhanced Oil

Recovery targets. As time progresses well beyond the demonstration period and if the CO_2 capture capacity at the plant is expanded, there is ample capacity in the Bois Blanc and the St. Peter Sandstone Saline aquifer formations to support the CO_2 volumes generated from the Power Plant over the long term.

In collaboration with FTCH, Core Energy has identified a preferred 54± mile CO_2 pipeline route to transport the CO_2 from the proposed CO_2 capture project to the Storage site. This pipeline follows an existing pipeline corridor, which greatly improves the probability for obtaining the rights of way required for pipeline construction.

A conceptual design for the advanced CO_2 capture system, CO_2 compression CO_2 pipeline and CO_2 storage has been developed along with cost estimates to support project budget and schedule.

A CO_2 storage injection, monitoring, verification and accounting (MVA) plan has been developed to measure and document the CO_2 that is sequestered during the injection period. The plan incorporates baseline evaluation of the storage site(s), monitoring of ongoing injection operations and accounting of fluids injected over the project period. The commercial demonstration will document the movement of CO_2 in the geologic formations to support future growth in this emerging field.

An “Environmental Information Volume” (EIV) was prepared to provide information regarding the environmental aspects of the proposed WCCS Project to identify and plan for all of the necessary permits required for the Project.

A project capital cost estimate was developed using budgetary equipment cost estimates for all major equipment. Material quantity takeoffs and installation labor was estimated from conceptual design drawings that were developed for that purpose. An operation and maintenance cost estimate for the project was developed including fixed and variable operation costs for the plant. A cost estimate for the demonstration testing period was developed separately since this period would require a significant amount of testing that is not representative of commercial operation.

A project team structure has been developed to support the implementation of this project. If selected by the US Department of Energy and implemented, the project will support the development of a feasible and economically viable technology for CO_2 capture, a growth in public confidence in CO_2 transportation and storage and the expansion of Enhanced Oil Recovery operations in Michigan. At a scale of 50MW, the success of this project would pave the way for larger-scale projects and commercialization of CO_2 capture and storage in large industrial boilers and coal-fired power plants.

2 INTRODUCTION

2.1 PROJECT OBJECTIVES

Wolverine, along with BREI, Hitachi, CE, WMU and FTCH, has proposed to demonstrate a large scale carbon capture and storage (CCS) technology at the 600 MW WCEV power plant to be located near Rogers City, Michigan. The WCCS project has been designed for capture and beneficial storage of at least 1,000 metric tons per day (300,000 tonnes per year) of CO_2. The team has prepared a CCS system conceptual design, proposed pipeline route, completed cost estimates and environmental analysis for the proposed CCS project and infrastructure requirements to sequester CO_2. The WCCS project has been proposed in response to the US Department of Energy (U.S. DOE) funding opportunity announcement DE-FOA-0000015 Section III D, "Large Scale Industrial CCS projects from Industrial Sources" Technology Area 1, Phase 2. The goals of the WCCS project are:

§ Removal of 1,000 metric tons/day of CO_2 from one 300 MW CFB power plant flue gas for compression, transportation, injection, and monitoring by 2015.

§ Implementation of advanced amine-based solvent for CO_2 capture.

§ Integration of CO_2 capture with commercial-scale EOR operations and/or geologic storage.

§ Evaluation of thermal performance, and capital and O&M costs of the CO_2 Capture and Compression plant using Hitachi's advanced amine-based solvent.

§ Integration of the CO_2 Capture and Compression plant with balance of plant and optimization studies for full-scale operations.

§ Evaluations of technical performance of CO_2 compression, transportation, storage, and monitoring systems.

§ Definition of the monitoring requirements to employ in CO_2 capture, transmission, and safe storage.

§ Preparation of a storage monitoring, verification and accounting plan to document the storage of all captured CO_2

§ Documentation of the performance, EPC costs, and O&M costs of the completed demonstration Project.

A slipstream of about 17% of flue gas from a 300 MW unit will be diverted to the CO_2 capture system that has been designed to remove 90% of the CO_2 from the inlet flue gas and deliver 1,000 metric tons/day of CO_2 for compression and EOR application. The CO_2 capture system has been designed for, and will incorporate operational flexibility to permit the use of commercial solvents in addition to the latest Hitachi advanced amine-based solvent, which has significantly lower regeneration energy demand than that of the commercially available solvents. The CO_2 capture plant has been designed for suitable integration with the power plant steam cycle and CO_2 compression.

2.2 PROJECT HIGHLIGHTS

The proposed project will advance post-combustion technology development toward achieving the U.S. DOE objectives of reducing the cost of energy production and improving the efficiency of CO_2 capture technologies. These advancements and improvements will significantly contribute to rapid maturation of the CO_2 capture technology, its commercialization, and market penetration. Advantages and benefits of the WCCS project are as follows:

- The WCCS Project would reduce emissions of greenhouse gases to the atmosphere by at least 300,000 tons/yr.
- The proposed project would represent the first CCS demonstration with CFB technology, petroleum coke, and potentially, biomass and other opportunity fuels.
- The WCCS Project would be located adjacent to numerous existing EOR sites and ongoing EOR operations, capable of large-scale beneficial carbon storage.
- Hitachi, one of the most innovative companies in the world, will provide an advanced CO_2 Capture system, and proven solvents and additives for the project.
- The WCCS design incorporates system flexibility for accepting solvent improvements or replacements in the future, should they become warranted.
- Core Energy will demonstrate and document the injection of CO_2 from the CO_2 capture process to support longer term public confidence in storage.
- Expansion of the EOR operations will enable additional oil production from existing but previously unrecoverable oil reserves, thereby generating tax revenues and creating additional jobs in the State of Michigan,

3 PROJECT TEAM

Wolverine Power Supply Cooperative Inc. (Wolverine) has assembled a team of experts in the field of Carbon Capture and Storage (CCS). The team consists of Burns and Roe Enterprises Inc.(BREI), the Program Manager and Project Engineer; Hitachi Power Systems America, Ltd. (Hitachi), the supplier of the CO_2 Technology; Core Energy LLC (CE), the EOR for the Project; Western Michigan University (WMU), the performer of the EOR Geological Study.

The Wolverine project team has completed the Phase 1 work under the aforementioned U.S. DOE FOA. The carbon capture system will use Hitachi's advanced amines and commercially available amine supplied by Dow Chemicals, and is expected to reduce the CCS cost and energy requirements. EOR will be accomplished by Core Energy, an active EOR producer and operator in the State of Michigan.

Roles of each member of the Project Team are defined in Table 3-1.

Table 3-1: Project Team

TEAM MEMBER	ROLE
Wolverine Power Supply Cooperative Inc.	Wolverine leads and provides the site, the financing and the host power plant for the overall Project.
US Department of Energy	DOE provides overall direction, oversight and input and clarification on Phase 2 renewal application and EIV.

TEAM MEMBER	ROLE
Burns and Roe	BREI acts as the program manager on behalf of Wolverine. BREI also acts as Project Engineer to define the integration concept for the project. BREI has designed the Power Plant and will consider changes to the design necessary for the CO_2 Capture and Compression portion of the Plant at the end of Phase 1, and provided expertise in the sizing of new equipment and collaborated with Hitachi to integrate the CO_2 capture system with the WCEV power plant.
Hitachi Power Systems America, Ltd.	Hitachi has designed the Carbon Capture system and provides the advanced amine-based solvent and collaborated with Burns and Roe to optimize and integrate the CO_2 Capture system with the balance of the plant. Hitachi has provided a cost estimate and schedule for the CO_2 Capture System, key Energy Integration Equipment, and a testing plan for Phase 2.
Core Energy	Core Energy has evaluated pipeline route options and concluded on a final route. Core has completed the conceptual design of the pipeline, storage sites and the storage MVA plan for the Project. Core Energy is an EOR Producer with the site, knowledge, and experience of using CO_2 for EOR in Michigan.
Western Michigan University	WMU will complete Global Site Characterization studies required to support long term storage. Working knowledge of Geological Storage in Michigan, having supported the US DOE’s Midwestern Regional Carbon Capture Partnership. WMU has developed estimates of the regional storage potential in the vicinity of the WCEV power plant.
Fishbeck, Thompson, Carr and Huber Inc.	FTC&H prepared the Environmental Information Volume for the Project. FTC&H also prepared the draft permit for the host power plant site.

Figure 3-1 shows the project organization chart for this Project.

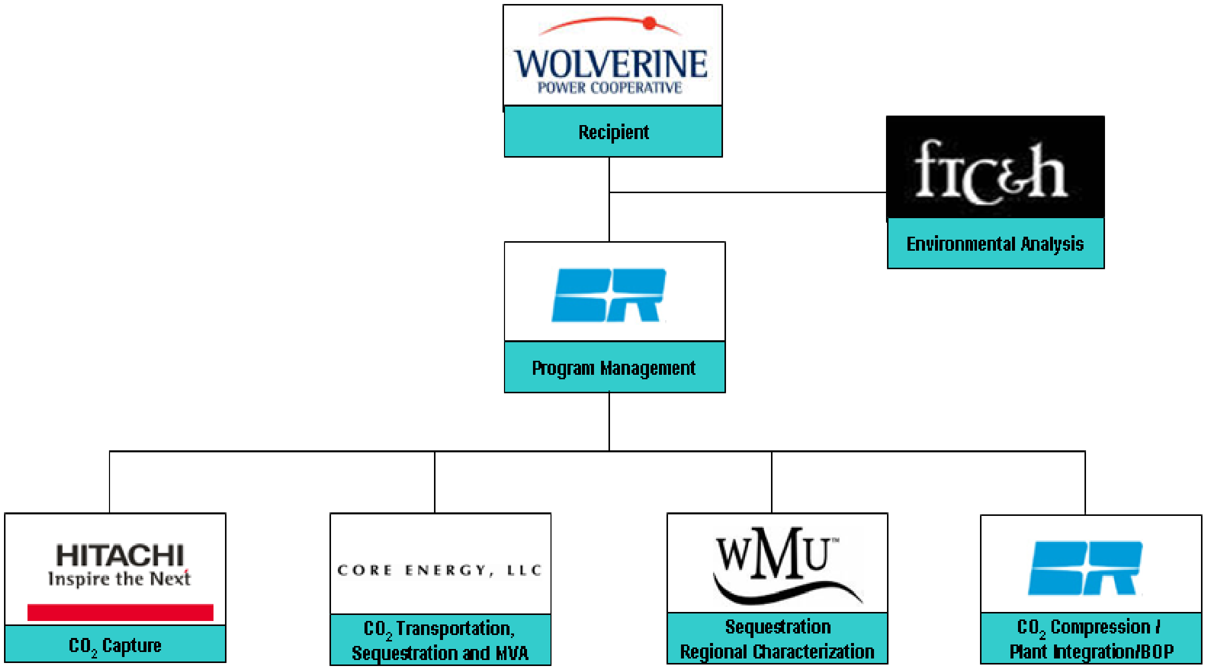


Figure 3-1: Project Organization Chart

WOLVERINE POWER SUPPLY COOPERATIVE INC

Wolverine owns and operates five electric generating facilities capable of producing approximately 200 megawatts of internal generation, primarily peaking capacity. The plants are located in Tower, Gaylord, Hersey, Vestaburg and Burnips. Wolverine owns and operates an extensive electric transmission network in the western and northern portions of Michigan's Lower Peninsula. Wolverine has nearly 1,200 miles of 69 kV and 138 kV looped transmission lines and associated facilities. Wolverine also owns and operates approximately 390 miles of radial transmission facilities that provide transmission service to distribution substations connected to their network. Wolverine's Clean Energy Venture will be the host site for the CO_2 Capture and Compression demonstration Project.

As the recipient, Wolverine's role was to provide overall Project direction, with input from the US Department of Energy.

UNITED STATES DEPARTMENT OF ENERGY: NATIONAL RENEWABLE ENERGY TECHNOLOGY LABORATORY (NETL)

NETL is providing 80% cost share of the overall Project costs for the Phase 1 effort. The US Department of Energy's Role was to provide Project oversight, review and clarification of the requirements of the Phase 2 renewal application, overall goals of the DOE's CCS program and review of all Project team submittals.

BURNS AND ROE ENTERPRISES, INC.

Burns and Roe Enterprises, Inc., established in 1932, is a global independent consulting engineering organization devoted to the practices of engineering, design, construction, and related support services for the power generating industry. These activities encompass the entire spectrum of technical and project management services, from project inception through start-up and operation. This vast experience base includes planning, project financing, due diligence, technical and economic studies, cost estimating, site selection, engineering, design, procurement, scheduling, logistics support, construction supervision and management, quality assurance, owner's engineering, start-up and testing, operator recruitment and training, technical manual preparation, and plant maintenance and operation. The team has an average of more than 25 years of experience on owner's engineering, feasibility studies, engineering, design, procurement, and construction for power generating stations. In addition to the premier key staff, BREI has balance of plant experts on staff that is readily available as required.

Burns and Roe's role in this Project was to provide overall program management services and defining the overall conceptual design and integration concept between the existing power plant, CO_2 capture and compression plant and enhanced oil recovery operations.

HITACHI POWER SYSTEMS AMERICA, LTD.

Hitachi is a global leader in the energy market with over 390,000 employees worldwide. It manufactures over 20,000 products including advanced ultra-supercritical boilers, steam turbines, and air quality control products. Hitachi is a pioneer in the $DeNO_x$ SCR and FGD technologies used on a large market share of utility and industrial units worldwide.

Hitachi brings advantages of its long experience in CO_2 Capture technology development to this Project. In fact, Hitachi developed CO_2 Capture processes and amine technologies prior to the Kyoto Protocol of 1997. Since Kyoto, Hitachi has re-energized this process and presently moves full speed ahead in the development of advanced processes taking into account its vast knowledge of the impacts on the thermal cycle and balance of plant aspects. Babcock Hitachi K.K (BHK), a subsidiary in Japan, has developed the H series proprietary, amine-based solvents; the latest H series solvent H3-1 will be used for the current Project. Another subsidiary, Hitachi Power Europe (HPE) is currently constructing a 5 MWth mobile CO_2 capture pilot plant in Europe that will be operational in late 2010. This important pilot plant is capable of testing a variety of flue gases with commercial as well as proprietary amine solvents to achieve the best possible match resulting in improved capture efficiency. Hitachi Power Europe has been very active in CCS testing and demonstration activities in Europe and has developed multiple designs for demonstration plants up to 250 MWe in size. These designs incorporate the process and solvent knowledge developed in Japan, as well as novel system integration concepts.

Hitachi is providing the CO_2 capture technology process design, equipment, and controls for the WCCS Project. In collaboration with Burns and Roe, Hitachi will integrate the power plant with the CO_2 capture and compression system in the most efficient manner possible. With access to the Hitachi global organization's experience and knowledge of CO_2 capture technology and a dedicated team of highly skilled engineers and designers experienced in the design and execution of similar projects, Hitachi will continue to provide thoughtful insight on a variety of issues for this implementation including interaction with the thermal cycle, and reactant properties of the commercially available amines.

During Phase I of the WCCS project, Hitachi has:

§ Worked with various US manufacturers to obtain design and price estimates of major common components, including packing and its auxiliaries, reboiler, heat exchangers, tanks, pumps, instruments, and control equipment.

- Evaluated various energy optimization concepts and utility requirements for the integration of the CO_2 Capture system with the power station and also CO_2 compression as a joint effort between Hitachi and BREI.
- Developed details of the mechanical, structural, electrical, and I&C aspects of the CO_2 capture island, and worked with Wolverine and BREI to integrate with the balance of the plant.
- Developed cost estimates for the design and supply of the CO_2 capture island, and worked with Wolverine and BREI to integrate this with the overall Project estimate.

CORE ENERGY

Core Energy is an independent oil and gas exploration company, based in Traverse City, MI, that specializes in CO_2 Enhanced Oil Recovery (EOR) operations in Northern Michigan. In addition to the EOR operations, Core is working closely with Battelle Memorial Institute as a site host for the Midwest Regional Carbon Sequestration Partnership (MRCSP) Phase II Demonstration Project testing the storage capacity for the Bass Island Dolomite formation in Northern Michigan. Core Energy has professionals on staff with expertise in the areas of geophysics, reservoir engineering, accounting and financial reporting, land management (ownership research, document procurement and management), facility and pipeline design, construction and management and field operation of CO_2 compressors, CO_2 pipelines and CO_2 injection wells. Core Energy's experience with CO_2 operations in this region of Michigan uniquely and strategically positions the company to bring actual operations field experience along with regulatory experience and legislative awareness to the Wolverine Clean Energy Venture project in Presque Isle County, MI.

Core Energy's role in this Project was to provide the sites for the storage concept, as well as the conceptual design and cost estimates for the CO_2 pipeline, storage and the storage MVA plan. Core will also identify and plan for necessary CO_2 pipeline rights of ways and environmental permits.

Core Energy and Western Michigan University (WMU) have defined the EOR and geologic storage options for the development of the pipeline, storage, and the storage MVA portion of the Project. Core Energy currently has Enhanced Oil Recovery operations in Michigan. Pipeline route options have been planned, which extend from the plant site to Core's existing and extensive CO_2 EOR infrastructure. The sites already under Core's control lend themselves well for sequestering CO_2 in either EOR formations or in deep saline aquifers. In addition to the sites already possessed by Core Energy, Core and WMU are quantifying the EOR and the geological storage potential that exists in rings that are centered on the WCEV power plant site. The characterization of the storage volumes in these rings provided the initial data needed for long term planning of the EOR and the storage potential that surrounds the WCEV power plant.

Core Energy and FTC&H have characterized the pipeline routes in terms of the number of miles through existing Rights of Way, New Rights of Way, types of ownership, routing through wetlands and forests, and proximity to the known presence of endangered species. The conceptual design for the Project has led to the development of the Phase 2 Statement of Project Objectives, which will define the Engineering, Procurement, Construction and Operation phase of the Project. The conceptual design and Statement of Project Objectives have been used to support project development activities consisting of cost and schedule development, teaming arrangements and the Project's financial analysis.

- Core Energy is an active EOR producer/operator in the State of Michigan, the only commercially operating EOR application east of the Mississippi, which produces tax revenue for the State of Michigan.

WESTERN MICHIGAN UNIVERSITY

Dr David A. Barnes of WMU is an expert geological consultant to WPC on this Project. Dr. Barnes is the Professor of Geosciences with expertise in Sedimentology and Michigan Subsurface Geology. His most recent research emphasis is on characterization of Geological storage of Carbon Dioxide in the Michigan Basin subsurface. Dr. Barnes is currently project manager for the Michigan Basin portion of DOE/NETL Regional Carbon storage Partnership Program in Michigan, as part of the Midwest Regional Carbon storage Partnership lead by Battelle Memorial Institute, Columbus, OH. In support of this Project, Dr. Barnes has developed regional site characterizations to support the long term storage of CO_2 in the vicinity of the Project site.

FISHBECK, THOMPSON, CARR AND HUBER

Fishbeck, Thompson, Carr & Huber (FTC&H) is a full service engineering, architectural, and environmental consulting firm located in Grand Rapids, Michigan, with branch offices in Farmington Hills, Kalamazoo and Lansing, Michigan and Cincinnati, Ohio. FTC&H has provided environmental consulting services to Wolverine for many years. With regards to the WCEV power plant, FTC&H completed air dispersion modeling, air permitting, and geologic/hydro-geologic investigations, including landfill design and permitting. FTC&H researched, wrote and assembled the EIV, working with Wolverine, BREI, CE, WMU and Hitachi to obtain necessary documentation for each phase of the Project (carbon capture plant, pipeline, and CO_2 injection operation).

4 HOST PLANT DESCRIPTION

The WCEV project is a 600 MW clean coal power plant planned for construction near Rogers City, Michigan, with the goal of being operational by the end of 2012. The plant will consist of two (2) subcritical 300 MW CFB boilers feeding two (2) 300 MW steam turbines. The plant is being designed as a low emissions base-load plant to serve Michigan.

4.1 CFB BOILER AND AIR QUALITY CONTROL SYSTEM

The WCEV project will utilize two Circulating Fluidized Bed (CFB) Boilers to produce the steam necessary to drive the two 330 MW (gross) steam turbine generators, as depicted in Figure 4-1. In the CFB boiler, limestone is added to the furnace bed contributing to greater than 95% sulfur capture. NO_x emissions are relatively low due to moderate low combustion temperatures, which are around 1600 °F. Further reduction in NO_x emissions is achieved by air staging, whereby air is diverted from the furnace bed where the bulk of fuel combustion happens. This causes combustion processes to operate at sub-stoichiometric conditions, which contributes to low NO_x emissions. The remaining combustion air, called secondary air, is fed above the furnace bed and is also referred to as “staged” air. The boiler’s exhaust exits an air heater where flue gas heats the incoming air thus, maximizing the efficiency of the boiler.

In addition to the low emission produced from the Circulating Fluidized Bed Boiler, the WCEV project also includes additional systems which make up the Air Quality Control System (AQCS). The AQCS includes a Selective Non Catalytic Reduction System (SNCR), a Polishing Scrubber, and a Pulse Jet Fabric Filter or Baghouse.

In the SNCR, flue gas NO_x emissions are reduced by spraying reagent (ammonia or urea) into the CFB cyclone at optimal conditions. In this region, there is very efficient mixing, appropriate reaction temperatures and reasonable residence time. The SNCR systems can achieve 50% NO_x reduction at full load.

The Polishing Scrubbers used in CFBs are of a dry type, that is, all of the water evaporates and the ash is separated in dry form. The use of this type of scrubber enables the use of certain types of wastewater and contributes to wastewater management. Flue gas entering the polishing scrubber is devoid of about 90% of SO_2 that has been captured in the CFB furnace by the addition of limestone. The SO_2 reduction in the polishing scrubber is typically 80% of the incoming SO_2 and thus, a total SO_2 capture rate of 98% can be achieved.

In the polishing scrubber, hydrated lime is added into the flue gas and flue gas temperature is simultaneously reduced down to 155 °F – 175 °F by water addition. In addition to acid gases (SO_2, HF and HCl), the scrubber will reduce trace element emissions. Cooling of the flue gas promotes the condensation of sulfuric acid mist, allowing it to be partially captured as an aerosol in the fabric filter along with heavy metals (mercury and lead).

The WCEV design includes a pulse-jet fabric filter baghouse for particulate matter control. The most significant benefit of the baghouse is the very intimate contact between the emissions (at low velocity) and the filter cake which forms on the surface of the fabric filters. The particulate matter is separated with greater than 99% efficiency in the baghouse.

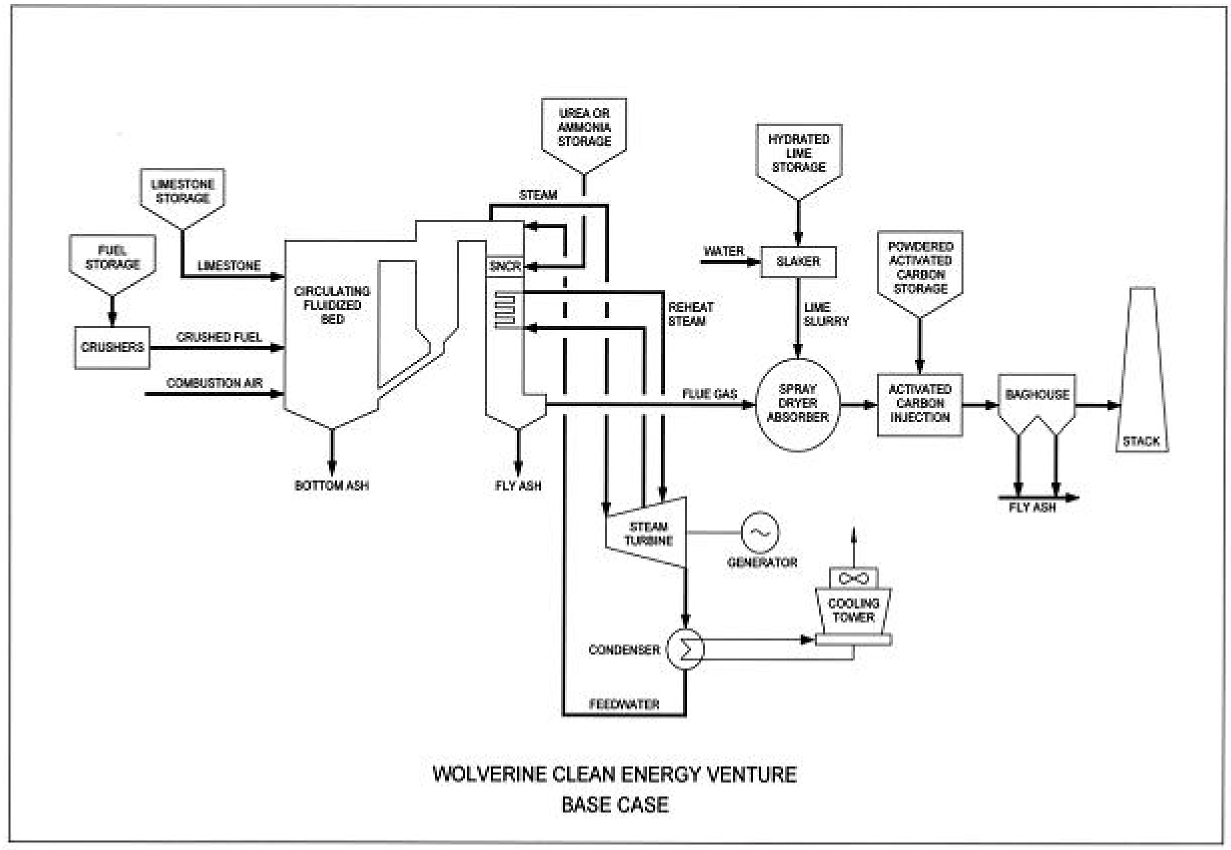


Figure 4-1: Wolverine Clean Energy Venture

4.2 STEAM TURBINE AND CIRCULATING WATER SYSTEM

4.2.1 Steam Turbine

Steam generated from the CFB will be used for driving an indoor type, tandem compound, reheat, double flow, extraction, down exhaust, condensing steam turbine generator. The steam turbine will operate within a range of steam flows and will be versatile in its operation. The steam turbine will be designed for both fixed and sliding pressure mode of operation, with constant pressure between 80 to 100% load and with sliding pressure below 80% load. The turbine will be base loaded, however with variations expected in throttle and steam extraction flows depending on electrical load requirements. The steam turbine generator unit package and auxiliary equipment will be located indoors.

4.2.2 Circulating Water System

The circulating cooling water system is comprised of circulating water pumps, a nine cell, mechanical draft cooling tower, and a chemical treatment system. The system rejects heat from the WCEV plant’s steam turbine exhaust and the auxiliary cooling water system. Heat is rejected to the atmosphere through evaporative and convective cooling in the cooling tower. Treated water from Quarry Pretreatment System will be used as normal make-up for the Cooling tower. Blowdown from the cooling tower basin is directed to the Process Wastewater Treatment System.

4.3 WCEV PROCESS WATER AND WASTEWATER SYSTEM

The WCEV plant will receive process water from quarry groundwater. This quarry groundwater is currently discharged directly into Swan Lake. The WCEV Plant process water system will receive a portion of this water, thus diverting some of the water from the discharge stream to the lake. The quarry groundwater contains a high degree of dissolved solids. These solids become concentrated in the facility cooling towers and must be blown down to reduce the solids content. The design of the facility incorporates quarry water pretreatment system to reduce water usage and process water discharge. The pretreatment system is comprised of clarifiers which reduce the solid content of the water through the introduction of lime and a coagulant.

The demineralized water make-up system is a combined reverse osmosis system and electro-deionization system. The WCEV plant is designed to produce 400 gallons per minute of demineralized water.

The process wastewater treatment system will receive cooling tower blowdown, equipment floor drains after treatment in an oil/water separator, fuel storage pond effluent, and air heater wash. These process wastewaters will be combined in equalization basins or tanks, and then treated by precipitation, clarification and filtration. To the maximum degree possible, treated effluent from the wastewater tank will be consumed in fuel dust suppression, ash handling, and as dilution water in the dry flue gas scrubber systems. There are, however, times when there is more treated process water effluent than there are facility needs. This water could potentially be treated and discharged to Swan Lake or Lake Huron under an SPDES permit. However, Wolverine has established the design of the facility as a zero liquid discharge facility (no process wastewater discharge). During periods of time when there is more treated process water effluent than there are facility needs, vapor compression evaporators are used to treat the excess wastewater. These will produce a distillate that will be recycled back to the cooling towers and a concentrate that will be sent back to the process wastewater treatment system.

A water balance diagram for the Wolverine WCEV facility (not including carbon capture) is shown below in Figure 4-2.

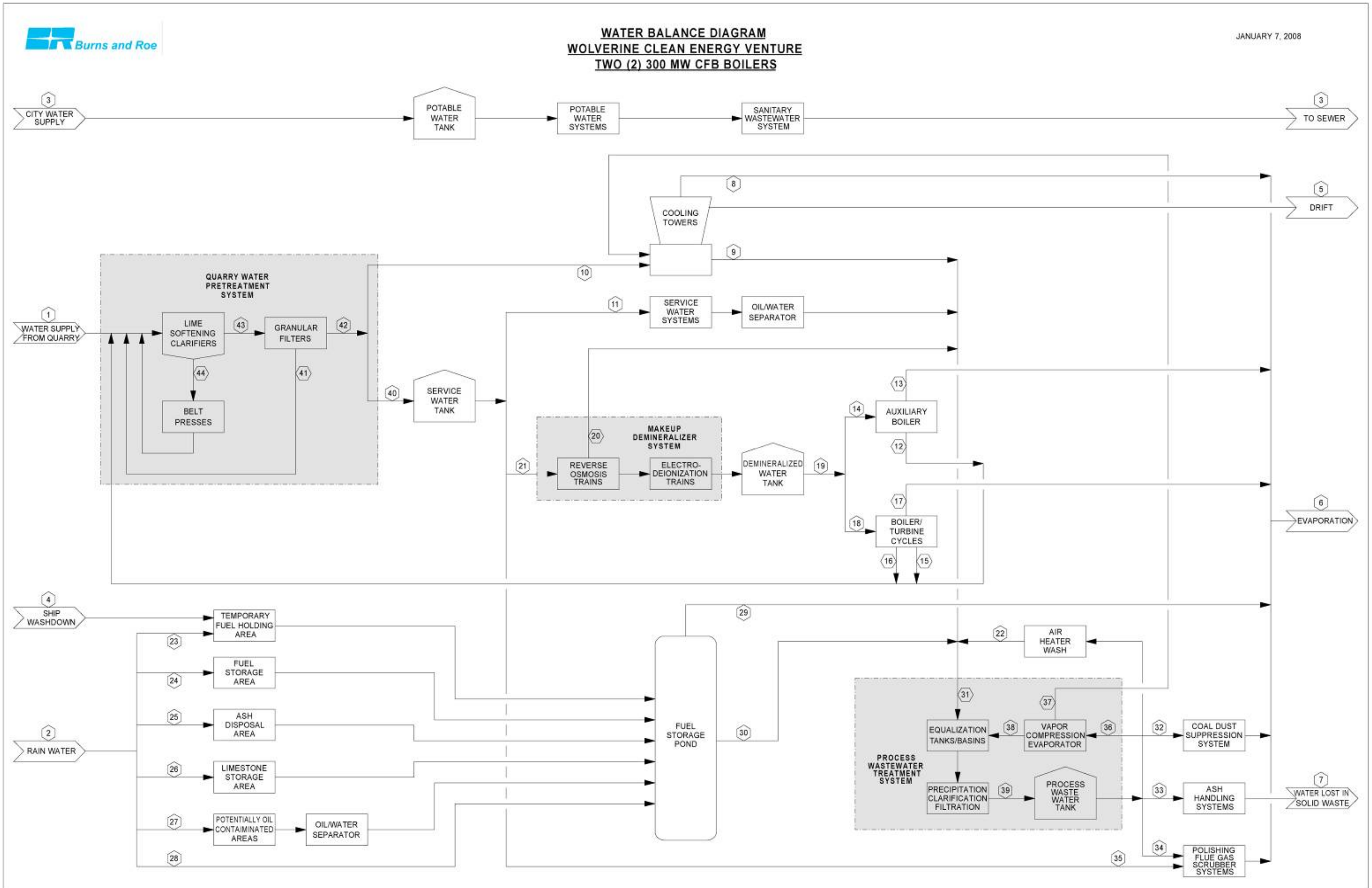


Figure 4-2: Wolverine Clean Energy Venture Water Balance

4.4 CO_2 CAPTURE & COMPRESSION PLANT SITING

The Project site is located in Rogers City, Michigan. The WCEV project is located within the limits of an active limestone quarry southeast of Rogers City, Michigan in Presque Isle County. The site is comprised of a 1,124-acre parcel of land located primarily in Rogers Township (dock is in Rogers City), Presque Isle County, Michigan, within the northwest quadrant of the existing O-N quarry. The current quarry operations are contained within a total of 2,300 acres. A map showing the relative location of the WCEV plant can be seen in Figure 4-3.

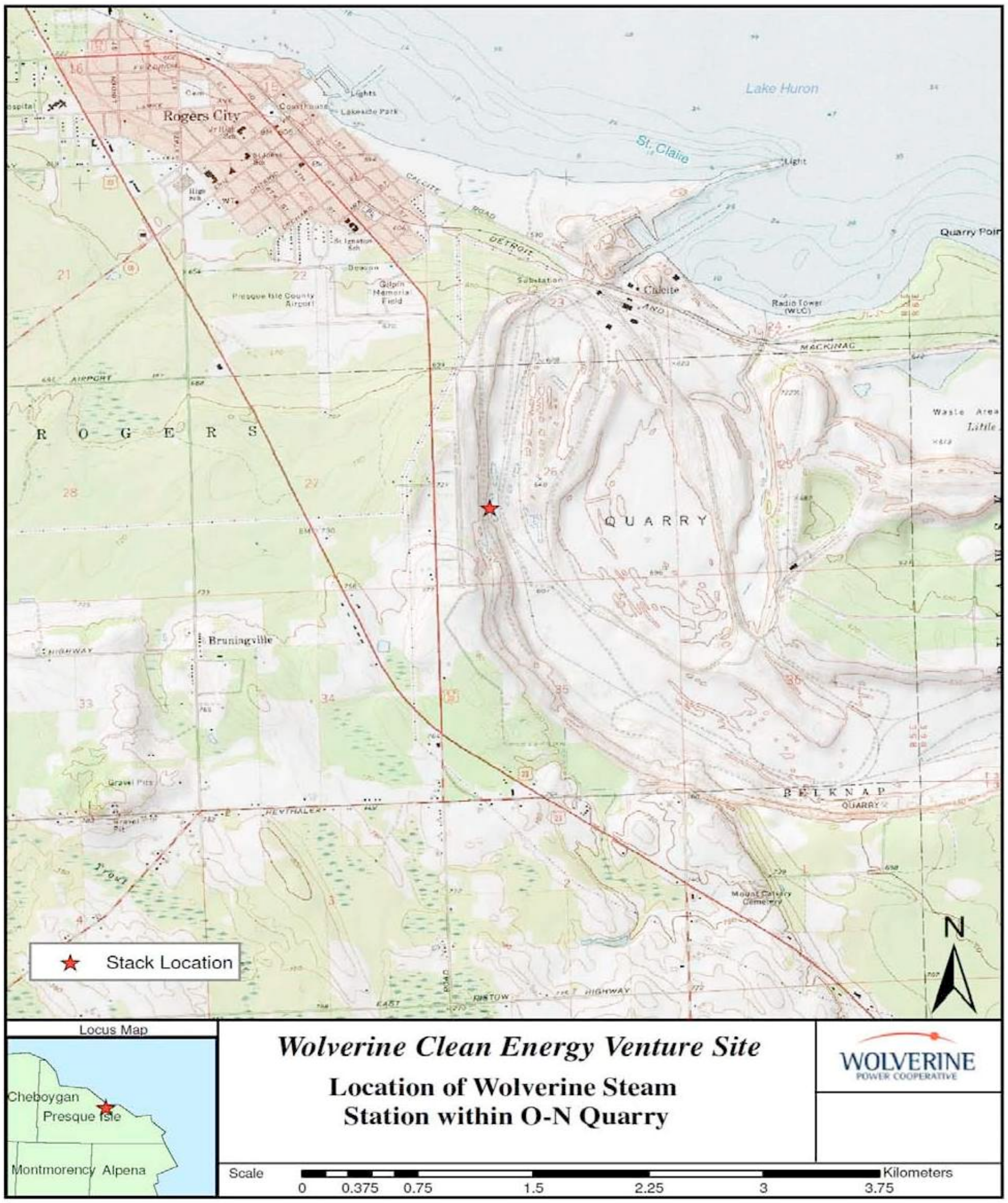


Figure 4-3: Wolverine Clean Energy Venture Site

5 DESIGN BASIS

The Wolverine Carbon Capture and Storage Project (WCCS Project) will be sized to produce 1,000 metric tons per day of CO_2 for subsequent compression, transportation and injection for EOR and/or geologic storage operations. Specifically, the Wolverine Project will employ a CO_2 capture system using advanced amine-based solvent technology to capture and sequester 90% of the CO_2 from the treated flue gas stream. The WCCS project will remove 300,000 metric tons per year of CO_2 from the flue gas produced by one of the two 300 MW units of the WCEV power plant. The capture system will draw flue gas from the Unit 1 ID Fan outlet flue.

The WCEV power plant shall be designed to capture 90% of the CO_2 when the power plant is operated from 70-100% load. The WCCS plant would operate at 100% capacity while the load on the unit of the WCEV that it is connected to, varies between 70% and 100%.

The WCCS process and balance of plant equipment will be enclosed in buildings and heated to above freezing temperatures. The plant site conditions are provided in Table 5-1.

Table 5-1: Site Design Conditions

Location:	Rogers City, MI
Elevation above sea level (ft)	627.0
Temperatures:	
Extreme Ambient:	
Mean Maximum (°F)	94 DB
Mean Minimum (°F)	-16 DB
Design Ambient:	
Maximum (°F)	100 DB
Minimum (°F)	-28 DB
Cooling & Heating:	
Summer (°F)	81 DB / 67 WB (2% Cooling)
Winter (°F)	-1 DB (99% Heating)
Rainfall:	
Annual Average (inches)	28
24 Hours Maximum (inches)	4
Snowfall:	
Annual Average (inches)	60
Basic Frost Depth (inches)	42
Design Wind Speed, (MPH)	90
Seismic Design	$S_5 = 0.068$; $S_1 = 0.028$
Ground Snow Load (psf)	50

The WCCS capture facility will be controlled separately, independent of the control system in the WCCS CO_2 pipeline and the WCEV plant while maintaining data communication between the three systems. DCS cabinet and control room will be located within the WCCS facility.

The design life of the WCCS Project will be 10 years.

CO_2 Pipeline shall be designed for 1,100 metric tons per day of CO_2 to allow for additional capacity to demonstrate improved performance anticipated from the advanced Hitachi solvent.

The Hitachi Carbon Capture process will be designed according to the flue gas flow conditions and flue gas compositions given in Table 5-1. The capture system shall draw flue gas from the Unit 1 ID fan outlet.

Table 5-2: Flue Gas Properties

Case	Unit	**70%Petcoke/ 30%PRB**				**56%Petcoke/ 24%PRB / 20%Biomass**			
Load		100%	75%	70%	50%	100%	75%	70%	50%
Fuel Gas Flow									
Location: AH Outlet (For Purposes of Options Study)									
Temperature (deg F)	F	295.0	300.0	301.0	305.0	295.0	300.0	301.0	305.0
Pressure (psia)	Psia	13.9	14.2	14.3	14.4	13.9	14.2	14.3	14.4
Flow (lb/hr)	lb/hr	2,959,763	2,219,822.4	2,071,834	1,819,444.9	3,009,308.5	2,256,981.4	2,106,516	1,844,320.4
Flow (scfm)	SCFM	631,650.7	473,738.0	442,155.5	390,722.8	648,530.6	486,398.0	453,971.4	399,161.4
Location: ID Fan Takeoff Point to CO2 Capture									
Temperature (deg F)*	F	176.06	163.49	161.38	155.21	182.22	169.68	167.59	160.78
Pressure (inch H2O, guage)	inch H2O								
Flue gas takeoff point to Hitachi CO2 Cap	inch H2O	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Flow (lb/hr)	lb/hr	2,959,763	2,219,822	2,071,834	1,819,445	3,009,309	2,256,981	2,106,516	1,844,320
Flow (scfm)	SCFM	643,441	482,581	450,409	397,903	660,340	495,255	462,238	406,351
Location: Stack Inlet (Hitachi Return Point)									
Pressure Stack inlet (in. H2O guage)	in. H2O	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Fuel Gas Composition									
Location: AH Outlet (for purposes of Option Study)									
CO2	%-vol	13.98	13.98	13.98	11.33	13.73	13.73	13.73	11.19
H2O	%-vol	8.01	8.01	8.01	6.85	10.43	10.43	10.43	8.85
N2	%-vol	73.82	73.82	73.82	74.48	71.76	71.76	71.76	72.78
O2	%-vol	4.19	4.19	4.19	7.34	4.08	4.08	4.08	7.18
SO2	ppmvd	105.84	105.84	105.84	84.39	86.27	86.27	86.27	68.80
NOx	lb/mmBtu	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Flyash Flow	lb/hr	46,210.17	34,619.13	32,333.12	24,317.15	40,261.27	30,181.95	28,186.39	21,656.81
CO	lb/mmBtu	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Location: ID Fan Outlet									
CO2	%-vol	13.33	13.33	13.33	10.80	13.09	13.09	13.09	10.67
H2O	%-vol	12.31	12.31	12.31	11.19	14.58	14.58	14.58	13.06
N2	%-vol	70.37	70.37	70.37	71.01	68.44	68.44	68.44	69.42
O2	%-vol	4.00	4.00	4.00	7.00	3.89	3.89	3.89	6.84
SO2 (based on 0.06 lb/MMBtu)	ppmvd	23.46	23.46	23.46	18.70	23.87	23.87	23.87	19.04
NOx	lb/mmBtu	0.07	0.07	0.07	0.14	0.07	0.07	0.07	0.14
PM10	lb/hr	82.42	61.82	61.82	41.21	83.96	62.97	62.97	41.98
CO	lb/mmBtu	0.15	0.15	0.15	0.20	0.15	0.15	0.15	0.20

CO_2 will be provided to Core Energy in accordance with the below pipeline specifications in Table 5-3.

Table 5-3: CO_2 Conditions at Interface for Storage

Gas Analysis at CO_2 Interface for Transportation and Storage (with Core Energy)			
	DESIGN BASIS	**EXPECTED VALUES**	
		By Volume	**By Mass (%)**
Carbon Dioxide (CO_2)	> 99.9 $\%_{vol}$	99.9%	99.9%
Water Vapor (H_2O)	< 420 ppm_v	314 ppm_v	129 ppm_w
Nitrogen (N_2)	< 10 ppm_v	4.14 ppm_v	2.6 ppm_w
Oxygen (O_2)	<10 ppm_v	2.07 ppm_v	1.5 ppm_w
Sulfur Dioxide (SO_2)	Below Detection Level	0.07 ppm_v	0.1 ppm_w
Hydrogen Chloride (HCl)	Below Detection Level	0.03 ppm_v	0.03 ppm_w
Hydrogen Fluoride (HF)	Below Detection Level	0.06 ppm_v	0.03 ppm_w
Particulate Matter	< 1 ppm_w	--	0.03 ppm_w
Ammonia (NH_3)	Below Detection Level	0.52 ppm_v	0.2 ppm_w

CO_2 Conditions at CO_2 Interface for Transportation and Storage	
Pressure	2,000 psia
Temperature	95•F
Flowrate	101,490 lb/hr

6 POST-COMBUSTION CO_2 CAPTURE SYSTEM

The Hitachi post-combustion CO_2 capture demonstration unit for the WCEV Project is designed to achieve 90% capture with large cost savings and efficiency improvement over current amine scrubbing technologies. It is designed with the robustness and reliability according to power industry standards and with the flexibility to allow the plant owner to utilize common commercial amine solutions and future advanced amine-based reagents.

6.1 CO_2 CAPTURE PROCESS ISLAND SUMMARY

The CO_2 capture system is based on proven process engineering principles. As shown in Figure 6-1, the main system components are a prescrubber, an absorber, a stripper and a reboiler. A slipstream of about 17% of the total flue gas from the power plant, sufficient to capture and produce 1000 metric tons of pure CO_2 per day, is diverted to the carbon capture system via control dampers.

Flue gas from the power plant is first sent to the prescrubber to reduce SO_2 and SO_3 to below 10 ppm (combined), as well as to cool the flue gas to 40-60 °C (100-140^{o}F) range for maximum CO_2 capture in the absorber. Caustic soda (NaOH) solution is used to remove SO_x and therefore, minimize formation of heat-stable salts (HSS) in the downstream absorber-stripper loop. The clean and cool flue gas leaving the pre-scrubber enters the packed bed absorber where it reacts with the amine-based solvent. Counter-current flow through the structured packing maximizes contact surface area and mass transfer. Solvent solution is injected into the top and collected from the bottom of the packing layers. CO_2-depleted flue gas leaving the top of the absorber is vented to the stack. The CO_2-rich solution leaving the bottom of the absorber is sent to the stripper via a cross heat exchanger where it gets heated. In the packed-bed stripper, pure CO_2 gas is stripped away from the CO_2-rich solution by contacting it with steam in a counter current direction. A part of the CO_2-lean solution from the stripper circulates through a reboiler where auxiliary saturated steam is utilized to partially vaporize the amine solution which, upon returning to the stripper provides the heat needed for amine regeneration to release CO_2. Regenerated solvent is re-sent to the absorber after it gets cooled in the cross heat exchanger.

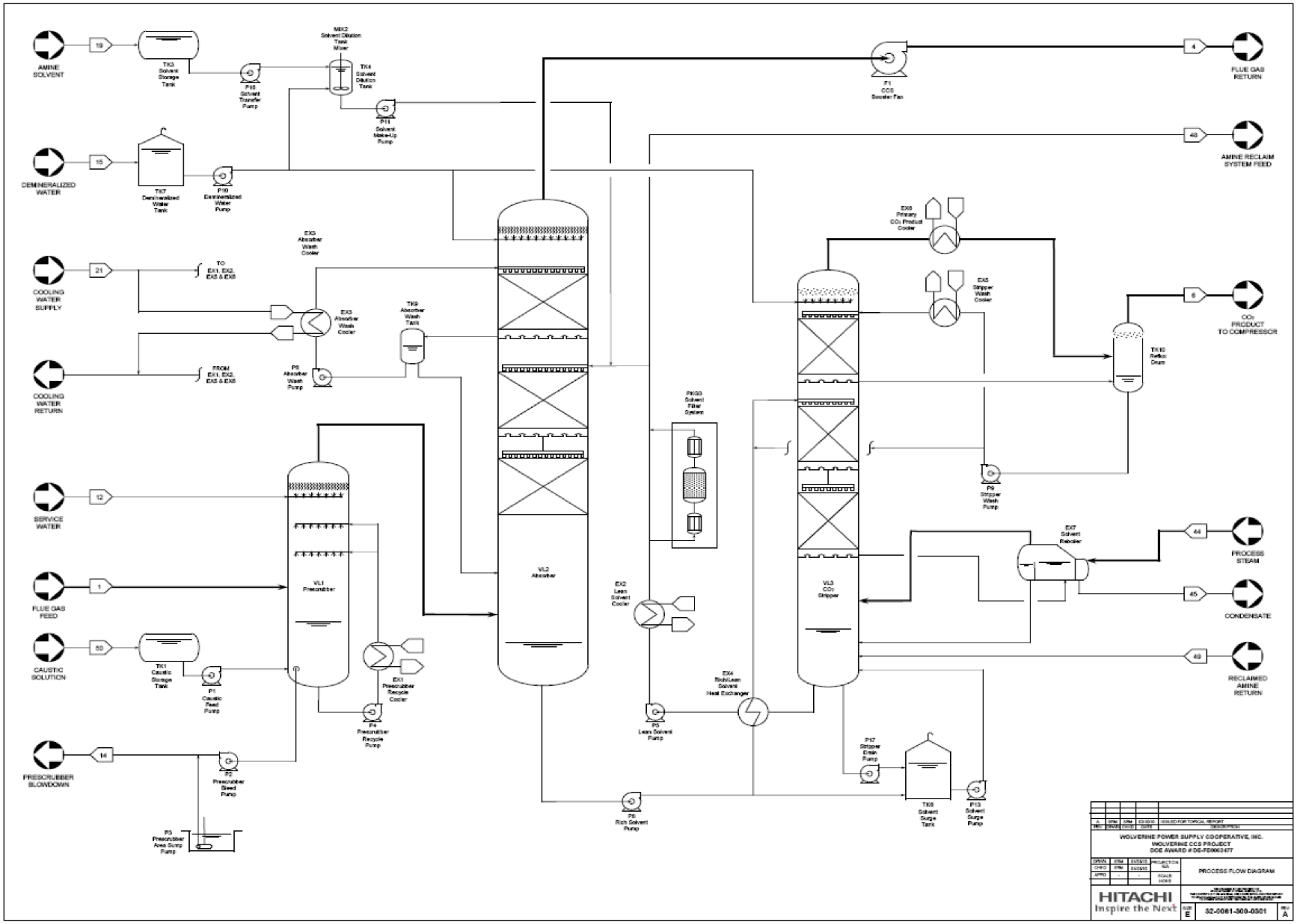


Figure 6-1: Process Flow Diagram for the 1000 ton/day Wolverine CO_2 Capture System

6.2 PROCESS DESCRIPTION

6.2.1 Prescrubber

Flue gas enters the caustic prescrubber from the bottom, flowing counter-current to weak aqueous caustic soda (NaOH) solution sprayed from the top of the prescrubber. Caustic soda reacts with SO_2 as per Equation 6-1. The products of the reaction (largely sodium sulfate and small quantities of sodium bisulfate) collect in the liquid sump at the bottom of the vessel.

$$4\ NaOH + 2\ SO_2 + O_2 \bullet\ 2\ Na_2SO_4 + 2\ H_2O \qquad \text{Equation 6-1}$$

Amine solvents react easily with SO_2 to form undesirable heat-stable salts (HSS) that could result in degradation of the solvent and thereby, affect the performance of the CO_2 absorption process. HSS can also increase the risk of corrosion of the system. Therefore, it is necessary to remove these sulfur compounds to very low levels.

In addition to SO_2 removal in the prescrubber, the flue gas is cooled within an optimum temperature range for maximum CO_2 capture in the absorber. The cooled and cleaned flue gas passes through a mist eliminator before exiting the prescrubber to remove entrained caustic and water droplets. The mist eliminator is periodically washed to remove any solid deposits.

To maintain a constant chemical balance in the prescrubber, spent caustic soda is continuously replenished with fresh NaOH solution. The sodium sulfate (Na_2SO_4) resulting from the chemical reaction is extracted together with the water condensed from flue gas in the prescrubber and discharged.

6.2.2 Absorber

Flue gas leaving the prescrubber enters the bottom of the packed bed absorber where it reacts with the amine-based solvent which is injected into the top. Counter-current flow through two stages of structured packing maximizes gas-liquid contact surface area and mass transfer. In the contact zone of the absorber (structured packing region), carbon dioxide is absorbed from the flue gas by amine solvent solution. In the case of a primary amine such as MEA, carbon dioxide and aqueous amine react to form an intermediate product (carbamate) by the process of chemisorption. The reaction of MEA with CO_2 may be described by the two steps given by Equations 6-2 and 6-3. This process is most effective in a temperature window of approximately 40 to 60 °C. CO_2 absorption is an exothermic process. Hence, the CO_2-rich solution collected at the bottom of the absorber column is at a higher temperature than the liquid injected at the top of the packing sections.

$$RNH_2 + CO_2 \bullet\ RHNCOOH \qquad \text{Equation 6-2}$$

$$RHNCOOH + RNH_2 \bullet\ RHNCOO^- + RNH_3^+ \qquad \text{Equation 6-3}$$

Where R is CH_2CH_2OH and RNH_2 is MEA. Therefore, two moles of amine are used per mole of CO_2 reacted and the overall reaction may be written as:

$$2\ RNH_2 + CO_2 \bullet\ RHNCOO^- + RNH_3^+ \qquad \text{Equation 6-4}$$

Equation 6-4 is a reaction of the second order, i.e. the reaction speed rCO_2 depends on the concentration of both MEA and CO_2. The reaction speed constant, k includes the temperature dependency of the reaction:

$$rCO_2 = -k\ [CO_2]\ [MEA] \qquad \bullet H \bullet\ -85\ kJ/mol\ CO_2 \qquad \text{Equation 6-5}$$

When high purities of pure CO_2 gas are present, the reaction with MEA will result in a comparatively stable carbamate in the absorbent. While theory[1,2,3] suggests 0.5 moles of CO_2 per mole of MEA for the reaction, 0.6 to 0.7 moles of CO_2 are used up per mole of MEA in practice. An initial loading after regeneration amounts to 0.2 mol CO_2 per mole MEA and in the absorption column, 0.4 to 0.5 moles of CO_2 is absorbed per mole of MEA.

While tertiary amines have a slower reaction rate with CO2 than primary (and secondary) amines, they have lower oxidative degradation and corrosion rates than MEA. MDEA is one such tertiary amine commonly used for acid gas treatment. Since MDEA does not have a hydrogen atom attached to the nitrogen, the CO_2 reaction can only occur after the CO_2 dissolves in the water to form a bicarbonate ion. The bicarbonate then undergoes an acid-base reaction with the amine and the overall CO_2 reaction is given by Equation 6-6.

$$CO_2 + H_2O + R\ NCH_3 \bullet \quad R\ NCH_4^+ + HCO_3^- \qquad \text{Equation 6-6}$$

CO_2-depleted flue gas leaving the absorber packing sections passes through a wash stage and a mist eliminator where any trace amounts of amine solvent entrained in the gas stream gets removed. Washing fluid (mostly water) is re-circulated through the washing stage such that the temperature, flow rate and quality of the washing fluid are maintained at consistent levels for every cycle. Excess condensate is purged from the wash loop and sent to the sump at the bottom of the absorber. The mist eliminator is periodically washed to clean out any solid deposits that may collect over time.

With the help of a booster fan clean flue gas devoid of CO_2 is vented to the stack from the top of the absorber. The CO_2-rich solvent solution at the bottom sump of the absorber is pumped into the stripper via a rich/lean solvent cross heat exchanger. In the cross heat exchanger, heat is transferred from the hot CO_2-lean solution leaving the stripper to the cold CO_2-rich solution leaving the absorber.

6.2.3 Stripper

The stripper serves to release pure CO_2 gas from the CO_2-rich solution and regenerate the aqueous amine solvent for reuse in the absorber. Similar to the absorber, the stripper internals comprise layers of structured packing for stripping, a wash stage and a mist eliminator. CO_2-rich solution from the absorber heated in the rich/lean cross heat exchanger is supplied at the top of the stripping packed sections and travels counter-current to the ascending steam flow. Most of the CO_2 is stripped off to the gas phase by the reverse reaction of absorption. Steam flowing through the gas provides the energy for the endothermic CO_2 stripping reaction.

The liquid leaving the packing sections gets collected in a collecting tray at the bottom of the packed bed along with a portion of the stripping steam that has condensed. The collected liquid mixture gets circulated through a kettle-type reboiler where it is partially evaporated by auxiliary steam. Vapor generated from the reboiler is returned to the stripper. The regenerated CO_2-lean amine liquid stream in the reboiler is discharged to the bottom sump of the stripper wherefrom a desired flow is re-circulated to the absorber via the rich/lean solvent cross heat exchanger. The CO_2-lean solvent stream is further cooled in a lean solvent cooler before it is injected into the absorber to continue the absorption-desorption cycle. Small quantities of fresh amine solvent are added to the cool lean solvent stream to compensate for solvent losses occurring due to solvent degradation and evaporation.

The CO_2 gas stream leaving the top of the stripper column passes through the washing section and the mist eliminator to remove any solvent that may be entrained in the gas stream. From the top of the stripper, the CO_2 gas stream is cooled in a condensing heat exchanger and the condensate (moisture with any residual solvent) is recovered in a condensate tank equipped with a mist eliminator. The product CO_2 gas stream is sent to the CO_2 compressor for compression and storage.

Wash water discharged from the wash cycle of the stripper column is returned to the condensate tank. A desired portion of the liquid collected in the tank is cooled in a stripper wash cooler and returned to the washing stage in the stripper column. The remaining condensate is sent to the stripper packing section along with CO_2-rich amine stream.

In the packing section of the stripper, the chemical bonds between the carbon dioxide and the amine molecules are broken down by a charge of heat provided by steam. The reactions occurring are the reverse reactions of Equations 6-2 to 6-4. The ascending steam flow strips the CO_2 from the solvent solution and the released CO_2 is drawn off for compression and subsequent storage.

6.2.4 Reboiler

Reboiler is designed such that amine-water solution from the stripper is partially evaporated. Energy required for the partial evaporation is provided by means of steam extracted from the main plant's steam turbine. Since the slipstream CO_2 capture system demonstration unit treats only 17% of the flue gas of one 300 MWe power train, all of the reboiler steam is extracted from the crossover pipe connecting the IP section and LP section of the steam turbine. The extracted steam is pressured regulated and de-superheated, and the resultant saturated steam at desirable temperature is supplied to the reboiler. This saturated steam gets condensed in the reboiler and the condensate is returned to the deaerator of the main power plant. The vapor from the reboiler is returned to the freeboard above the stripper sump. Liquid return (amine solvent solution) from the reboiler is discharged to the stripper sump from where it is drawn off to the absorber. The reboiler is designed with a very high process throughput so as to achieve uniform temperature distribution to prevent any hot spots that can potentially cause accelerated thermal degradation of the solvent.

6.2.4.1 Process Steam

Steam will be supplied to the CO_2 capture system reboilers at a suitable temperature and pressure for the process needs. Presently, the only suitable steam tap to meet the CO_2 capture process conditions for a varying steam turbine load of between 70% and 100% is in the steam turbine IP to LP crossover pipe.

Flash steam from the process steam flash tank will be returned to the cycle at a point which matches cycle pressure and temperature conditions. Return will be to low pressure feedwater heater #2, shell side.

The steam supply and flash steam return lines between the Turbine Building and CO_2 Capture Process Building will be run on an overhead pipe rack with suitable loops to handle thermal expansion. The steam integration concept can be seen in Figure 6-2.

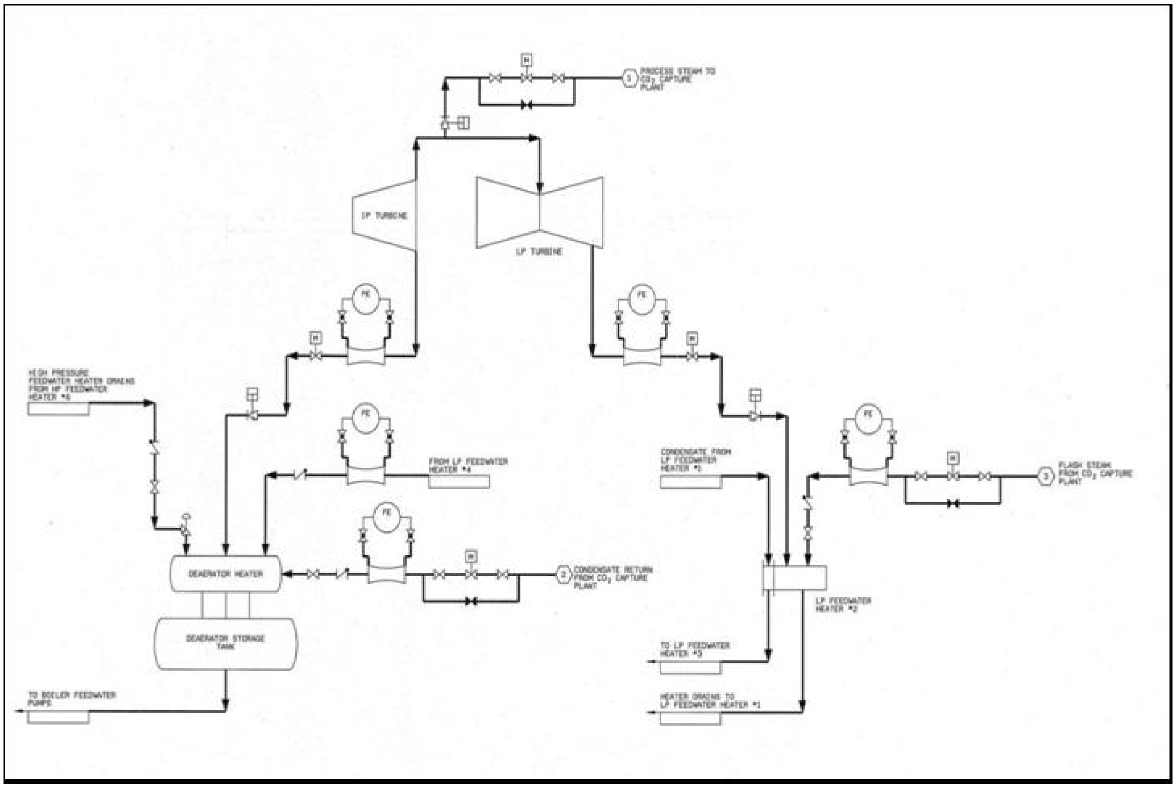


Figure 6-2: Steam Integration and Condensate and Flash Steam Return

6.2.4.2 Condensate Return

Condensate from the carbon capture plant will be returned to the steam turbine cycle at the inlet to the deaerator. The condensate return will be mixed with low pressure condensate exiting the last low pressure feedwater heater and then scrubbed with steam in the deaerator heater.

6.2.5 Reclamation

A solvent reclamation system is operated in batch mode, when needed, to remove heat-stable salts (HSS) and degradation products from the amine solvent that may have generated from the absorption process. Solvent is extracted from cool lean solvent stream prior to entering the absorber for treatment and the reclaimed solvent is returned to the stripper. The frequency of reclamation will be determined in Phase 2 based on long-term monitoring of system CO_2 capture performance and solvent quality deterioration.

6.2.6 Process Summary of 1000 ton/day CO_2 Capture System

The most cost-effective capture level has been determined during the Phase 1 sensitivity study and will be verified during parametric testing of Phase 2 demonstration. Table 6-1 summarizes the main process conditions such as mass flow, temperature, pressure and composition of flue gas streams and CO_2 at system boundary.

Table 6-1: Process Parameters for CO_2 Capture System

Parameters	Units	Flue gas entering the Prescrubber from the Power Plant	Flue gas leaving the Prescrubber & entering the Absorber	Clean flue gas leaving the CO_2 Absorber	CO_2 stream after the Stripper & before the Compressor
Gas Flow rate wet	scfm w	111,550	105,622	92,766	13,831
Gas Flow rate dry	scfm d	97,818	97,806	84,426	13,375
Gas Flow rate dry	acfm w	131,826	116,430	109,535	6,658
Composition					
N_2	vol % w	69.5	73.4	83.6	0.0
O_2	vol % w	4.0	4.2	4.8	0.0
H_2O	vol % w	12.3	7.4	9.0	3.3
CO_2	vol % w	13.3	14.1	1.6	96.7
SO_2	ppm d	26.1	1.8	0.9	0.1

In the prescrubber, about 94% of the SO_2 is scrubbed out so that the flue gas entering the absorber contains less than 2 ppm of SO_2. The temperature of flue gas leaving the prescrubber is cooled to maximize CO_2 absorption by the amine solution. About 50% of water in the flue gas entering the prescrubber gets condensed out along with the pre-scrubber liquid discharge. As the clean flue gas passes through the absorber, 90% of the CO_2 is removed by the amine solvent. Since CO_2 absorption is an exothermic process, the gas temperature increases slightly while picking up additional moisture from the process (<10% excess) and exits the absorber as a saturated gas stream. As can be seen in the table, the purity of the CO_2 stream sent to the compressor is about 97% on a wet basis.

Figure 6-3 shows a 3-D representation of the elevation view looking south of the Hitachi carbon capture island. Drawn to scale, the figure shows major equipment such as the prescrubber (far left), absorber, stripper, heat exchangers, storage tanks (far right) and main gas duct/piping. Figure 6-4 shows the elevation view looking north surrounded by the building enclosure frame to protect personnel from severe weather conditions experienced in northern Michigan where the plant is located.

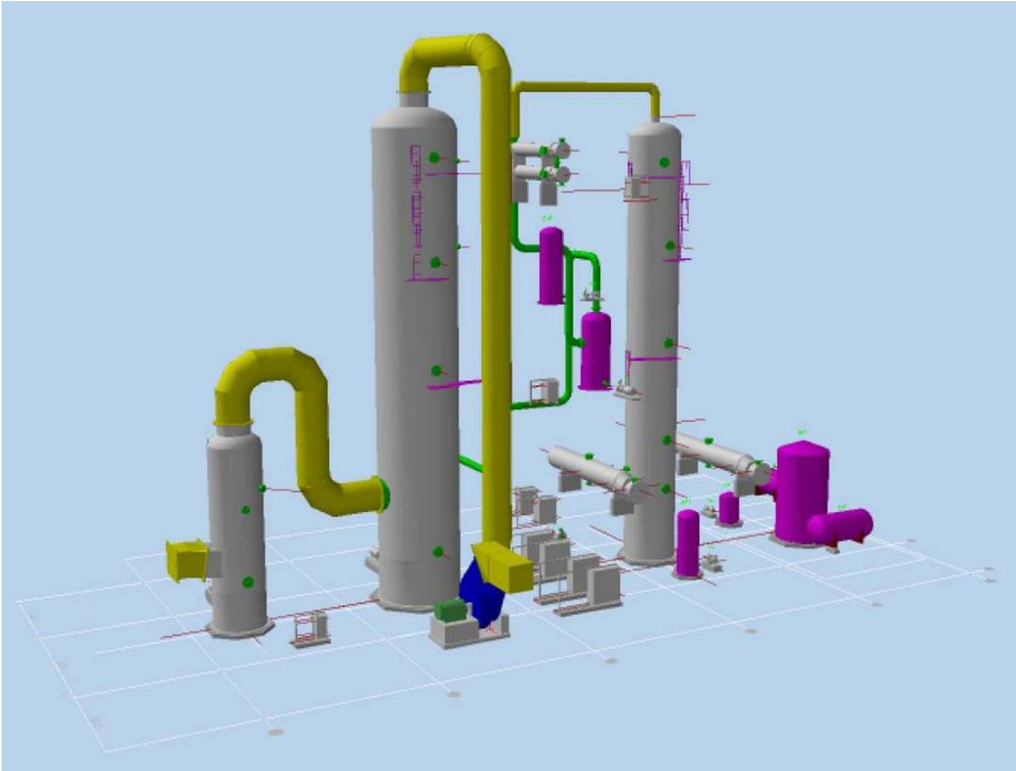


Figure 6-3: 3-D Representation of Carbon Capture Island (Elevation view looking South)

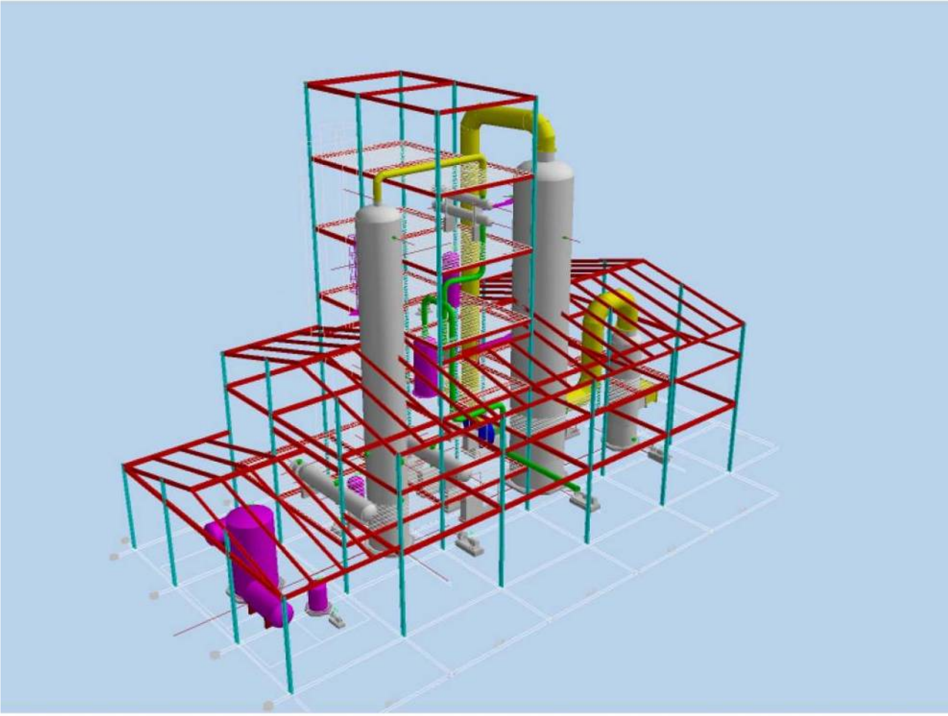


Figure 6-4: 3-D Representation of Carbon Capture Island (Elevation view looking North), with Building Enclosure

6.2.6.1 Control of Amine Emissions

From the absorber, trace levels of amine can be carried over to the stack and emitted to the atmosphere. The degradation products of amine react with certain trace constituents in the air to form new compounds, some of which may have potential health-related concerns. To eliminate this problem, a tall packed section with dedicated water wash-cooling loop and high efficiency mist eliminator are provided in the top sections of the absorber vessel. The wash stage removes entrained amine from the gas phase. By utilizing cold wash water to maintain the flue gas at a low temperature, the vapor phase amine is also minimized.

6.2.7 Solvents

6.2.7.1 Design Range of Solvents

The Wolverine CO_2 capture system is designed with the flexibility to use a wide range of solvents. This system will be used to demonstrate Hitachi's advanced amine-based solvent, H3-1. It can also be operated with generic MEA to generate baseline test data in order to correlate the Phase 2 demonstration test results with the literature data. MEA is the most extensively studied solvent for CO_2 capture in published sources. A widely used commercial solvent, UCARSOL AP 814 produced by Dow Chemicals, is used as the design basis.

UCARSOL AP 814 is a proprietary formulated MDEA based amine solution targeted at separation of CO_2 from CO_2 containing mixtures. AP 814 is one product in a family of UCARSOL products designed for this type of separation. It is a stronger solvent than other products in this line. The characteristics that make it a stronger solvent are the ability to react with CO_2 faster than other amine products and to remove CO_2 to lower residual concentrations in the targeted mixture.

Strong primary amines such as MEA work well for CO_2 absorption but suffer from CO_2-amine reaction product formation. MDEA based formulated amines such as AP 814 resist the formation of CO_2-amine and other reaction products. Separation process based on AP 814 is more chemically stable and much less corrosive than generic MEA-based processes.

6.2.7.2 Hitachi Advanced Amine-based Solvent (H3-1)

In 1990, researchers and engineers at Babcock Hitachi K.K., a wholly owned subsidiary of Hitachi Ltd., started working on a CO_2 capture system specifically designed for flue gas from coal and other solids fuels. In 1991, a 1000 m^3N/h (620 scfm) CO_2 capture pilot plant was commissioned in co-operation with Tokyo Electric Power Co. to treat flue gas from Yokosuka Thermal Power Plant's Unit 2. This was the first pilot testing of amine-based CO_2 separation from the flue gas of a coal-fired power plant by Hitachi. From the early laboratory and pilot plant testing, the shortcomings of MEA-based process became clear, and Hitachi soon embarked on a focused development program for advanced amine solvent formulations that are less energy intensive and more resistant to flue gas impurities.

The initial five-year CO_2 capture pilot test program was successfully completed in 1994, three years before the Kyoto Protocol of 1997. Five solvent solutions were tested, including a commercial MEA as benchmark and three proprietary formulations, H1, H2, and H3. The test for H3, the best performing solution of the five, lasted 2000 hours under various plant loads and other operating conditions and generated a large database of solvent and system behavior, laying a solid foundation for future work. Figure 6-5 shows that in over 2000 hours of testing under various loads and inlet CO_2 concentrations, H3 consistently achieved greater than 80% CO_2 removal with the average well above 90%. The capture process with H3 has a much lower regeneration energy requirement than that of commercial MEA-based process.

The latest refinement of the H3 solvent formulation is H3-1, which will be demonstrated during the Wolverine project. H3-1 is a proprietary blend solvent that has the same advantages of high CO_2 absorption capacity and low regeneration heat as H3, and has further reduced amine loss. The sterically hindering effect of the base amine in H3-1 results in a lower CO_2 absorption heat than that of MEA solutions. Minor ingredients of the H3-1 solvent further improve the performance.

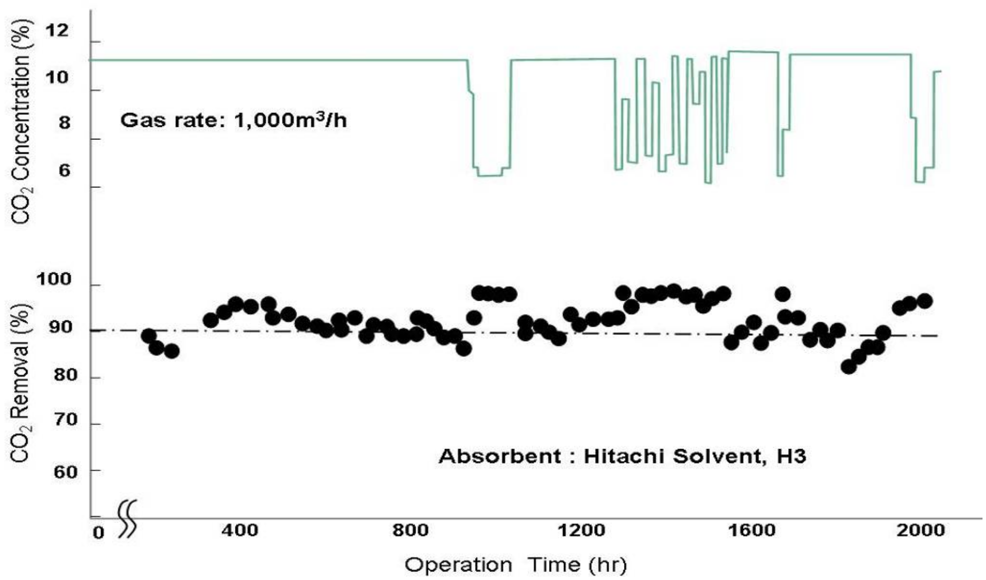


Figure 6-5: Long-term Pilot Testing of H3 Solvent under Various Inlet CO_2 Concentrations

Compared with generic MEA-based processes, the absorption process with H3-1 solvent has significantly lower corrosion tendency. Unlike MEA based solvents which are typically limited to a concentration of about 30% due to corrosion concern, H3-1 allows the use of much higher amine concentrations. The high amine concentration coupled with high absorption capacity of H3-1 reduces the solvent circulation rate required for a given level of CO_2 removal, and the associated operational energy / power cost for the CO_2 capture plant. For 90% capture the solvent recirculation rate needed is 20% lower than that for MEA, resulting in significant operating cost savings.

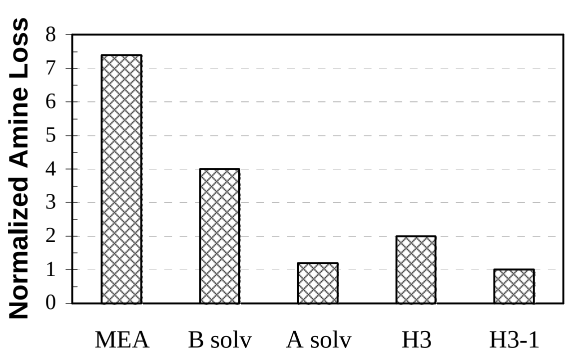


Figure 6-6: Comparison of Amine Loss from Different Solvents

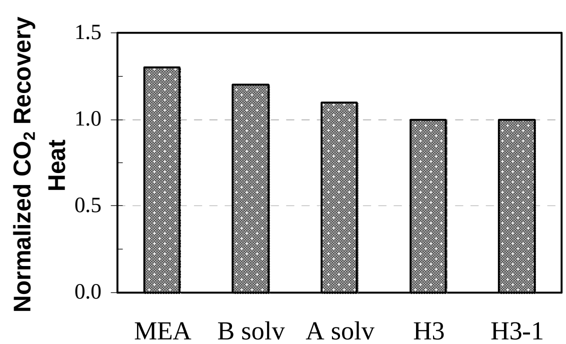


Figure 6-7: Comparison of CO_2 Recovery Heat from Different Solvents

The H3-1 based process has a regeneration energy requirement of less than 2800 kJ/kg CO_2. Extensive R&D is ongoing to further lower the regeneration energy to 2500 kJ/kg CO_2 through both solvent improvement and optimization of the absorber-stripper loop.

Figures 6-6 and 6-7 show a comparison of solvent performance based on in-house and published data, including data by a government research institute in Japan. H3 and H3-1 have the lowest regeneration heat compared to 30% MEA solution and two advanced amine solutions by other leading developers (A solv and B solv). H3-1 also has the lowest amine loss, which is 86% lower than that of the MEA solution. The reduced level of solvent losses and lower heat requirement of H3-1 translate to great savings in utility and operating costs.

In February 2010, the H3-1 solvent was independently tested by Energy and Environmental Research Center (EERC), University of North Dakota at the 400 m^3N/h (250 scfm) CO_2 capture pilot plant. The week-long test is a part of the DOE – Industry co-sponsored “Partnership for CO_2 Capture” program in collaboration with 15 private sector partners including utilities, engineering companies and technology providers. Figure 6-8 is a snapshot of the preliminary test data (Source: “Partnership for CO_2 Capture Project - Status Report by EERC, March 2010). Ninety percent CO_2 capture was easily achieved with the H3-1 solution. Compared to MEA that was tested immediately before H3-1, testing with H3-1 clearly had lower reboiler heat input and lower solvent recirculation rate for the same CO_2 removal level.

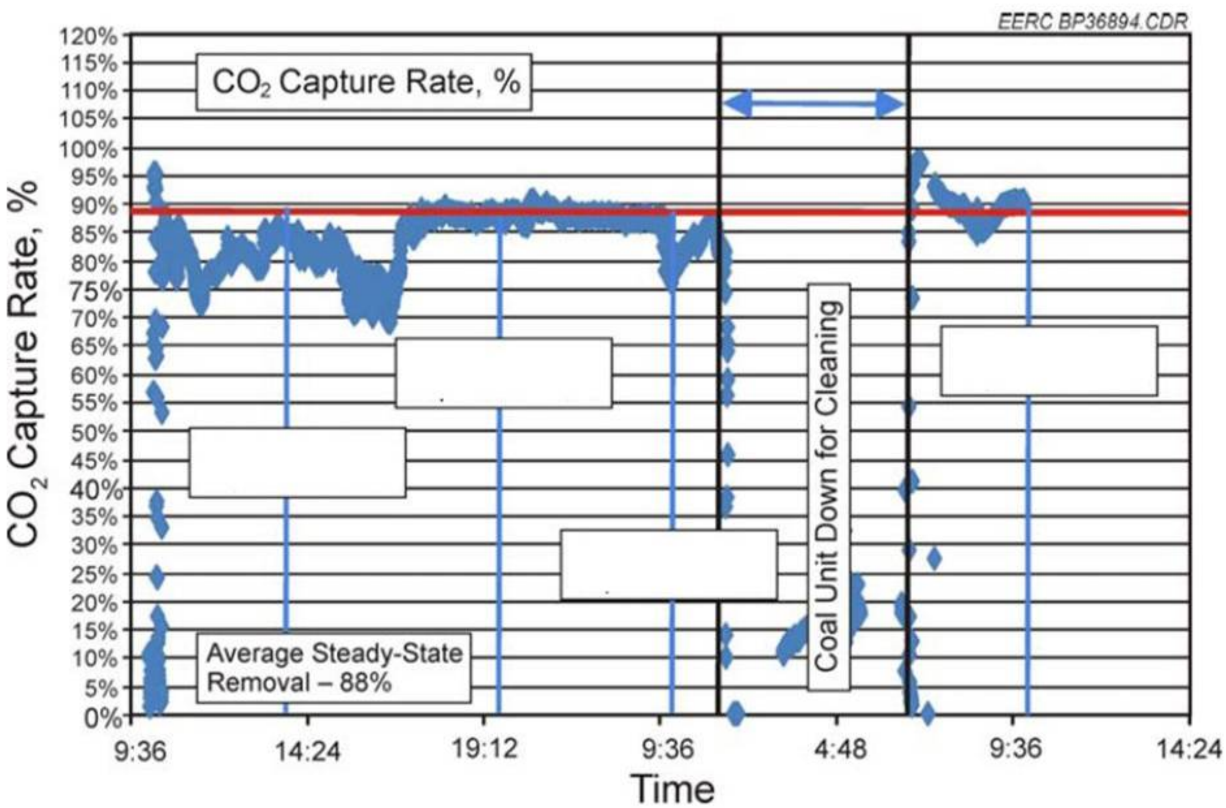


Figure 6-8: An Example of H3-1 Test Data from EERC Study (Courtesy of Energy and Environmental Research Center)

Based in Midland, Michigan which is close to the project site, Dow Chemicals is a world leader in gas separation technologies including amine-based scrubbing. As discussed previously, UCARSOL AP 814, a widely used commercial solvent recommended by Dow Chemicals, was chosen as the design basis solvent for the Wolverine demonstration plant in order to design the plant with the ability for testing of multiple solvents during the project demonstration phase. This will also give the Wolverine Power Cooperative the flexibility for using both currently commercial solvents and new solvents for long term operation of the CO_2 Capture and Compression plant.

7 INTEGRATION OF CO_2 CAPTURE INTO BALANCE OF PLANT SYSTEMS

7.1 PROJECT CONCEPT

The Wolverine Carbon Capture and Storage Project will be sized to produce 1,000 metric tons per day of CO_2 for subsequent compression, transportation and injection for EOR and/or geologic storage operations. Specifically, the WCCS Project will employ a CO_2 capture system using advanced amine-based solvent technology to capture and sequester 90% of the CO_2 from the treated flue gas stream. The WCCS Project will remove 300,000 metric tons per year of CO_2 from the flue gas produced by one of the two 300 MW units of the WCEV power plant. The capture system will draw flue gas from the Unit 1 ID Fan outlet flue. The overall concept for the implementation of the project is shown in Figure 7-1.

The WCCS capture facility will be controlled separately from the WCCS CO_2 pipeline and the WCEV plant while maintaining communication of data between the three systems. The WCCS will have its own DCS cabinet and control room located within the facility.

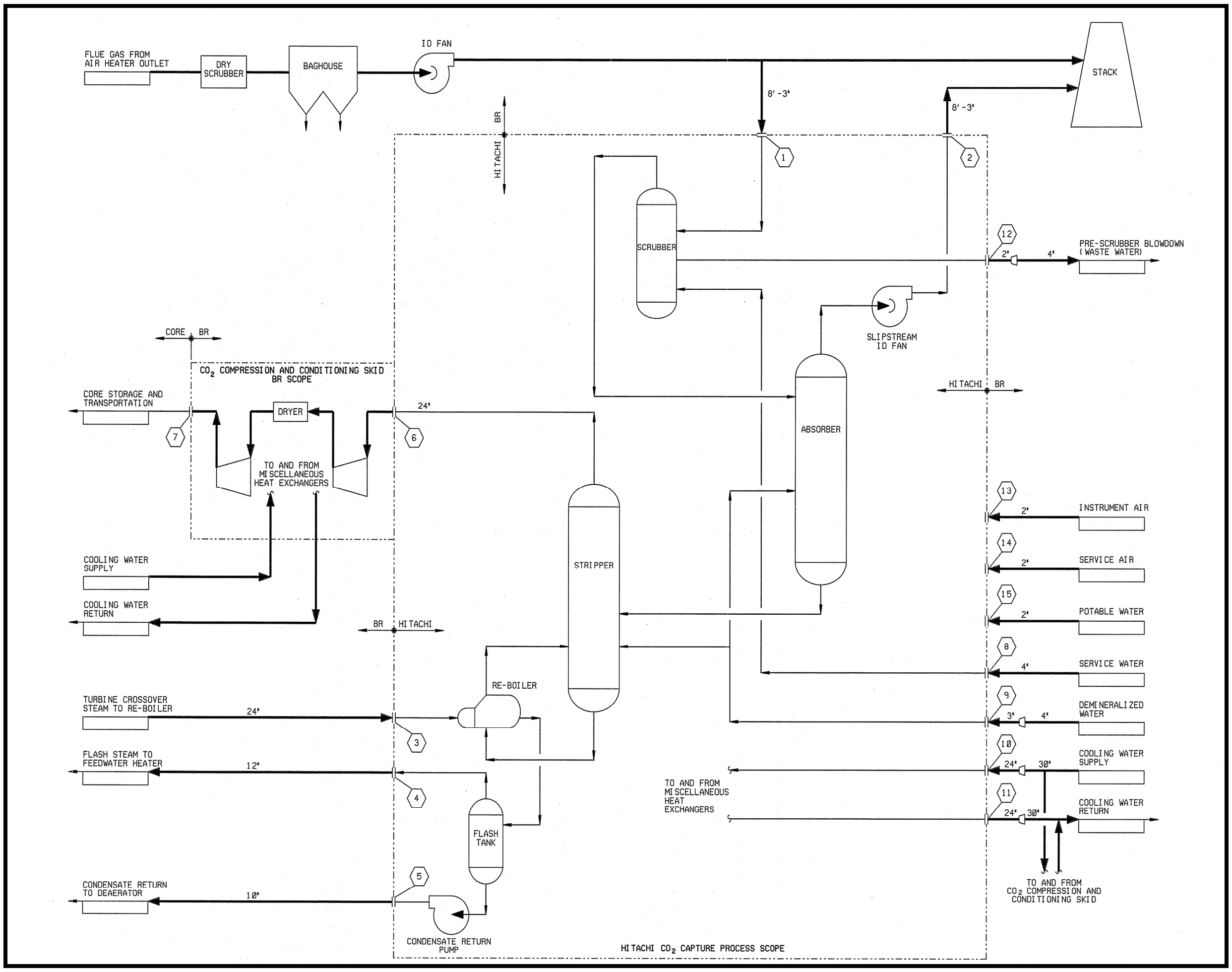


Figure 7-1: Wolverine CCS Project

7.2 STEAM INTEGRATION

The preliminary design analysis revealed that capture plant performance at loads less than 70% introduces additional complexity to the design, as well as additional capital cost. The CO_2 capture process requires minimum steam pressures of approximately 85 psia at the location of the steam turbine extraction. The location on the steam cycle where this steam can be extracted is dictated by the pressure profile across the steam turbine. As can be seen in Figure 7-2, the pressure at the crossover from the Intermediate Pressure to the Low Pressure Steam Turbine is 123.9 psia at a 100% load steam condition.

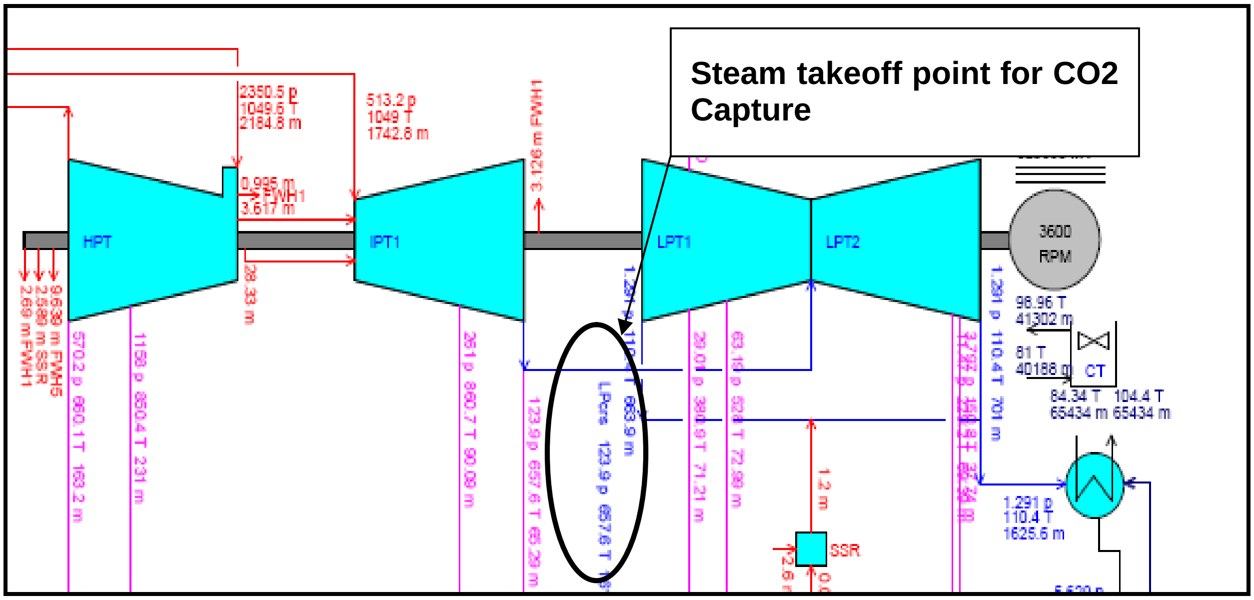


Figure 7-2: 100% Load Steam Turbine Heat Balance (CO_2 Capture)

At 100% load, there is more than sufficient pressure to meet this requirement. As the steam turbine load is decreased, the pressure at the IP to LP crossover decreases. As can be seen in Figure 7-3, the IP to LP crossover pressure decreases to approximately 86 psi at 70% load and further decreases to approximately 65 psia at 50% load.

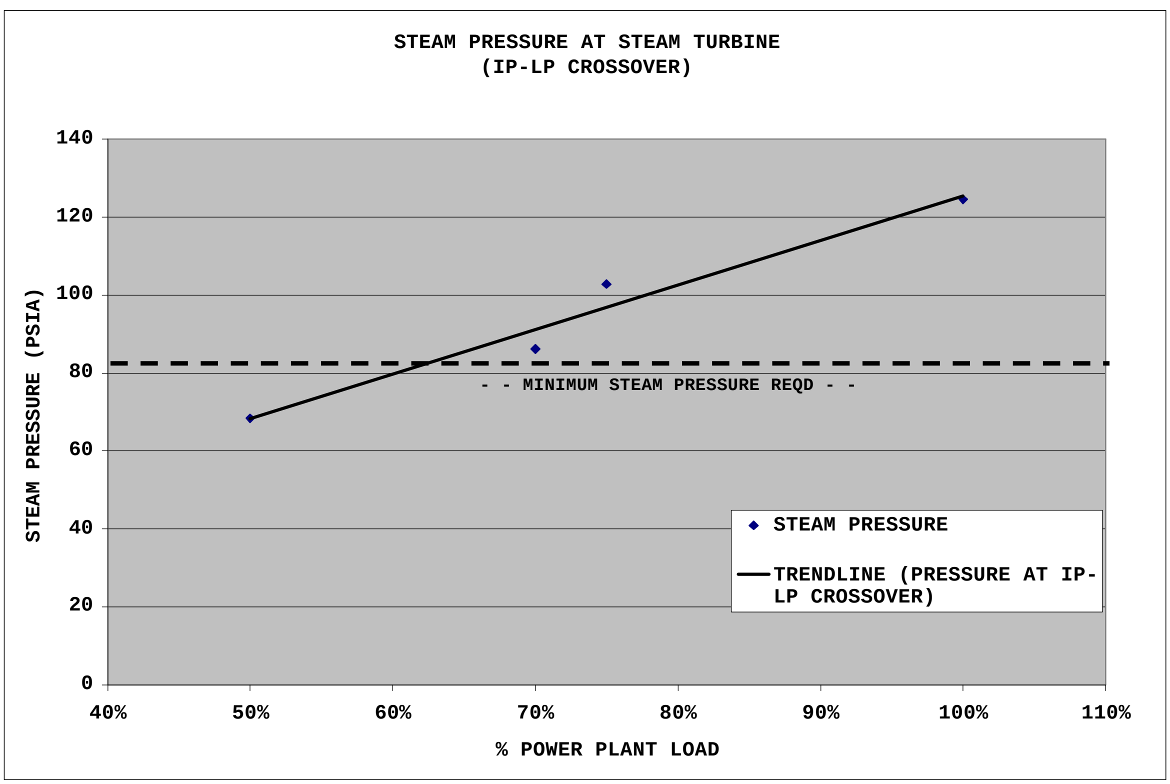


Figure 7-3: Integration with CO_2 Capture System (Steam Pressure vs. Load)

Designing the capture system such that it operates at full capacity at 50% load condition would necessitate either the use of a higher pressure steam extraction or an additional steam extraction port. Each of these options negatively impacts either the cost or the efficiency of the proposed concept. Since the power plant will operate primarily as a base loaded power plant operating between 75-100% load, and the pressure at the IP-LP is sufficient to support the Hitachi capture system across this load range, the Project team has defined design range for the CO_2 capture plant in the operating range of the 70% to 100%. As a result, the CO_2 capture plant will be designed to meet at least 1,000 metric tons per day of CO_2 production capacity with the power plant operating between 70% and 100% output.

7.3 CO_2 COMPRESSION HEAT INTEGRATION

During the compression of carbon dioxide from near atmospheric conditions to the high pressure requirements for transport, the temperature of CO_2 increases. The reduction of the temperature of CO_2 at the inlet of each compression stage is necessary as this minimizes the work required for compressing the fluid and also does not subject the compressor parts to high temperatures, which would otherwise require higher strength materials. For the base design, circulating water from the cooling tower basin, available at a temperature of 85 ºF, has been used to cool the CO_2 stream at each stage of intercooling. The CO_2 is estimated to exit each compression stage (prior to interstage cooling) at a temperature exceeding 210 ºF. Water entrained in the CO_2 will condense out of the stream during each compression stage, releasing its heat of vaporization. This heat of vaporization will also be removed by the circulating water system.

Normally, the hot circulating water would be returned to the cooling tower for cooling, essentially using the atmosphere as a heat sink and not utilizing the heat recovered from the compressors. One method to recover this waste heat is by sending the circulating water to the water-steam cycle of the power plant for pre-heating of the condensate. By pre-heating the condensate, less steam could be extracted from the steam turbine that serves as the steam source for the feedwater heaters. With less steam extracted, the turbine generator is expected to have increased power output.

Based on the estimated maximum temperature of the circulating water that can be recovered from the compressors, an appropriate location for preheating the condensate is upstream of the lowest-pressure feedwater heater (the one closest to the condenser). The hot water from the compressors would be provided to this new heat exchanger and would then exit and return to the cooling tower for final heat removal. A sketch of this concept is shown in Figure 7-4.

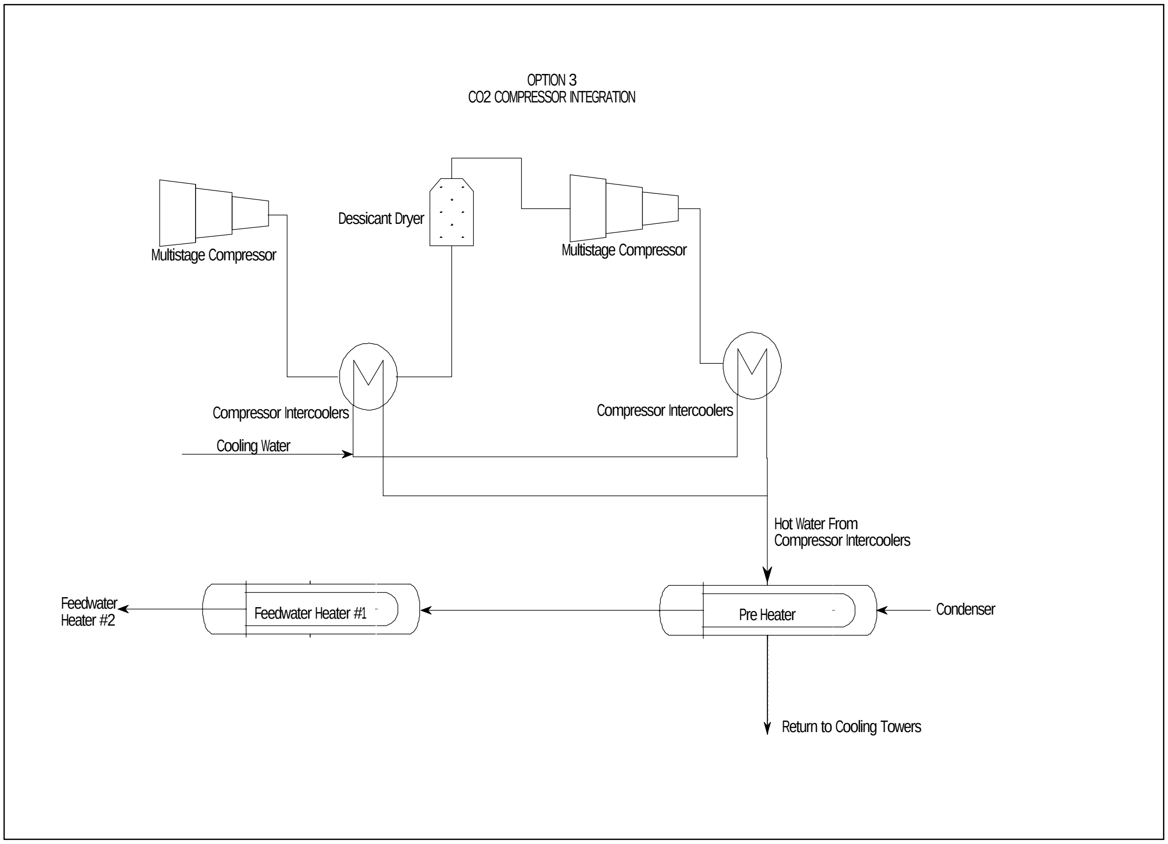


Figure 7-4: CO_2 Compressor Integration Concept

A heat exchanger for the condensate and the hot circulating water would be required. It is assumed that a countercurrent shell and tube heat exchanger will be used for this application.

The condensate/hot circulating water heat exchanger would be located near the condenser. Additional piping would be required to pump the circulating water to the heat exchanger. Circulating water booster pumps would need to be slightly larger to account for the additional total discharge head required to accommodate the pressure drop of the circulating water through the heat exchanger.

In comparison with the performance of the plant with CO_2 capture, but without CO_2 compressor heat recovery, this concept does induce the intended effects of lowering steam extraction from the turbine to the feedwater heaters. Originally, approximately 34,100 lb/hr steam was extracted for condensate heating in feedwater heater #1. Recovering heat from the CO_2 compressor, the required extract is only 23,610 lb/hr of steam, for a reduction by more than 30%. However, the gain in power output at the generator terminals is marginal, only 70 kW for a plant with a gross output of approximately 319,200 kW. This is due to the fact that the reduction in extraction steam flow is only from a very low pressure steam source, which does not contribute significantly to the overall turbine output.

Table 7-1 identifies the key results of the simulation in comparison to the plant without CO_2 waste heat recovery.

Table 7-1: Key Results of Comparison of Plant Configurations

Configuration	Gross Output at Generator Terminals [kW]	Turbine Heat Rate [BTU/kWh]
Plant with CO_2 capture and no CO_2 compressor waste heat recovery	319,107	7,586
Plant with CO_2 capture and CO_2 compressor waste heat recovery	319,177	7,584

Based on the performance realized in the analysis, this concept was not considered further for detailed analysis.

7.4 OPTIONS ANALYSIS

7.4.1 Single-stage Wet FGD to Replace Multi-stage SO_2 Scrubbers

Amine based solvent solutions are known to react readily with acids formed from the SO_2 and SO_3 in the flue gas resulting in the formation of heat stable salts and amine degradation. Heat-stable salts are non-regenerable under solvent regeneration conditions and therefore, remain and accumulate in the absorbent. This accumulation not only causes a reduction in CO_2 absorption capacity, but also causes a significant increase in corrosion of the system components. Generally, the combined SO_2 and SO_3 concentration in the flue gas entering the CO_2 absorber needs to be 10 ppm or less (commonly referred to as “single digit” SO_2 in flue gas) to avoid excessive solvent loss in the CO_2 capturing process.

To reduce SO_x emissions to such low levels, the most common approach, is to install a dry or wet FGD unit (unless one already exists) and a separate polishing scrubber, also called a “prescrubber”, located between the FGD and the CO_2 absorber. Typically the prescrubber is an open or packed bed direct contact spray tower that utilizes a caustic solution to reduce SO_x to single digit concentrations. The prescrubber is often used to reduce the flue gas temperature to the level required for optimal performance of the CO_2 absorber, as well. Where boiler emissions of SO_x are high, a dry FGD followed by a pre-scrubber is a practical approach.

An alternative approach for low SO_x carbon capture applications, which is possible as a result of Hitachi wet FGD technology, is to either install a wet FGD capable of achieving single digit SO_2 emissions or upgrade an existing absorber (by upgrading the FGD internals and/or applying an organic acid to the FGD slurry as a pH buffer) to achieve this performance, thereby eliminating the need for a prescrubber (although a smaller flue gas direct contact cooler is still required). For installations where high concentrations of SO_3 are present in the flue gas, an additional system for removing SO_3 is necessary, since a wet FGD removes only a small percentage of this pollutant. Some methods typically used to capture SO_3 are lime, limestone, or trona injection upstream of the particulate collection device. In addition, Hitachi has developed a Clean Energy Recuperator (CER), designed to recover heat from flue gas while simultaneously removing nearly all SO_3. Used in conjunction with a wet FGD, the CER can reduce FGD make-up water use by about 50%.

Hitachi's open spray tower wet FGD technology, with its computational fluid dynamic-guided design of high spray flux and variable spray density to prevent localized flue gas bypass, is capable of achieving SO_2 concentrations in the single digit ppm range. In fact, seven Hitachi wet FGD units, including two units recently commissioned in the United States, are in commercial operation with SO_2 removal efficiencies well above 99% and FGD outlet SO_2 well below 10 ppm. Five of these units have outlet SO_2 concentrations in the low single digits. These units were designed to achieve ultra-low SO_2, because of stringent emissions regulations at these plant locations, not for carbon capture applications. These single digit FGD units are treating flue gas from fuels with very low to very high sulfur content, including Kawasaki Unit 3 and Unit 4 that are firing high sulfur petroleum coke similar to the fuel to be used for the Wolverine Project.

The single digit wet FGDs are designed with extra spray levels and high liquid-to-gas ratios. Therefore, they have higher capital and operating costs than ordinary FGDs. However, for post-combustion carbon capture systems, a single stage wet FGD may be more advantageous than a combination of a primary FGD and a polishing pre-scrubber, even with the addition of a CER for SO_3 control.

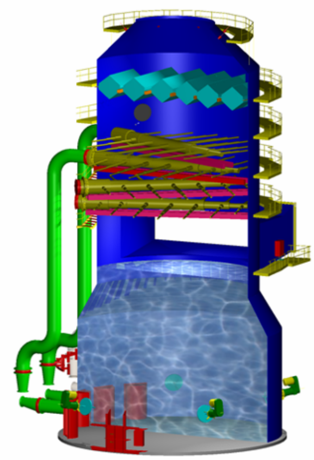


Figure 7-5: Single Digit Wet FGD

The Wolverine power plant will utilize CFB boiler technology for in situ sulfur capture by injection of inexpensive limestone from an adjacent quarry. A dry FGD (spray dryer absorber) using lime as a reagent is proposed to further reduce the SO_2 and SO_3 levels to meet the stack emission limits. A pre-scrubber using caustic soda as a reagent is needed to control SO_2 from the 26 ppm at the FGD outlet to a level of 2 ppm at the inlet of the CO_2 absorber. As an option, a design of a single digit wet FGD and CER has been developed that could replace both the SDA and the pre-scrubber.

In addition to removing nearly all SO_3, installation of the CER would improve the plant heat rate, reduce FGD make-up water requirements, reduce the size and duty of the direct contact flue gas cooler (which could then be incorporated into the bottom section of the absorber tower), and reduce the required capacity of the plant cooling tower.

The proposed single digit wet FGD would consist of a grade-mounted forced oxidation countercurrent open spray tower absorber. The recycled slurry would be sprayed into the absorber through banks of nozzles mounted on 4 levels of internal, single penetration type, spray headers. Highly erosion and corrosion resistant, rubber-lined centrifugal pumps would circulate slurry from the reaction tank to the absorber spray nozzles. Each pump would be connected to a dedicated spray level by a riser pipe.

The nozzles would be designed to provide a high spray flux density to achieve intimate gas to liquid contact for SO_2 removal. Higher spray flux densities would be provided around the perimeter of the vessel to ensure that there is minimal bypass of untreated flue gas along the walls of the absorber. In addition, the absorber would be equipped with annular baffles located at each spray level that minimize any remaining low resistance regions created by coverage gaps along the circumference of the absorber wall, further reducing bypass of untreated flue gas.

The low chloride concentration in the flue gas would result in an equilibrium chloride ion concentration in the absorber of 25,500 ppm. This moderate equilibrium chloride level would permit the absorber to be operated with no blow down, making this a zero waste water discharge system.

Figure 7-6: FGD Nozzles

As a result of the low SO_2 concentration in the incoming flue gas, the FGD would require only very simple reagent feed and slurry dewatering systems. The reagent used in the FGD would be the same limestone used in the CFB boiler, ground to 90% through 325 mesh. The ground reagent would be stored in a silo and fed to the FGD reactor tank through a pneumatic transport and feed system.

Spent reagent slurry from the FGD reactor tank would be extracted and pumped to a dewatering system consisting of two rotary drum vacuum filter trains (one operating and one spare). The gypsum, dewatered to 15% moisture, would be trucked to a landfill.

Wet FGD Design

Dimensions	35 ft diameter x 100 ft tall
Material of Construction	6% molybdenum alloy or lined CS
Number of Spray Levels	4 (3 + 1 spare)
Oxidation" Agitators per reaction tank	3
Oxidation Air Blowers	2 (1 + 1 spare)

Process/Consumption Data

Limestone Consumption:	1,027 lb/hr
Make Up Water Consumption:	263 gal/min Service Water
Gypsum Production (80% Solids Cake):	2,112 lb/hr
Wastewater Production:	None
Power Consumption:	1,300 kW

As noted above, the wet FGD would utilize the same, inexpensive limestone as the CFB boiler (~$15/ton), as opposed to requiring two, additional and more expensive reagents for the dry FGD, pre-scrubber option (~$100/ton for lime for the dry FGD and ~$300-$400/ton for the caustic soda used in the pre-scrubber).

7.4.2 Hitachi Clean Energy Recuperator (CER)

In an amine absorption CO_2 capture system, the flue gas entering the absorber must be cooled in order to increase the efficiency of the exothermic CO_2 absorption reaction, and minimize solvent loss. The optimum operating temperature range for amine based CO_2 capture systems is typically 104 °F to 140 °F (40 °C to 60 °C). Operating in that temperature range has the added benefit of decreased absorber, duct, and flue gas booster fan size resulting from the lower volumetric flow rate.

A CO_2 capture system employs a direct contact flue gas cooler at the inlet to the system to achieve the desired absorber flue gas temperature. The heat captured by the cooler is normally removed by a heat exchanger in the spray water circulation loop and is ultimately discharged as waste heat through a cooling tower. In the case of the Hitachi carbon capture system, the prescrubber is designed to act both as a direct contact flue gas cooler and as a sodium scrubber to reduce SO_2 in the flue gas to an acceptable concentration.

In a boiler system, the air preheater is typically the last means of extracting energy from the combustion flue gas prior to discharge to the stack. The design flue gas exit temperature from the air preheater can range from 250 °F to 350 °F, depending on the acid dew point temperature of the flue gas, which is dependent on the concentration of sulfur trioxide and moisture. If the plant is equipped with a wet flue gas desulfurization system, the flue gas is further cooled to approximately 125 °F in direct contact with the flue gas desulfurization reagent slurry before being treated in the CO_2 capture system.

The heat removed from the flue gas between the air preheater outlet and the CO_2 capture system absorber is generally lost to the atmosphere. However, it is possible to recover some of this energy in the flue gas that would otherwise be lost, and return it to the water/steam cycle by preheating the condensate via the use of a heat exchanger. Hitachi has developed such a heat exchanger, the Clean Energy Recuperator (CER), which was derived from Hitachi's patented high dust Gas-Gas-Heater (GGH) technology, which has been used successfully on five large supercritical coal-fired power plants in Japan.

The CER is a finned tube heat exchanger with the flue gas flowing over the tubes and the cooling medium within them. Located downstream of the air preheater and upstream of dust collecting and SO_2 removal equipment, it cools the flue gas, recovers a large amount of low grade energy and, due to its operation in high ash environment and the deep cooling of flue gas, removes almost all SO_3 in the flue gas. If employed in conjunction with an amine absorption carbon capture system, the CER also reduces the heat load on the direct contact flue gas cooler (and, consequently, the required cooling tower capacity). When used in conjunction with a wet flue gas desulfurization system, the CER reduces the make-up water requirement of the SO_2 absorber by about 50%.

The CER is comprised of a number of modular tube bundles contained within a gas-tight casing, all supported on a steel structure. Soot blowers are furnished to remove ash accumulated on the finned tubes. Figure 7-7 shows a Hitachi CER.

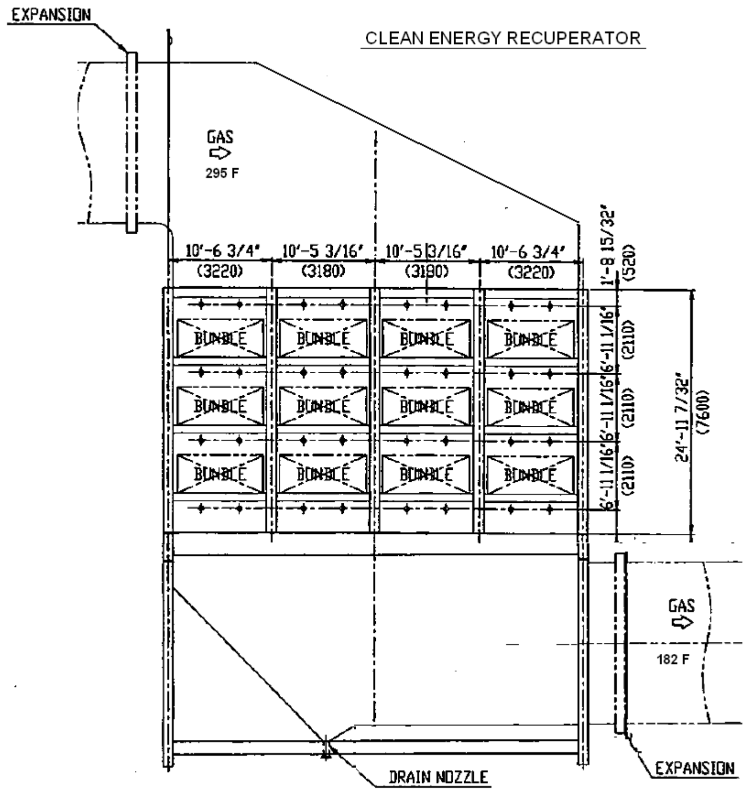


Figure 7-7: Clean Energy Recuperator

An analysis of the integration of the CER into the Wolverine plant was conducted. One consideration was to recover the energy from the flue gas and use it in the CO_2 capture process by either supplying heat to the solvent directly, or by supplying heat to the solvent indirectly through an intermediate fluid (in this case, water). The other consideration was to recover the energy from the flue gas and use it in the water/steam cycle.

7.4.3 Use of Flue Gas Energy in the Solvent

There are only two solvent streams where heat recovered by the CER could be added directly to the carbon capture process - the cold rich solvent feed to the stripper and the hot lean solvent feed to the reboiler. In the proposed process, heat is recovered from the hot lean solvent returning to the absorber from the stripper as it is cooled by the cold rich solvent from the absorber. The amount of heat recovered is already the maximum amount of heat that the cold rich solvent can absorb without causing excessive degassing of the solvent, therefore, the CER heat cannot be added to this process steam.

Adding heat to the hot lean solvent feeding the reboiler is possible at the Wolverine plant, since the design temperature of the flue gas leaving the CFB air preheater (295 °F) is high enough to heat the lean solvent to the required operating temperature of the stripper, if it were to be circulated through the CER. However, there is a large mismatch in the required duty of the reboiler (152.5 million Btu/hr) and the available heat in the flue gas (73.1 million Btu/hr), meaning that a reboiler and all it's appurtenant equipment and systems would still be required to make up the remaining heat input. In addition, the hot lean solvent is only available at a higher temperature than the available feedwater (the alternative flue gas cooling medium), even if cooler, semi-lean solvent is extracted from higher in the stripper tower, resulting in less heat extracted from the flue gas and a higher flue gas outlet temperature from the CER.

7.4.4 Use of Flue Gas Energy in the Steam Cycle

Analysis of all cases for the Wolverine Project shows that the more practical solution, in this case, would be to recover the energy from the flue gas with the CER and add it to the steam cycle by heating the condensate. To have the greatest impact on cycle efficiency, the heat should be added to the cycle at as high a temperature as practical, taking into account the impact of the approach temperature to the size and cost of the CER. Using the design heat cycle, the optimal solution would be to replace the number two low pressure feedwater (condensate) heater with the CER. In the cycle without a CER, at 100% load, the condensate is heated in feedwater heaters #1 and #2 by extraction steam from the LP turbine to 191 °F. If heater #2 is removed and the condensate is routed from heater #1 outlet to the CER, the condensate temperature at the outlet of the CER is raised from 191 °F to 208 °F and the LP extraction steam flow for heater #2 is eliminated. The higher condensate temperature out of the CER also results in a reduction in the required duty of low pressure feedwater heater #3 and, therefore, the LP extraction steam flow to heater #3 is reduced.

The steam cycle diagrams shown in Figures 7-8 and 7-9 present detailed configurations of the Wolverine power plant integrated with CCS, and with and without CER.

The overall impact of incorporating a CER to the steam cycle is an increase in unit power output of approximately 3 MW, and a reduction of unit net heat rate of approximately 70 Btu/kWh at 100% load. The thermodynamic impact of CER is sizable. However, CER would decrease the flue gas temperature to a value below the polishing scrubber inlet temperature requirement. For that reason it was decided not to implement this feature on this project. In the future, this concept may be implemented in arrangements which include wet FGD.

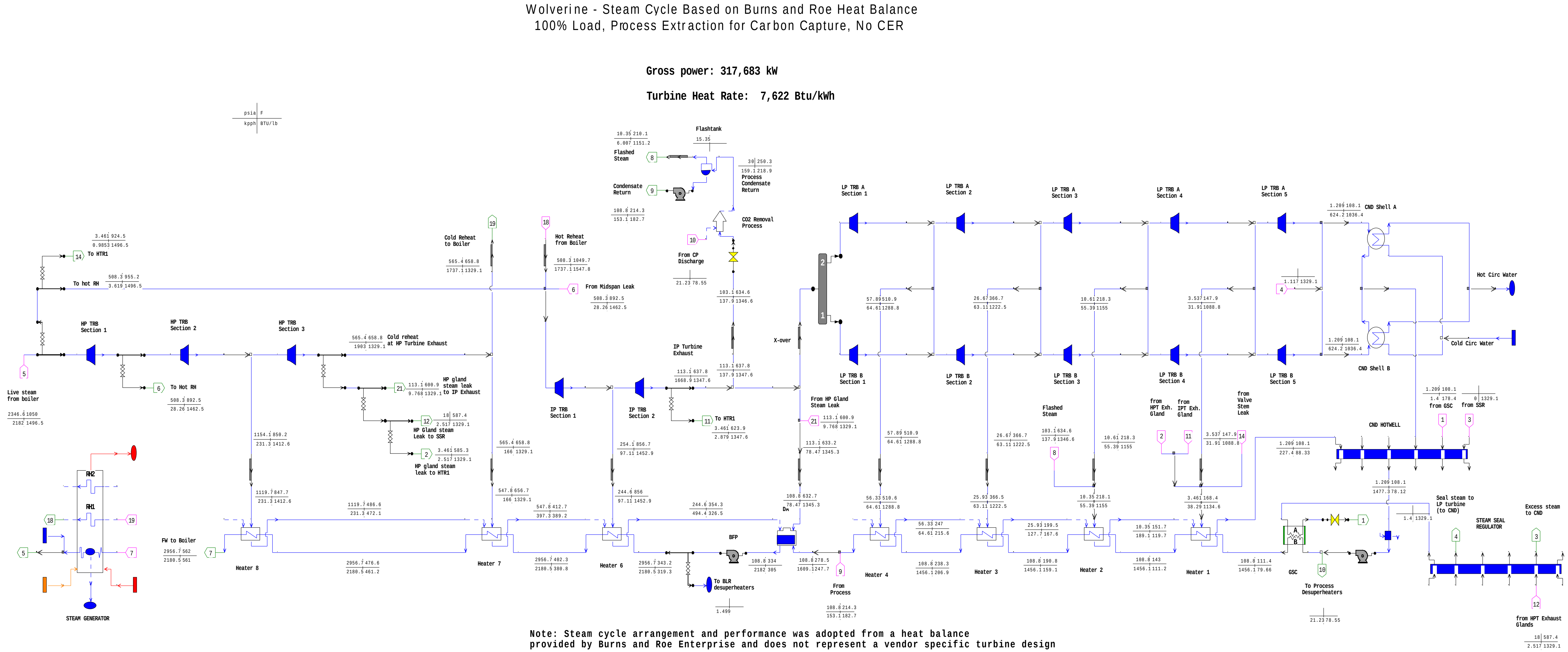
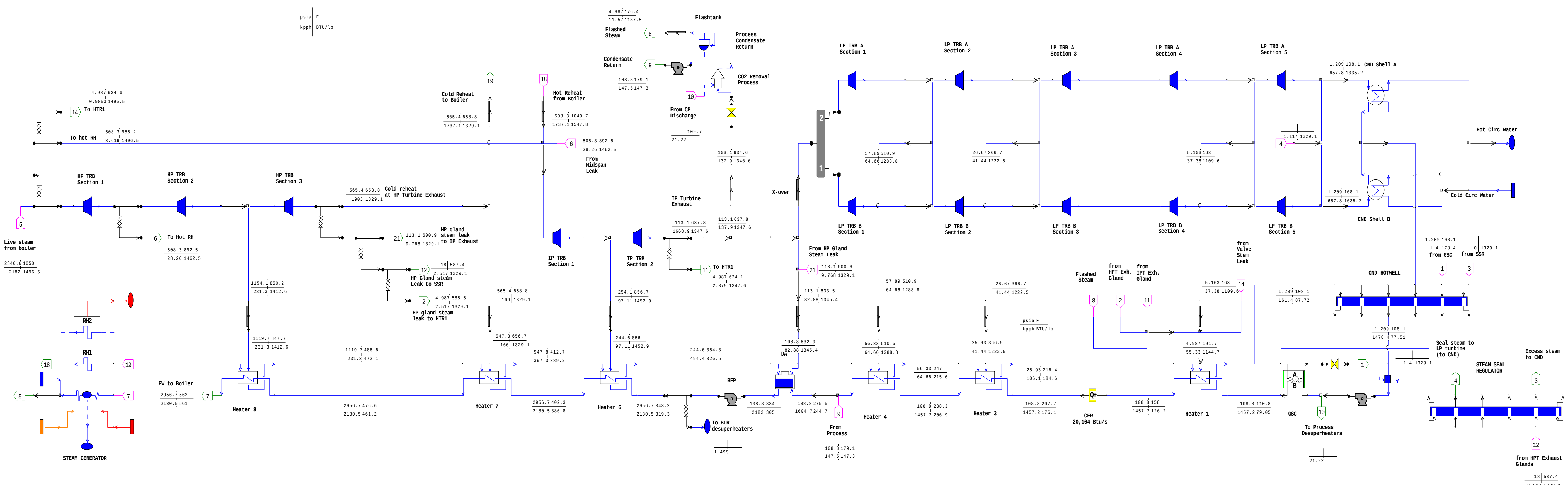


Figure 7-8: Wolverine Steam Cycle Based on Base Case BREI Heat Balance - 100 % Load, Process Extraction for Carbon Capture, No CER

Wolverine - Steam Cycle Based on Burns and Roe Heat Balance
100% Load, Process Extraction for Carbon Capture, CER with Heat Exchange to Condensate

Gross power: 320,479 kW

Turbine Heat Rate: 7,555 Btu/kWh



Note: Steam cycle arrangement and performance was adopted from a heat balance provided by Burns and Roe Enterprise and does not represent a vendor specific turbine design

Figure 7-9: Wolverine Steam Cycle Based on Hitachi Heat Balance - 100 % Load, Process Extraction for Carbon Capture, CER with Heat Exchanger to Condensate

8 CO_2 DEHYDRATION AND COMPRESSION

8.1 CO_2 DEHYDRATION

The gas that is provided from the CO_2 Capture process is saturated with water vapor. CO_2 is an acid gas and will react with water to form carbonic acid. Carbonic acid corrosion is a considerable challenge for facilities that process CO_2. Carbonic acid corrosion of carbon steels has been recognized for years as a major source of damage in oilfield equipment and gas pipelines, and is commonly referred to as “sweet gas” corrosion. In wet CO_2 applications, the use of stainless steel is required. Because long lengths of stainless steel pipelines could be considerably expensive, CO_2 from amine capture processes must be dehydrated to remove moisture. Several dehydration processes are available and their performance depends on the parameters of the raw gas and the requirements of the product gas.

Three major options were under consideration for the Wolverine CCS project, namely:

§ Direct Cooling
§ Molecular Sieve or Solid Desiccant Adsorption
§ Triethylene Glycol Absorption

8.1.1 Direct Cooling

The saturated vapor content of CO_2 gas decreases as the pressure increases or as the temperature decreases. Hot gases saturated with water may be partially dehydrated by direct cooling. CO_2 compressors normally employ an intercooler stage where cooling will remove water from the gas in knockout drums. The cooling process must reduce the temperature to the lowest value that the gas will possibly encounter at any pressure at any point along the pipeline route to prevent further condensation of water within the pipeline. The concept was evaluated for the Project and the direct cooling approach was not suitable to reduce the gas to below the pipeline specification limits.

8.1.2 Molecular Sieve or Solid Desiccant Adsorption

An adsorption dehydration plant consists of adsorption towers filled with solid desiccant. Each dryer train typically consists of two adsorption towers. One of the adsorption towers is used for the dehydration of wet inlet gas while the parallel installed tower aims to regenerate loaded (water saturated) desiccant. All liquid and solid impurities are removed from the feed stream of a molecular sieve plant by an inlet separator or scrubber (upstream). As wet gas contacts the solid desiccant bed, water vapor is adsorbed until equilibrium is established between the water content in the gas stream and on the solid desiccant particles. Dried gas leaves the bed, flows through the exit switching valve, and finally leaves the dehydration unit via the dry gas outlet header.

While one bed is on “drying”, the other bed has to be regenerated. Regeneration can be carried out using dry product gas or wet inlet gas. Regenerator gas has to be heated upstream the regeneration tower to raise the gases saturation point. Hot regeneration gas heats up the bed, drives the water off the desiccant particles, and carries the resulting water vapor out of the bed. The regeneration stream is cooled down and the water content is separated in the regeneration separator where the water is condensed from the gas. “Heatless” regeneration cycles are also possible. However, these regeneration concepts require taking a stream of dry CO_2 to dry the desiccant bed. The wet CO_2 is then purged to the atmosphere which wastes a small portion of the product gas.

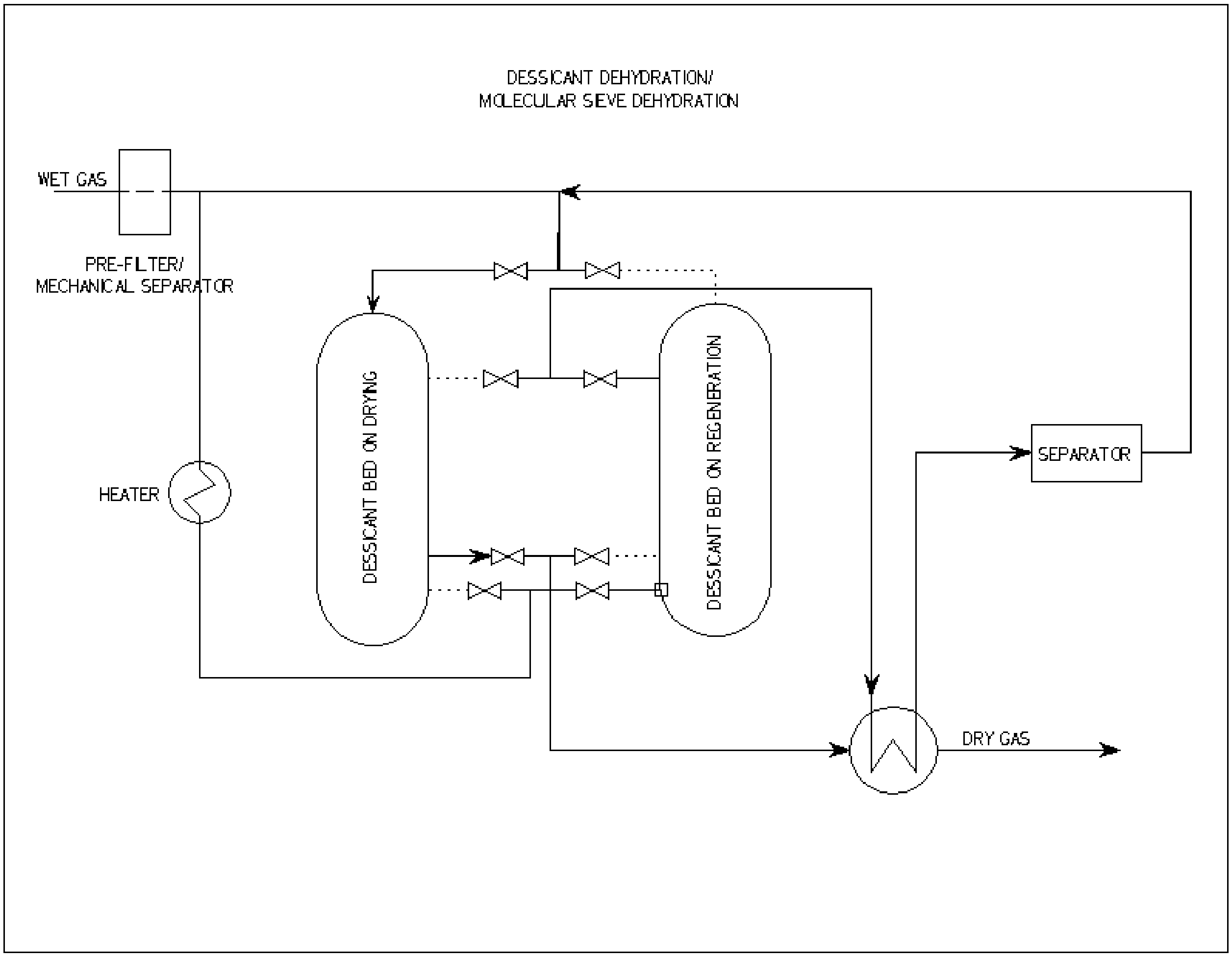


Figure 8-1: Molecular Sieve/Desiccant Dehydration

8.1.3 <u>Tri-ethylene Glycol (TEG) Dehydration</u>

Scrubbing of wet gas with glycol (in most cases TEG – tri-ethylene glycol) is one of the most applied dehydration technologies for natural gas pipelines and is commonly applied in dehydration of CO_2. The wet gas flows through an absorber column where glycol flows in counter-flow to the gas. The glycol absorbs the moisture and the loaded glycol is regenerated in a distillation column (still) which is heated by a reboiler. The heat that is provided to the reboilers releases the moisture from the glycol. The regenerated glycol flows in a closed circuit back to the glycol column. The gas that is released from the still, which is composed primarily of moisture, is released to the atmosphere. Because of the additional emission point associated with the TEG process, the project team decided to eliminate this option and proceed with the dessicant dehydration concept discussed in Section 8.1.2.

8.2 CO_2 COMPRESSION SYSTEM

The Carbon Dioxide product from the capture process is compressed in the Product CO_2 Compressor. The compressor consists of a multiple stage compression with intercooling provided. Each stage of compression is followed by intercooler heat exchangers where the carbon dioxide product is cooled against cooling water. After each stage of cooling, moisture is condensed from the CO_2 stream. At an interstage pressure of approximately 475 psig, the compressed carbon dioxide is sent to a Dehydration Package, which reduces the moisture level to 15 lb/MMSCF through the use of a desiccant dryer package. The CO_2 is then routed back to the remaining stages of compression where the CO_2 is finally compressed to 2,000 psig. The following Process and Instrumentation Diagram depicts the CO_2 compression and dehydration concept.

9 BALANCE OF PLANT SERVICES AND UTILITIES

9.1 WATER

9.1.1 Cooling Water

Cooling Water will be supplied to the CO_2 Capture Facility heat exchangers including the heat exchanger for the CO_2 gas compressor. One (1) additional cooling tower cell will be provided for the Wolverine Unit #1 Cooling Tower to account for additional cooling water requirements associated with the WCCS facility equipment.

A circulating water booster pump is required to compensate for additional head requirements for WCCS equipment.

The circulating water booster pump will be located in a pre-fabricating insulated building which shall be heated to maintain a minimum indoor temperature of 50 °F.

9.1.2 Potable and Service Water

The WCCS Project will require various quality water streams to satisfy process and/or building needs. The water streams given in Table 9-1 shall be delivered to the WCCS Plant:

Table 9-1 Water Services for the WCCS Plant

Service water	Required for the CO_2 Capture System pre-scrubber and for area washdown stations.
Potable Water	Required for caustic and chemical handling areas in the CO_2 Capture Process Building.

9.1.3 Process Water Supply

Because the CO_2 capture and compression system requires cooling water, process water and discharges process wastewater, water balances were completed to design and account for the changes in the process water supply and the process waste water from the CO_2 capture system. Water balances were completed to establish the change in capacities of various water pre-treatment, demineralized water systems, and wastewater systems. Figure 9-1 shows the CO_2 Capture Facility incorporated into the WCEV facility water balance.

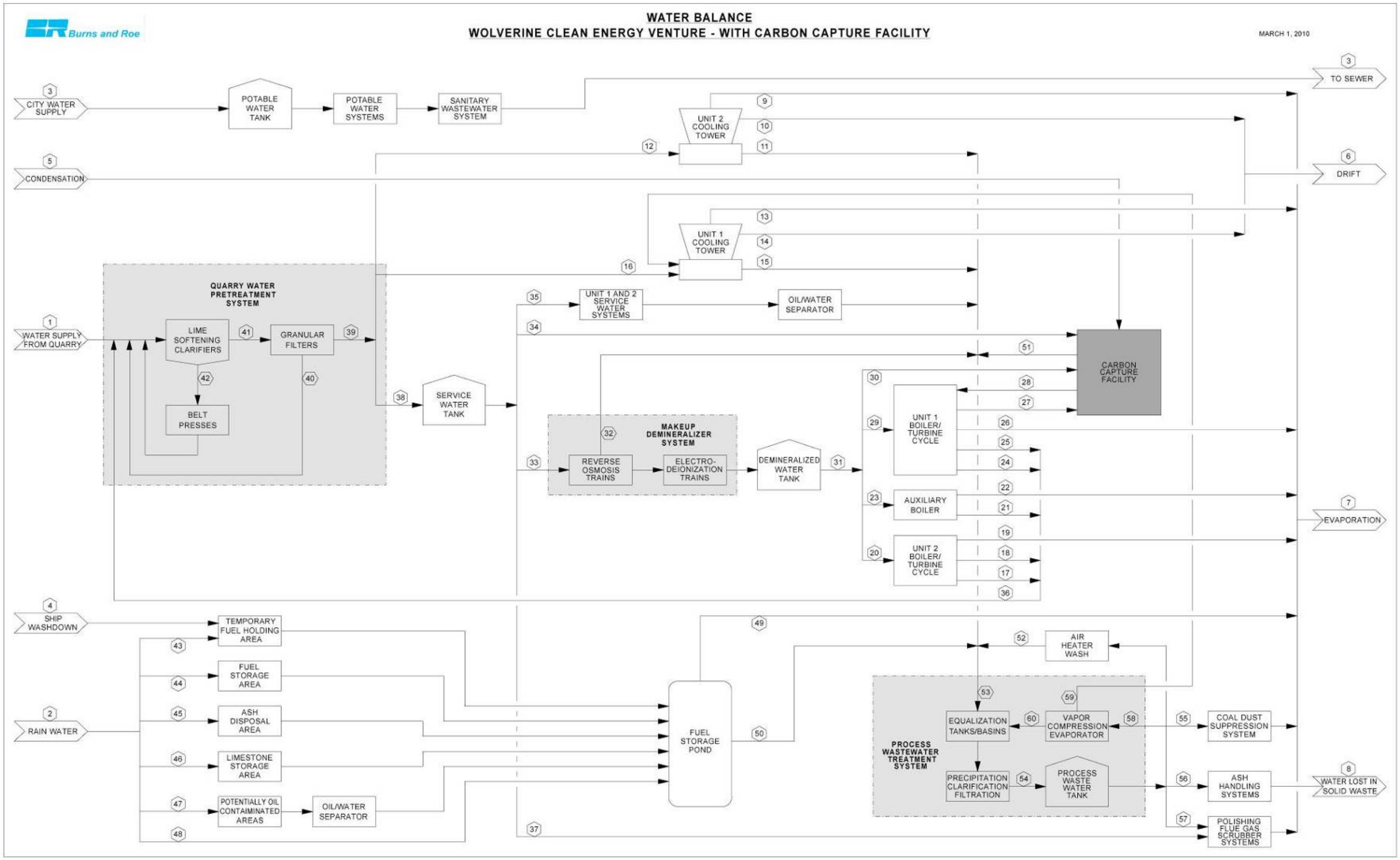


Figure 9-1: WCEV Water Balance with Wolverine CCS Project

9.1.4 Process Water Needs

In addition to the needs for the WCEV Project, process water needs for the CO_2 Capture Concept include:

- Demineralized Water
- Makeup to Cooling Towers
- Service water
- Potable water

9.1.5 Process Wastewater

In addition to the needs for the WCEV project, process wastewater needs for the Wolverine CCS Project Concept includes:

- Changes in Cooling Tower Blowdown
- Pre-scrubber Blowdown from CO_2 Capture Process Island
- Condensate from CO_2 Compressor

Water balances were developed for various operational scenarios and seasonal rainfall periods for the base WCEV concept and the concept with CO_2 capture. These water balances were analyzed to establish the affected water system design capacities. The design system capacities for the base WCEV concept and the concept with the WCCS Project implemented are presented in Table 8-2.

Table 9-2: Design System Capacities

SYSTEM	WCEV Plant Capacity	WCEV + WCCS Project Capacity
Quarry Water Pretreatment System	5,500 GPM	NO CHANGE
WCEV Demineralized Water System	400 GPM (2x50%)	450 GPM (2x50%)
WCEV Process Wastewater Treatment System		
- Precipitation, Clarification, And Filtration	800 GPM (2x50%)	875 GPM (2x50%)
- Vapor Compression Evaporator System	360 GPM (2x50%)	460 GPM (2x50%)

9.1.6 WCEV Quarry Pretreatment System

The maximum amount of water that is required for the WCEV plant is 5,500 gallons per minute. Operation of the WCEV plant coinciding with the WCCS Project does not result in an increase in water required from the quarry groundwater and there is not additional water required for the facility.

9.1.7 Demineralized Water System

Based on flow rates determined from the water balances, it is necessary to increase the size of the makeup demineralizer system to include two (2) 50% trains designed for a total flow of 450 gallons per minute (an increase of 50 GPM from the WCEV base plant design).

9.1.8 Process Wastewater Treatment System

Based on flow rates determined from the water balances, it is necessary to increase the size of the precipitation, clarification, and filtration portion of the process wastewater treatment system to include two (2) 50% trains designed for a total flow of 875 gallons per minute (an increase of 75 GPM from the WCEV base plant design). Also, it is necessary to increase the size of the vapor compression portion of the process wastewater treatment system to include two (2) 50% trains designed for a total flow of 460 gallons per minute (an increase from the base plant design of 360 gallons per minute).

9.2 COMPRESSED AIR

The CO_2 Capture Plant will require instrument air for control valves and service air for pneumatic tool usage. Supply lines will run on the pipe rack to supply air to the following buildings:

§ CO_2 Capture Plant Process Building
§ Circulating Water Booster Pump House
§ CO_2 Gas Compressor/Dryer Building

An instrument air receiver and service air receiver will be provided to permit a reserve volume of air due to the distance of the CO_2 capture plant from the Turbine Building.

9.3 HEATING, VENTILATION AND AIR CONDITIONING

The HVAC systems will provide an environment within the buildings suitable for personnel and/or equipment operations, by maintaining acceptable conditions of temperature, humidity, filtration, fresh air supply, air movement, and exhaust removal of vitiated or contaminated air. Heating, ventilating, and air conditioning systems will be capable of maintaining the required conditioned space temperatures under all plant operating or non-operating conditions.

9.4 FIRE PROTECTION SYSTEM

The 12” yard main for the Wolverine Fire Protection System will be extended to provide a minimum of two (2) fire hydrant stations for exterior protection of the WCCS facility buildings.

9.5 POWER DISTRIBUTION CENTER AND CONTROL ROOM

The 4.16 kV switchgear, 480 V switchgear, 480 V motor control centers, DC system, UPS, DCS and control room equipment shall be located inside the Power Distribution Center (PDC). Areas allocated for switchgear and the motor control centers shall be sized in excess of the initial installation requirements. Sufficient space shall be provided for future expansion and maintenance work, including the removal and transportation of circuit breakers. The Distributed Control System (DCS) cabinet will be located in the Power Distribution Center.

10 CO_2 TRANSPORTATION AND STORAGE

10.1 CO_2 PIPELINE SITING

The Project team has identified a preferred 54 (+/-) mile pipeline route that mostly follows an existing pipeline corridor, which greatly improves the probability for obtaining the rights of way required for line construction. As a back-up, the Project team has also identified an alternative route that runs primarily along an above ground electrical transmission line corridor. This route is much longer at 66 (+/-) miles and is not as centrally located to the EOR targets as the preferred route being proposed.

Figure 10-1 depicts the proposed (purple) and alternate (green) pipeline routes as currently sited. Modeling, planning and estimating has focused on the preferred route.

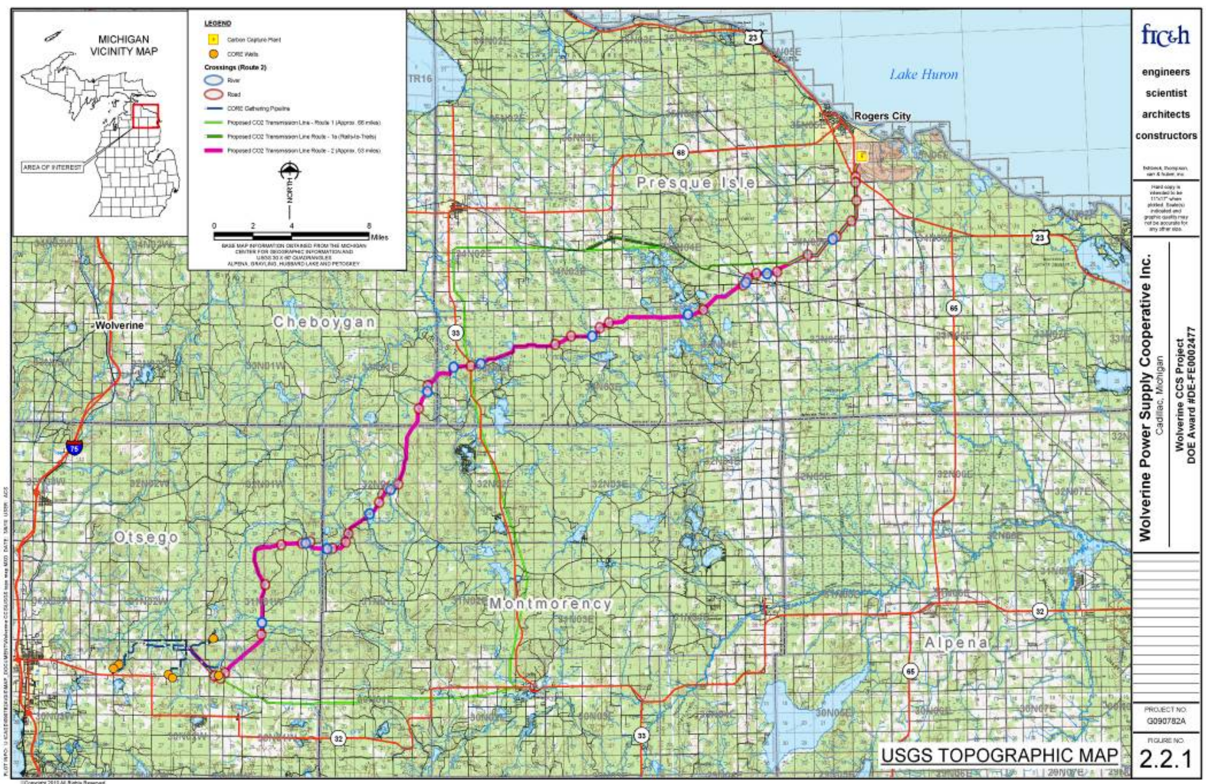


Figure 10-1: CO_2 Pipeline (Proposed and Alternative Route)

10.2 CO_2 STORAGE SITING

The Participant has a unique and very beneficial position for this demonstration due to the significant CO_2 EOR infrastructure that is currently owned and being operated by a member of the Team, Core Energy, LLC. As a result, the project approach is to sequester CO_2 primarily for the purposes of Enhanced Oil Recovery. Core Energy has supplemented these proposed Enhanced Oil Recovery targets with a contingency plan. If, due to project timing, additional injection volume is needed to demonstrate the 1,000 MTD rate, Core Energy proposes to use existing wells completed in the Bois Blanc Formation to demonstrate deep saline geologic Storage. In addition, since the Wolverine Clean Energy Venture Power Plant over the long term, will produce larger volumes of CO_2, than will be demonstrated during the one year DOE demonstration, the project team has defined longer term saline aquifer geologic Storage targets.

Calculation of potential geologic storage capacity for the project area that was estimated by WMU targets two primary formations; the Bois Blanc Formation and the St. Peter Sandstone. The St. Peter Sandstone demonstrates that there is ample storage capacity to handle the generated CO_2 volumes. Injection into the St. Peter Sandstone is not planned to be a part of the initial Wolverine Carbon Capture and Storage Project. The Core Energy Infrastructure provides a great deal of flexibility as to where the CO_2 can be delivered; primarily for EOR, and with the secondary purpose of deep saline aquifer storage.

The map in Figure 10-2 depicts the current infrastructure and two proposed deep saline storage sites that target the Bois Blanc Formation, a formation that recently demonstrated a capability of sequestering at least 1,000 metric tons per day, as a part of Midwest Regional Carbon storage Partnership (MRCSP) Phase II Demonstration.

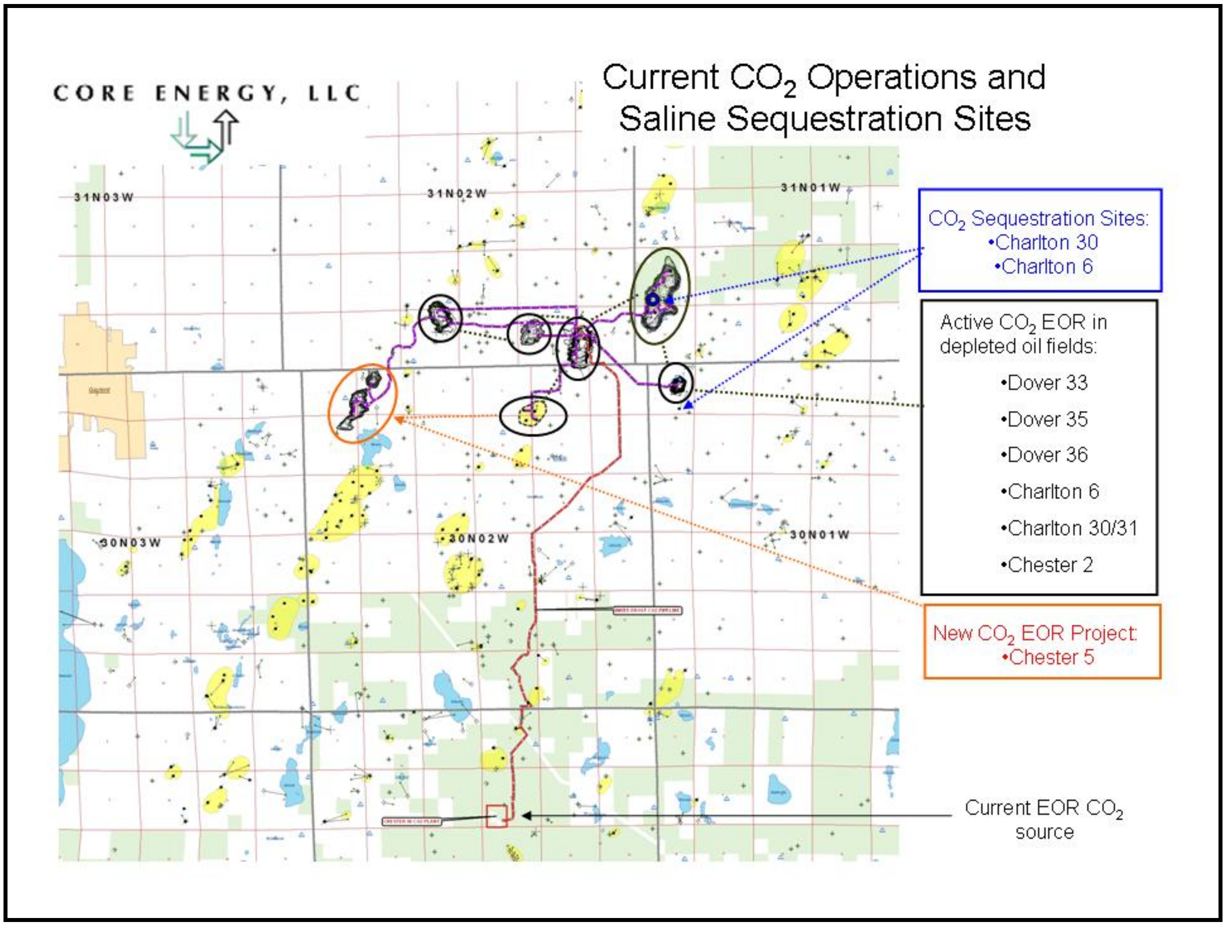


Figure 10-2: Current Infrastructure and Proposed Saline Storage Sites

In addition to being in close proximity to the extensive existing CO_2 EOR infrastructure, the site was chosen due to the volume of the EOR potential and geological storage capacity as determined by team members Core Energy and Western Michigan University, respectively. These strategic parameters (i.e. EOR potential and saline aquifer storage capacity) are depicted in Figure 10-3. The EOR potential and saline aquifer potential is shown in rings that are centered from the WCEV plant in sectors along the pipeline route.

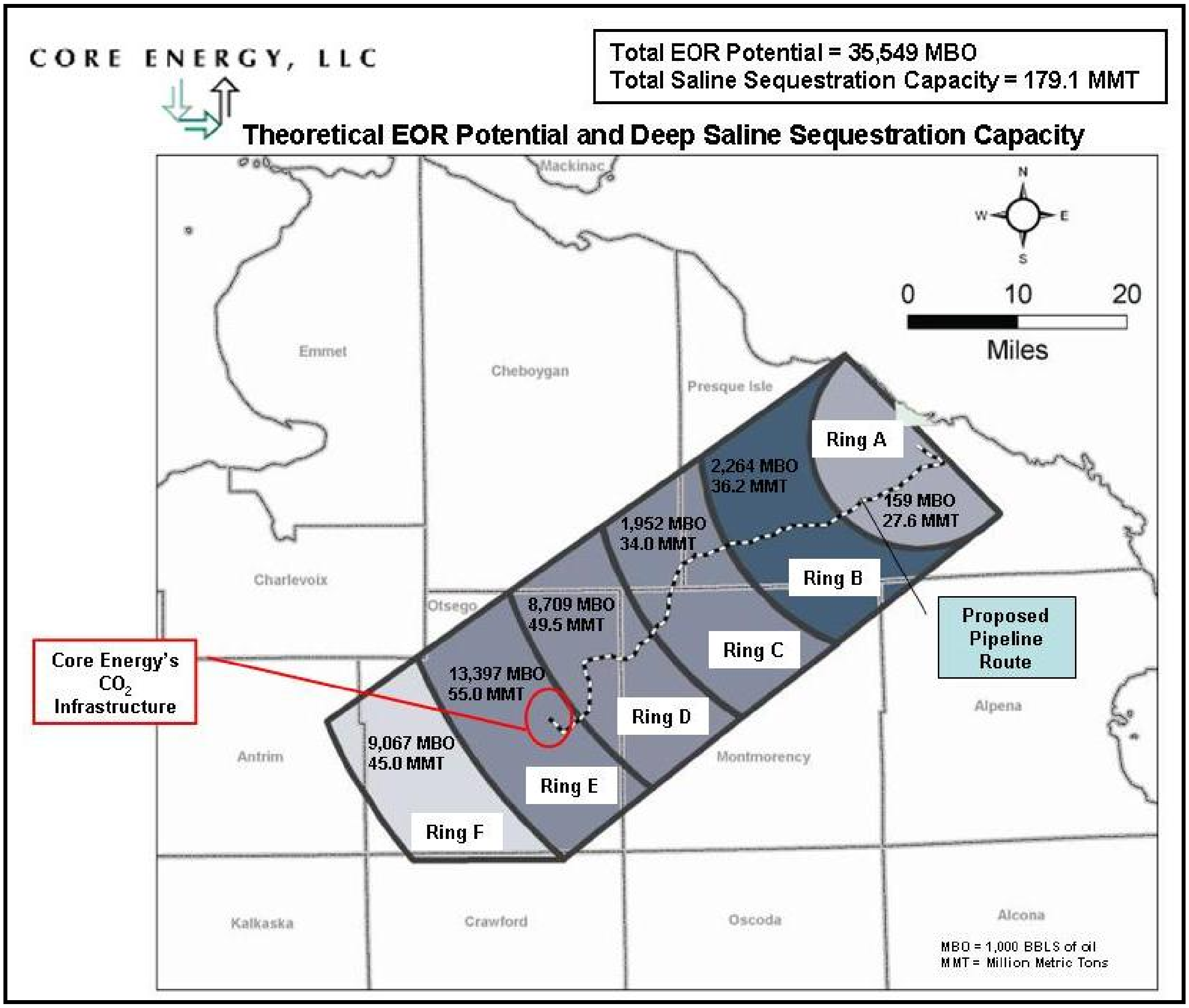


Figure 10-3: EOR Potential and Deep Saline Storage Capacity

The compressed and dried CO_2 coming off the capture technology at the plant will be transported via an approximate 54 (+/-) carbon steel 10 inch diameter pipeline to Section 36 of Dover Township in Otsego County (reference Section on CO_2 Pipeline Siting).

The construction of the proposed pipeline is depicted below on a one-line diagram, which shows the main components of the pipeline system.

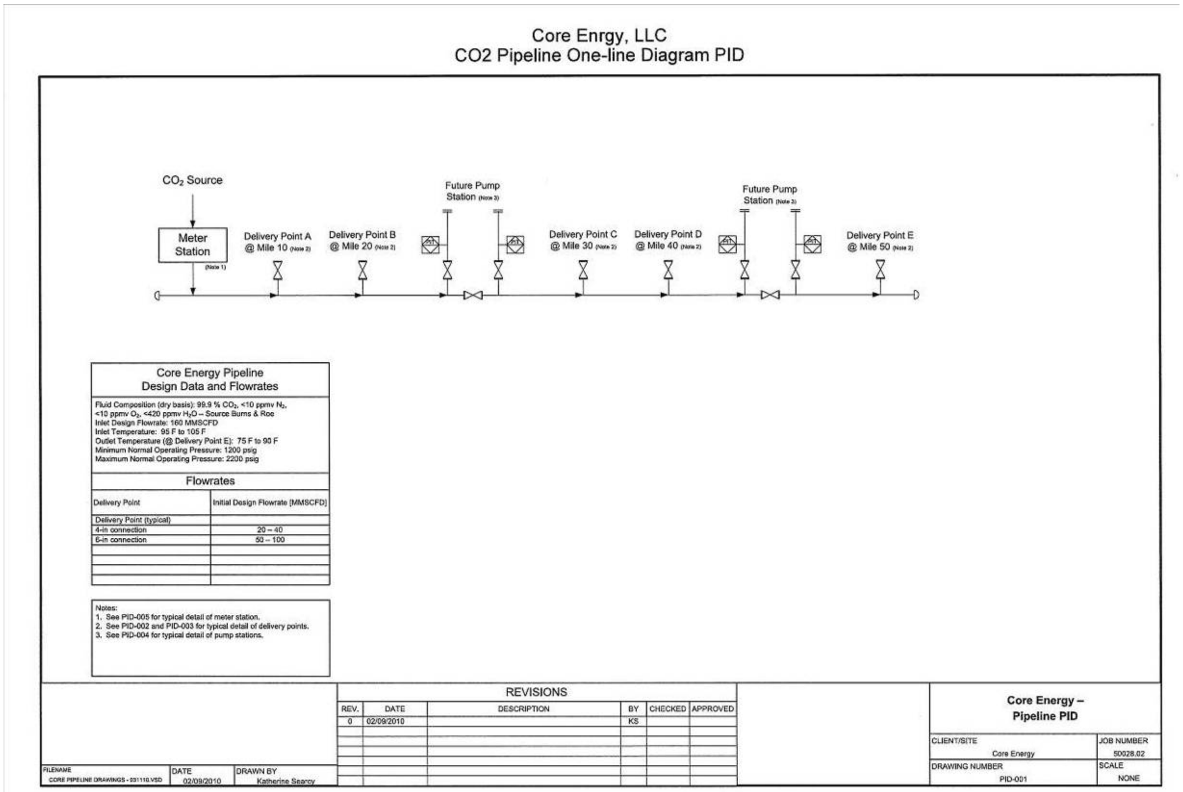


Figure 10-4: CO_2 Pipeline Process and Instrumentation Diagram

From the 54 (+/-) mile main pipeline, the CO_2 will then be transported via smaller diameter lines (e.g. 3", 4") to various sites for use in EOR operations, targeting Niagaran Pinnacle Reefs and/or deep saline aquifer storage, targeting the Bois Blanc Formation (i.e. same interval that successfully demonstrated commercial storage capacity by the MRCSP during a Phase II Demonstration in July 2009). At each of the sites where CO_2 will be utilized in the demonstration, the CO_2 will be metered and scrutinized as stipulated in the MVA Plan.

The block diagram below is a good depiction of the subsurface geology in the Project area and illustrates how CO_2 can be successfully utilized for both EOR operations in the Niagaran Pinnacle Reefs (geologically deeper in the section) and storage in the shallower Bois Blanc Formation, a formation demonstrated to be suitable for deep saline aquifer storage.

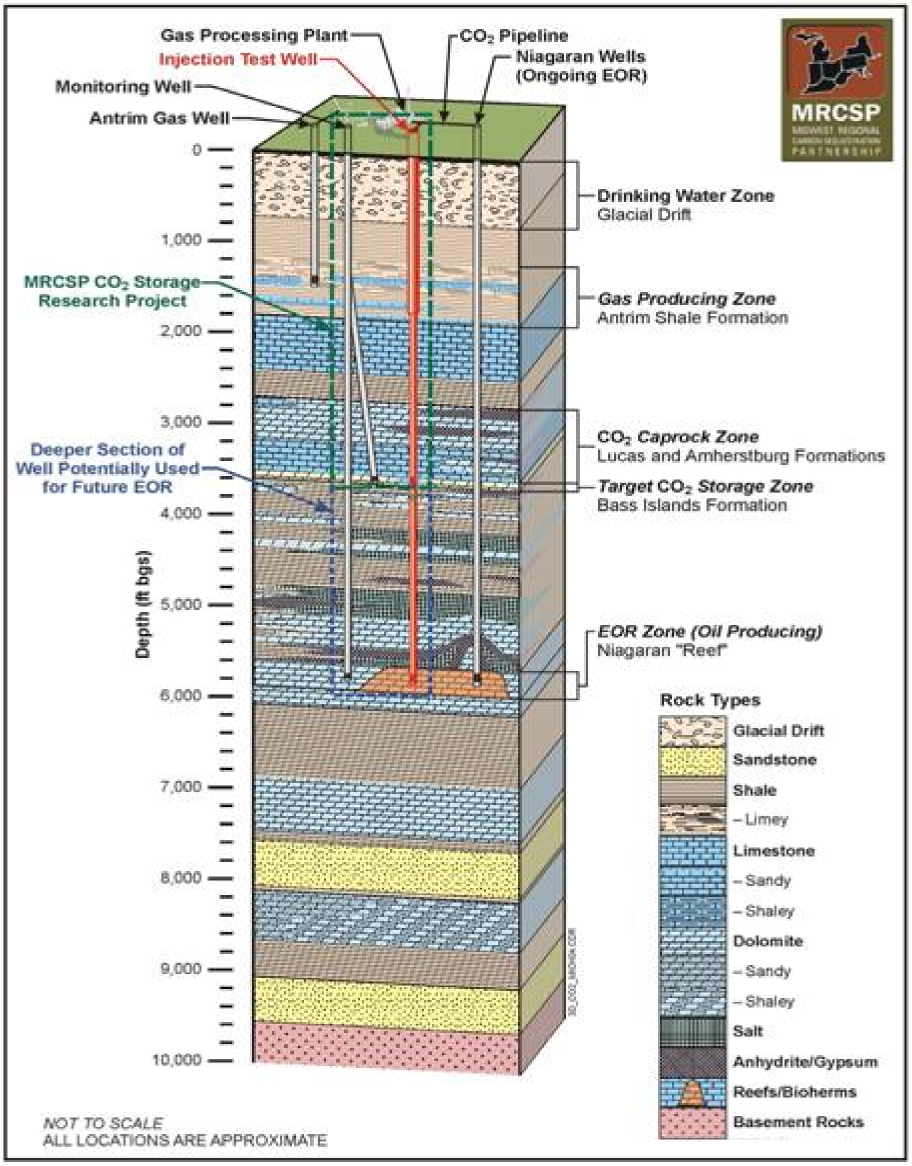


Figure 10-5: Subsurface Geology in the Project Area

10.3 CO_2 TRANSPORT AND LEAK MONITORING SCHEME

The leak monitoring scheme for the pipeline will be a coordinated effort of continuous automated tracking of pipeline process variables and periodic visual inspection of the pipeline and associated facilities. In its simplest form, the pipeline can consist of two meter stations – one at the beginning of the pipeline that measures the temperature, pressure, and flow of CO_2 going into the pipeline and another at the delivery point that measures temperature, pressure and flow where CO_2 exits the pipeline. It is expected that the pipeline will have multiple delivery points as it develops, and the future capacity of the pipeline may require one or two pump stations to maintain pressure in the pipeline at higher flows. In theory, a mass balance can be done on what goes into the pipeline and what goes out to determine if there are any major integrity or leak concerns on the pipeline. However, supercritical CO_2 is compressible at some process conditions, and changes in the density will occur due to changes in temperature and pressure in the pipeline. This fluctuation in density introduces variability into the system and makes the process of leak monitoring more difficult for small volumes.

10.3.1 Measurement of Process Variables

The primary pipeline parameters that will be monitored are flow, temperature, pressure, valve position, and equipment status. Each of these topics is discussed in greater detail below.

10.3.2 Flow Measurement:

The flow of CO_2 into the pipeline at the source, end and at each delivery point will be continuously measured so an ongoing mass balance can be done on the pipeline system. Also, with any pump station installation, CO_2 that moves through the pump station will be measured. Even though no CO_2 may be removed from the system at the pump station, measurement of the station flow serves as an additional check on line integrity.

Based on the inlet and transport conditions of the CO_2, a senior Daniels type orifice meter should yield very accurate and reliable data. During the Phase II detailed design, Coriolis mass flow type meters will also be evaluated and considered. The specific design and size of the meter tube will depend on flow conditioning devices and the flow capacity at each location. Each measurement tube will be equipped with pressure and temperature instrumentation to determine the density of the CO_2 at the measurement location and the differential pressure across the orifice plate. A flow computer associated with the meter tube uses the differential pressure across the plate and the density of the fluid to calculate the flow of CO_2 through the meter, which is typically reported in MMSCFD. The flow computer will be able to record data locally and also connect to a PLC module so data can be transmitted to a control center. It is important for the flow computer to have good thermodynamic and materials property set information and/or good built-in density correlations for the pressure/temperature range of the CO_2 stream.

10.3.3 Pressure Measurement:

The pressure of the fluid in the pipeline will be measured at each meter station and pump station location. Pressure will be measured with an indicating transmitter that will display the value locally and also transmit the value to a PLC control module at the station. This information will be communicated continuously to the main control center. Rosemount and Siemens offer transmitters that are standard in the industry, but other equivalent suppliers are also available.

10.3.4 Valve Position:

The location and placement of automated valves will depend on final pipeline design. Typical automated valve locations are at entry and delivery points on the pipeline. Operation of these valves might occur if the CO_2 product entering the pipeline was out of specification, due to high or low pressure conditions, or if there was a leak at a delivery point. Operation of these valves is rare, but it is important to transmit the position of these valves to a central control location.

10.3.5 Equipment Status:

The equipment and instrumentation at a pump station will be monitored and operated by a PLC based control system. A graphic interface with the control system will provide the station operators with a visual depiction of the operation, current status, and provide alarms for any process upsets. The status of key equipment and process variables would be part of the data communicated to the control center as part of the monitoring scheme.

10.3.6 SCADA System

Data will be measured, recorded, and transmitted from local station sites to a central control center most likely via cellular or satellite technology. During the Phase II detailed design and based on the realities of the final route and services available in the area; other technologies (e.g. modem phone line, DSL, T1, tower communication) will be explored and considered. It is expected that there will be one control center for the pipeline, but a mirror image of the data may be available at multiple sites. The data collected will be managed with a supervisory control and data acquisition (SCADA) system. The SCADA system will be configured to process the data in real time and continually compare the pipeline operation to expected values in order to identify a potential leak or line integrity issue. The relationship between local station sites and a central control center is shown graphically in Drawing PID-006 (Figure 10-6).

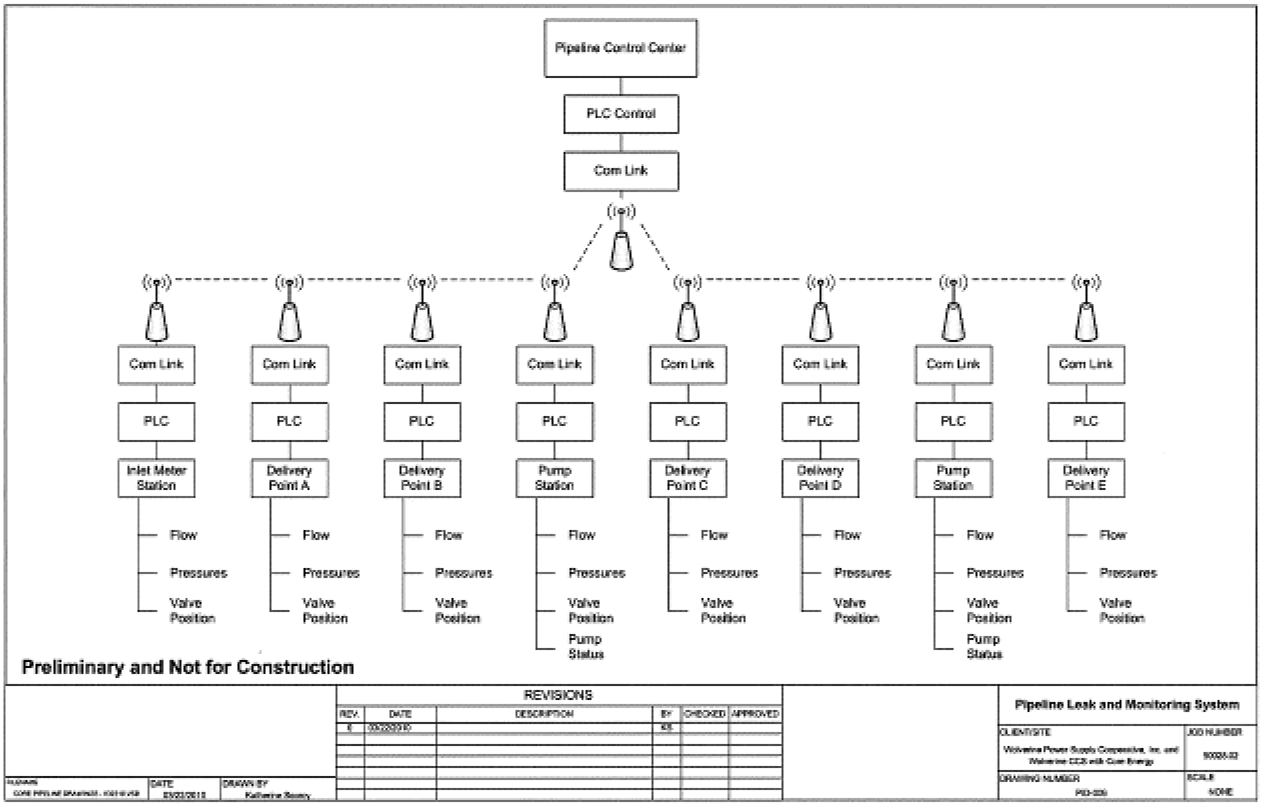


Figure 10-6: Pipeline Leak and Monitoring System

Pressure and CO_2 flow will be the primary variables that are monitored within the SCADA system. As mentioned previously, the supercritical state of CO_2 will cause some variation in density. Also, there is a transient effect of the CO_2 as it moves down the pipeline, and some packing effect can occur during normal operation. As such, when a material balance of the pipeline system is done (input – output), there will be a difference that is within an acceptable range based on normal operational experience of the pipeline. The SCADA system will be designed to identify when the system operation falls outside of the normal parameters and will alert control room operations personnel.

Monitoring of pressure drop will also be done with the SCADA system. Because the pressure measured down the pipeline will vary based on flow rate and other conditions, there will be a correlation of expected pressure drop based on CO_2 flow. If the pressure measurement would fall outside of normal parameters, the SCADA system would alert control room operations personnel and further investigation would be required.

The SCADA system will also manage and monitor the actuation of shut down valves on the pipeline and the operation of pump stations. Certain events or pressure / flow conditions would cause a valve to shut and isolate a segment or area of the pipeline. The SCADA system can also be used to operate a pump station remotely. The specifics of how the SCADA system operates equipment will be determined in the detailed engineering phase of project.

10.3.7 Visual Inspection

Field inspection of pipeline operations will be done on a periodic basis. A visual inspection is often the best method to identify a small leak on a pipeline system or to identify unauthorized activities taking place that could damage or otherwise encroach on the pipeline's use or access. Visual inspection may include periodic walking, riding, and/or flying the right of way and daily inspection of meter stations and/or pump stations.

10.4 DISTRIBUTION OF THE CO_2 TO SITES, WELLS AND RELATED INFRASTRUCTURE

10.4.1 Lateral Pipelines and Related Equipment

The planned end point for the preferred CO_2 pipeline route is Core Energy's Dover 36 Central Processing Facility located in Sec. 36, Dover Township, Otsego County, MI. Once the CO_2 has been delivered to this location, it can be easily tied into Core's systems for distribution to various locations for use in EOR operations and/or geological Storage. All CO_2 volumes that will be delivered to EOR operations and/or geological Storage sites for injection will be measured using coriolis mass flow type meters (e.g. Micro Motion R or F Series Coriolis Mass Flow Meters or equivalent). Core Energy uses mass flow type meters routinely to measure CO_2 injection volumes in its current EOR operations due to their accuracy and reliability. Mass flow meters are commonplace in CO_2 EOR operations.

With respect to the produced fluids and gas associated with EOR operations, Core will employ the same standard oil field practices and equipment for separation, handling, and measurement as it does in all of its existing EOR operations. Figure 10-7 is presented to show how CO_2 moves through Core Energy's existing EOR operations, and as a way to depict how CO_2 could move through a system as it relates to the WCCSP.

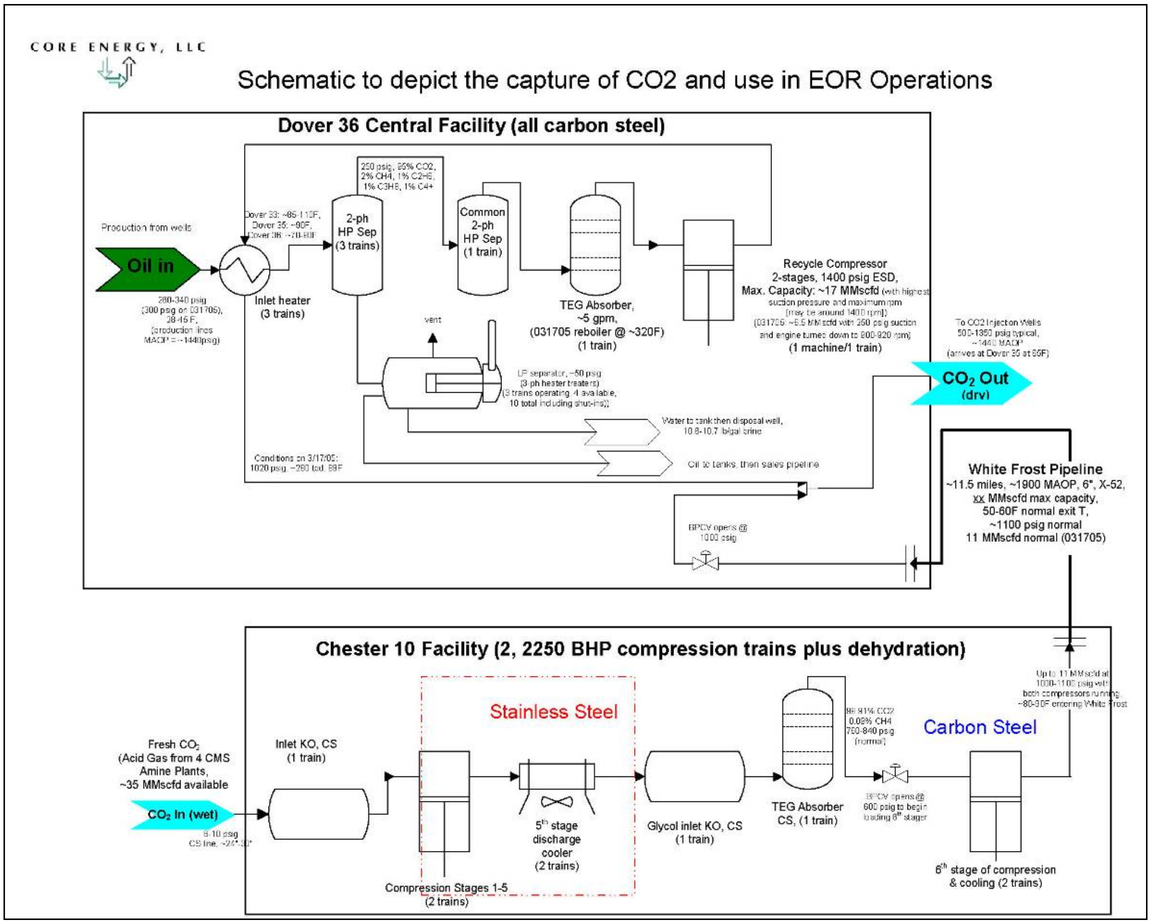


Figure 10-7: One-line Diagram of Existing EOR Flow Process

10.4.2 Injection Well Construction

10.4.2.1 EOR Injection Well Construction

All wells involved in the WCCSP that are related to the injection of CO_2 for EOR purposes, will be permitted, constructed and overseen according to the requirements of the United States Environmental Agency's (EPA) Class II Rules (40 CFR 144.28).

Currently Core Energy has 12 Class II EPA UIC Permits for wells that it owns and/or operates. Additionally, Core Energy has several more Class II UIC Permit Applications in various stages of the application process as a means to further expand its existing EOR operations in the subject area.

Due to Core's past history, current operations, and familiarity with the EPA's Class II UIC Permit process, there is a very high level of confidence in being able to secure the permits that will be necessary for EOR operations and construct wellbores that will meet all of the overseeing agencies' requirements.

Figure 10-8 is a wellbore diagram depicting a "typical" Class II Injection Well (Recently granted EPA Permit # MI-137-2R-0001).

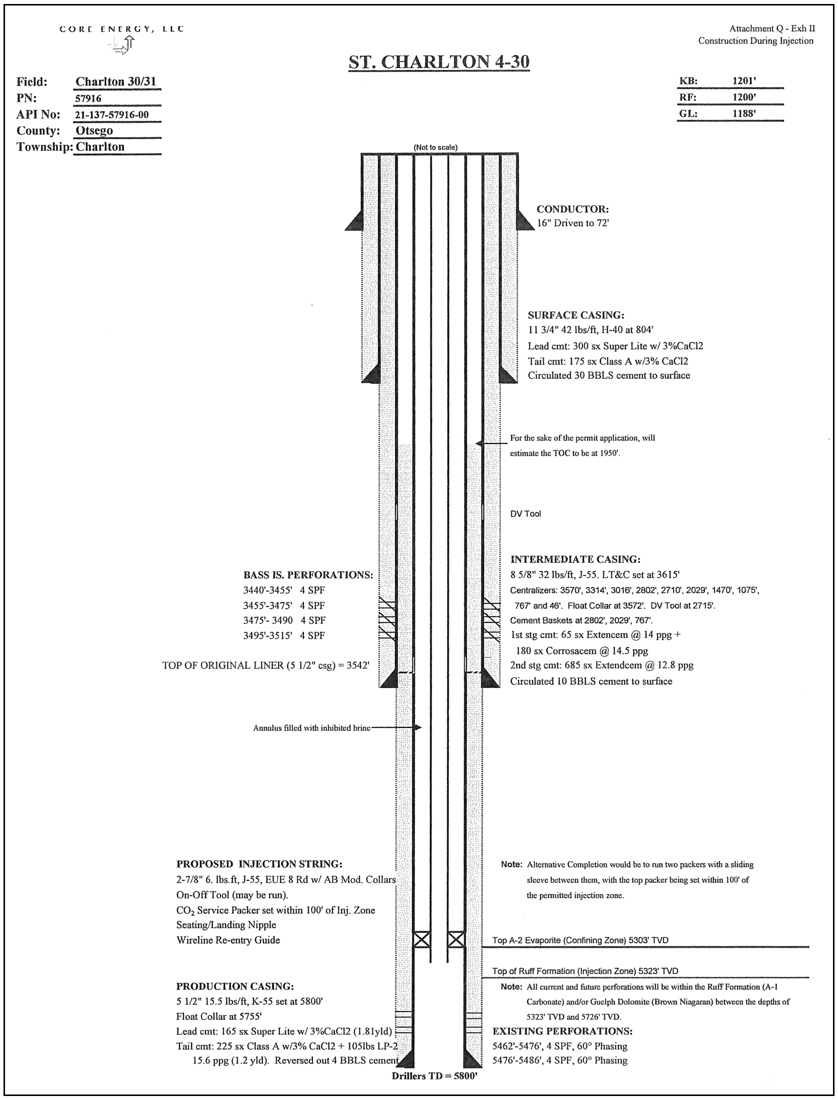


Figure 10-8: Typical Class II EPA UIC Permitted Well Construction

10.4.2.2 Geological Storage Injection Well Construction

All wells involved in the WCCSP that are related to the injection of CO_2 for geological storage purposes, will be permitted, constructed and operated in accordance with the requirements set forth by the United States Environmental Agency (EPA).

However, the specific EPA Rule that will dictate the construction and other requirements for geological storage well(s) will be determined during Phase 2 in concert with EPA Region V staff.

Currently, the EPA has a proposed rule for a new Class VI Well classification pending final approval, which at last check was scheduled for publishing in the early part of 2011. This Class VI Rule will describe the criteria specific to injection wells related to the geological Storage of CO_2.

Core Energy is familiar, however, with other Classes of EPA UIC Rules, specifically Class I and Class V that have been used around the country for other CO_2 geological storage projects and demonstrations.

Core Energy's recent hosting and involvement with the Midwest Regional Carbon Storage Partnership (MRCSP) in a DOE Phase II Storage Demonstration has provided an in depth understanding of the Class V Rules that were employed to oversee the construction and reporting of a 60,000 metric ton CO_2 test (done in two phases) in Core Energy's State Charlton 4-30 well (EPA Permit # MI-1379-5X25-0001). Therefore, Core Energy is confident in being able to partner with EPA Region V staff to secure a permit that will allow for the WCCSP demonstration to move forward without delay or interruption.

Presently, Core Energy has identified two potential CO_2 saline Storage sties, both of which are less than three miles from the Dover 36 CPF (Reference Figure 10-2).

10.5 ENHANCED OIL RECOVERY

Enhanced Oil Recovery (abbreviated EOR) is a generic term for techniques for increasing the amount of crude oil that can be extracted from an oil field. Using EOR, 30-60 %, or more, of the reservoir's original oil can be extracted compared with 20-40% using primary and secondary recovery. In CO_2 enhanced oil recovery, CO_2 is injected into the oil-bearing stratum under high pressure. That pressure pushes the oil into the pipe and up to the surface. In addition to the beneficial effect of the pressure, this method sometimes aids recovery by reducing the viscosity of the crude oil as the gas mixes with it. The CO_2 that is injected is "sequestered" in the underground formations. It is envisioned that EOR is a short term bridge to larger geologic storage opportunities.

In any Enhanced Oil Recovery project, there is a delay between CO_2 injection and oil production. This delay is the result of the injection of large amounts of CO_2 necessary to achieve the Minimum Miscibility Pressure.

The delay experienced between CO_2 injection and oil production will vary from reservoir to reservoir and area to area, depending on parameters such as MMP, injectivity rates, size of the reservoir to be flooded and the volumes of reservoir fluids and natural gas produced from the reservoir during the primary producing period.

The better EOR targets in the project area are those fields that produced the largest volumes of oil during their primary producing life and will, therefore, experience the longest delay between the commencement of CO_2 injection and oil production due to the larger volumes of CO_2 required to achieve MMP.

Large capital investments on the front-end of any CO_2 EOR project are typical. These costs include the infrastructure necessary for the compression, drying, transport, injection, production and processing of large volumes of CO_2. There is an additional investment on the front end of a CO_2 miscible EOR project attributable to the amount of CO_2 that must be injected to achieve minimum miscibility pressure (MMP). This investment is made knowing that there will be a delay in oil production and, thus, return on that investment until such time when adequate volumes of CO_2 have been injected into the (at least partially) depleted oil reservoirs to achieve minimum miscibility pressure (MMP) with an appropriate margin of safety. MMP is the pressure where oil and CO_2 combine to become a single phase.

10.5.1 Adding Oil Reserves to the Nation's Oil Supply

At the onset of the Project's planned one year injection period to sequester a volume of 300,000 metric tons of CO_2, it is estimated that 500,000 (+/-) barrels of proved oil reserves[1] for Petroleum Reserves Definitions) will be added to the nation's oil supply that without the development of this anthropogenic source of CO_2 would not otherwise be recoverable.

Once this CO_2 source has been developed and a pipeline installed to transport it from the source across the project area, an additional volume of 35 (+/-) million barrels of possible, perhaps even probable reserves will be able to be added to the nation's oil supply. At today's oil prices, 35 million barrels of oil represents more than $3 billion dollars in gross revenue (i.e. averaging the NYMEX forecasted oil price published on 3-29-10 over the one year injection period of July 2014 through June 2015).

10.5.2 Oil Production Rates During the Demonstration Period

Based on Core's experience in the project area, the delay experienced between initial CO_2 injection and peak oil rate has been in excess of 25 months.

During the actual demonstration period, very little to no oil will actually be produced during the one year demonstration period due to the small volume of CO_2 scheduled for injection. At the onset of the Demonstration's injection period, it is estimated that 500,000± barrels of proved oil reserves will be added to the nation's oil supply and the case can be made for an additional 35± million barrels of possible, perhaps even probable reserves to be booked.

10.5.3 Positive EOR Related Attributes of the WCCS Project

During the period from the commencement of CO_2 injection until MMP (plus a margin of safety) has been achieved (the fill-up period), 100% of the CO_2 volume injected will be prevented from entering the atmosphere and sequestered in the (at least partially) depleted oil reservoir.

The WCCS Project area is both rich in CO_2 EOR potential and saline aquifer storage capacity (see map in Section 10.2 CO_2 storage siting). A commitment to capturing CO_2 off the Roger's City Power Plant for the purposes of EOR will demonstrate for the nation a model whereby revenue from CO_2 EOR oil production can help to create a bridge to support long-term geological storage.

[1] Proved reserves are those quantities of petroleum which, by analysis of geological and engineering data, can be estimated with reasonable certainty to be commercially recoverable, from a given date forward, from known reservoirs and under current economic conditions, operating methods, and government regulations. Proved reserves can be categorized as developed or undeveloped.

11 SYSTEM PERFORMANCE

11.1 POWER PLANT WITH CO_2 CAPTURE AND COMPRESSION

The integration of the CO_2 capture system with the WCEV power plant requires steam, cooling water, electricity and additional utilities. The interfaces of the CO_2 capture and compression system and the power plant are provided in Table 11-1.

Table 11-1: CO_2 Capture and Compression System Interfaces

DESCRIPTION	FLOW	TEMP.	PRESSURE	NOTES
FLUE GAS FROM POWER PLANT	507,406 PPH	176	2 " W.G.	FLOW IS APPROX. 17% OF TOTAL UNIT 1 FG FLOW
FLUE GAS FROM ABSORBER	400,003 PPH			
STEAM FROM TURBINE (TO CAPTURE SYSTEM REBOILER)	141,900 PPH	630.8	105 PSIA	SH STEAM FROM IP-LP CROSSOVER
CO_2 TO COMPRESSOR INLET	93,540 PPH	104		
CO_2 TO CORE ENERGY FOR SEQUESTRATION	92,263 PPH	95	2,000 PSIA	
SERVICE WATER TO SCRUBBER	190 GPM	80	100 PSIA	
DEMINERALIZED WATER TO STRIPPER AND ABSORBER	50 GPM	80	45 PSIA	
COOLING WATER SUPPLY/RETURN FROM CO_2 CAPTURE PROCESS	16,500 GPM	85/108 F	80/50 PSIA	
INSTRUMENT AIR	40 SCFM	100	100 PSIA	
SERVICE AIR	70SCFM	100	100 PSIA	
POTABLE WATER	0GPM/ 30 GPM	--	--	
PRESCRUBBER BLOWDOWN TO WASTE WATER TREATMENT PLANT	40 GPM	122	95 PSIA	
AMINE MAKEUP TO ABSORBER	30.7 PPH	N/A	N/A	97% purity
CAUSTIC MAKEUP TO PRESCRUBBER	42.3 PPH	N/A	N/A	50% purity

A complete system heat material balance was completed to document the system performance for each of the following scenarios:

1. Base Case – Wolverine Clean Energy Venture (no CO_2 Capture)

2. Power Plant with 1,000 Metric Tons per Day Base Concept Design (Commercial Solvent)
3. Power Plant with 1,000 Metric Tons per Day Base Concept Design (Hitachi H3-1 Solvent)

As can be seen in Table 11-2, the application of a 1,000 tons/day of CO_2 capture and compression concept reduces the net output of the plant by almost 18 MW. System performance is improved when operated with the Hitachi H3-1 solvent. Gross Steam Turbine output and CO_2 capture auxiliary power losses improve by roughly 2.8 MW or 15% of the CO_2 capture and compression system loads when the system is operated with the advanced Hitachi solvent (H3-1).

Table 11-2: Power Plant Performance with CO_2 Capture

	Base Case	Commercial Solvent	Advanced Solvent
Plant Net Output (kW)	299,965.0	282,024.5	284,818.5
Plant Gross Output (kW) (Steam Turbine Output (kW))	329,580.0	319,107.0	321,808.0
Auxiliary Power (kW)	29,615.0	37,082.5	36,989.5
Net Heat Rate (Btu/kWhr)	9,056.1	9,632.1	9,537.7
CO_2 Captured (Metric TPD)	0	1,000	1,000
CO_2 Sequestered (Metric Tons/Day)	0	1,000	1,000

11.2 CO_2 STORAGE AND ENHANCED OIL RECOVERY

To fulfill the stated objective of sequestering 300,000 metric tons of CO_2 in one year, would require a sustained rate of 822 metric tons per day, assuming no downtime. Another stated Project objective is to be able to sequester the CO_2 at a rate of 1,000 metric tons per day.

The pipeline and other related infrastructure systems will be constructed to handle the aforementioned volumes with an appropriate margin of safety and to demonstrate the long-term commercial viability of the Storage aspects of the Project.

The primary objective of the WCCS Project is to utilize the produced CO_2 for EOR operations as a means to demonstrate the beneficial use of CO_2. The secondary objective is to utilize deep saline aquifer Storage to demonstrate the commercial viability of this means for disposing of CO_2 and to handle any volumes of CO_2 produced during the demonstration that cannot be injected into wells being utilized for EOR.

Though there is always some level of uncertainty when dealing with geological rock formations more than a mile beneath the surface, an abundance of analog data is available in the project area being sited that would suggest with a very high level of certainty that the volume of CO_2 to be generated as a part of the WCCS Project demonstration will be able to be safely sequestered with relative ease.

In support of this claim, Core Energy has actual history from wells/fields in proximity to the Dover 36 area, where a single well's average daily injection rate was more than 760 metric tons per day and injection volume was more than 233,000 metric tons over a period of one year.

To further substantiate the high probability of success in fulfilling the stated injection rates and volumes, Core Energy is currently injecting more than 1,400 metric tons of CO_2 per day in its on-going EOR operations with the capacity to inject even more. Over the previous twelve month period, Core Energy easily injected more than 264,000 metric tons as a part of its routine EOR operations and another 50,000 metric tons as a part of the MRCSP Phase II Demonstration.

12 ENVIRONMENTAL

An Environmental Information Volume (EIV) was prepared to provide information regarding the environmental aspects of the proposed Wolverine Carbon Capture and Storage Project. The EIV covered the scope of the WCCS Project, consisting of three separate operations:

- Removing and compressing carbon dioxide gas from a portion of the flue gas stream generated by the Wolverine Power generating plant, known as the Wolverine Clean Energy Venture.
- Transmitting the compressed CO_2 gas by buried pipeline from the WCEV near Rogers City to six existing wells, located in Otsego County, Michigan.
- Injecting the CO_2 gas into the six wells for Storage into underground formations and Enhanced Oil Recovery.

The EIV addressed the environmental aspects and impacts of the WCCS Project for each of these three distinct operations, as indicated in the following three sections of this report.

Although the site contains an active limestone quarry, limestone mining has been completed in the portion of the site containing the power plant. The CO_2 transmission pipeline will primarily follow an existing utility right-of-way (ROW). Two potential pipeline routes were evaluated, and the shorter route was selected as the preferred transmission route, as it impacted significantly fewer wetlands and water bodies and traversed less sensitive habitat. The route terminates at the existing Dover 36 oil field production and processing facility, where CO_2 gas will be distributed to four existing EOR wells and two existing Storage wells. These wells have been the subject of EOR projects and Storage pilot studies completed by Western Michigan University, the Battelle Memorial Institute, and Core Energy, through the US DOE Midwest Regional Carbon Storage Partnership.

12.1 CO_2 CAPTURE AND COMPRESSION

The WCCS Project is designed to capture 1,000 metric tons of CO_2 per day for compression, transportation, and subsurface injection for EOR and/or geologic Storage operations. The WCCS Project will employ a CO_2 capture system using advanced amine-based solvent technology to capture and sequester a minimum of 75 percent of the CO_2 from the treated flue gas stream. The Hitachi CO_2 capture system will be employed for this demonstration project. Advanced amines and additives supplied by Hitachi and Dow Chemicals are expected to reduce the cost and energy requirements of CO_2 capture, compared to current technologies. These technologies have not yet been attempted at a commercial scale and integrated with EOR and Storage operations.

The WCCS plant would be constructed in a remote location within a quarry. This location will minimize impacts related to site operations, especially visual impact and noise. Since the

WCCS plant would be located adjacent to the power plant, there will be no significant impact from construction and operation of the WCCS plant upon historic properties, cultural resources, endangered or threatened species, surface water, floodplains, or wetlands.

Operation of the WCCS plant will affect the composition of the power plant's flue gas exhaust. The carbon capture process will remove approximately 92,000 pounds of CO_2 per hour from stack emissions, as well as 23 lb/hr of SO_2, 5 lb/hr of PM_{10}, and 1 lb/hr of H_2SO_4. VOC emissions will increase by 2 lb/hr, due to amine slip. No other emissions are expected to increase or decrease. Exhaust gas mass flow will decrease by approximately 83,000 lbs/hr and the gas temperature will decrease by approximately 7 °F. Additional air emissions are expected to result from construction activities and mobile sources, such as trucks delivering bulk materials and employee vehicles.

Minimal wastes are expected to be generated during construction and operation of the WCCS plant. The plant will be a zero-liquid discharge facility. The WCCS plant's liquid waste stream will be sent to the WCEV power plant waste treatment plant. Solid wastes generated by the plant will be primarily non-hazardous. Process water utilized in the carbon capture plant will be obtained from the adjacent quarry.

Noise and vibrations will be generated during construction and operation of the WCCS plant. The largest source of noise from the WCCS facility will be the CO_2 compressing operation. The CO_2 extraction system will be located adjacent to a coal-fired power plant, which will also have a certain level of associated noise. The closest sensitive receptor to the WCCS plant is located 1 mile to the northwest (the Rogers City High School athletic field). The closest residence to the WCCS plant is approximately ½ mile to the southwest.

Since 1990, the unemployment rate in Presque Isle County has been significantly higher than that of the State of Michigan and the entire United States. Construction of the WCCS plant is expected to create 200 jobs, while operation of the plant will create 1,200 jobs. There are no potential concerns regarding the impact of this Project on the AI/AN population or other ethnic groups.

Construction and operation of the WCCS plant will require establishing a health and safety program in compliance with MIOSHA regulations. However, there are no outstanding health and safety risks associated with the proposed Project. In addition, a variety of permits will need to be obtained in order to construct and operate the WCCS plant, as is typical for an industrial facility. The overriding positive impact of constructing and operating the WCCS plant is that data will be obtained to verify the feasibility of carbon capture and storage technology and its impact upon managing the emission of greenhouse gases.

12.2 CO_2 TRANSPORTATION AND STORAGE

Two pipeline routes were evaluated as part of this EIV. Route 1 primarily follows an existing Wolverine ROW containing an aboveground, electrical transmission line, and it is approximately 66 miles long. Route 2 primarily follows an existing MichCon and/or Markwest ROW containing a buried natural gas pipeline and a buried liquid pipeline associated with oil-gathering operations. Route 2 is approximately 53 miles long. Route 2 was selected as the preferred route, since it is more direct, traverses significantly less wetland area, and avoids areas with a high probability of occurrence of T&E species.

The pipeline will be constructed in a newly established, 20-foot-wide ROW along the edge of the existing road and utility ROWs or wholly within existing utility ROW. Installing the pipeline will require clearing vegetation and temporarily disturbing the ground surface. The pipeline is expected to be installed using the open-cut trenching method, except under improved state, county, or village roads, where the directional drill or boring-and-jacking method will be utilized and under regulated streams and directly contiguous wetland areas, where the directional drill process will be employed. Trenching operations will consist of excavating a 3-foot-wide by 4-foot-deep trench, laying the pipe, backfilling to original grade, and seeding the disturbed area with an appropriate seed mixture. No significant noise or vibration is anticipated during construction or operation of the pipeline.

Minimal waste is expected to be generated during construction of the pipeline. Immediately after installation, the pipeline will be hydro-tested with water for not less than 8 hours. The water utilized in hydro-testing will be obtained from a nearby municipality water well or another rural source. Hydro-test water will be reused and then released onto the ground surface after pipeline integrity testing. Water will typically be discharged through hay bales or other temporary impoundments to prevent impact to surface water bodies.

Installation of the pipeline is expected to have a temporary impact on soils and plant communities due to excavation. After a portion of pipeline is installed, the area will be backfilled to the original grade using an excavator, and it will then be compacted. All trenched areas will be reseeded with a standard mixture of perennial grasses and legumes and a temporary cover nurse crop. After plant establishment, brush will be periodically removed in order to maintain site accessibility. This maintenance measure is currently in practice in the existing road and utility ROWs. Therefore, the only significant long-term impact to land use will be to newly established ROWs that will be cleared of trees prior to pipeline installation.

The route chosen for the pipeline is considered to be in attainment with the NAAQS for PM_{10}, $PM_{2.5}$, SO_2, CO, NO_2, lead, and O_3. The proposed Project will not interfere with the attainment status of any of these air pollutants. Exhaust from equipment with internal combustion engines used to install the pipeline will generate particulate, SO_2, CO, and NO_x, due to the combustion of diesel fuel and gasoline. In addition, excavation and backfilling will generate small amounts of fugitive dust, due to disturbing the ground via digging, trenching, and bulldozing. However, all emissions associated with pipeline construction are considered temporary and will only occur as the pipeline is installed. The potential for air emissions from the pipeline and injection sites during operation will be minimal, due to hydro-testing prior to pipeline use and routine maintenance during operation.

The preferred pipeline route will cross 13 streams and approximately 8.2 miles of wetlands. Wetlands are predominantly encountered in Presque Isle County, with forested wetlands being the most prevalent wetland type. Field verification is necessary to delineate wetland boundary locations and verify wetland types.

During construction, the pipeline will be installed through directional boring at each stream crossing to avoid stream, floodplain, and wetlands disturbances. Wetland impacts during pipeline construction are unavoidable, due to the prevalence of wetlands throughout Michigan's northeast Lower Peninsula. However, these impacts are temporary in nature. A field investigation will determine where directional boring is necessary, due to the presence of standing water.

Six T&E species have been documented in sections through which the pipeline route traverses. Potential impacts to slipper shell and Calypso orchid will be avoided through the use of directional boring in sensitive wet areas. It is unlikely the common loon will be impacted by the WCCS Project, since Route 2 avoids the loon's habitat on lakes and their shorelines.

Appropriate habitat for red-shouldered hawk may be present along Route 2, due to the prevalence of hardwood forest along the route. Large, mature hardwood trees may contain their nests and should be inspected prior to removing these trees during pipeline installation to avoid impacts to this bird.

Henry's elfin is known to occupy a variety of habitat types, many of which are present along Route 2. However, the last documented observance of this species was over 40 years ago and was limited to the Shoepac Lake area. Surveying this area at the appropriate time of year would provide additional information regarding the presence of this species and provide the necessary information to avoid impacts to this species.

Kirtland's warbler is an endangered species that potentially may be impacted by pipeline construction. A field survey is necessary to verify the presence of appropriate habitat and/or this species.

Goblin moonwort is known to be present in the sections containing the four EOR well sites. Field investigations have identified appropriate habitat adjacent to the existing well pads. The installation of monitor wells could potentially impact this species, if these wells are installed in beech/maple forest. Surveying potential monitor wells sites is necessary to determine the absence or presence of this species to avoid impacts to this species.

There are no Indian reservations or federal lands along the pipeline route or at the injection sites. A total of five archaeological sites were identified within one-fourth mile of the proposed Route 2 ROW. Impacts to archaeological sites are not expected due to pipeline installation, since the pipeline route will be located in existing utility ROWs in the vicinity of the documented archeaological sites.

Construction of the proposed pipeline will employ approximately 200 full-time employees. The labor force required to install the pipeline is expected to be obtained from local contractors or from pipeline installation companies, based in other parts of Michigan. This will beneficially impact the local economy, which has historically had a relatively high rate of unemployment.

During operation of the pipeline, the potential exists that CO_2 may emit from small leaks in the pipeline or there is a catastrophic event with a large release of CO_2 gas. It is expected that the CO_2 emitted during a catastrophic event would dissipate quickly and not cause harmful effects to the general public. Safeguards will be in place to detect and manage CO_2 releases. The pipeline route will be routinely inspected through aerial and land-based surveys. Leak detection safeguards will be engineered into pipeline design, including cathodic protection "on-off" surveys, "pig" in-line inspections, CPM systems, and SCADA systems.

13 PHASE 2 CCS DEMONSTRATION

13.1 CO_2 CAPTURE AND COMPRESSION

Demonstration of the Hitachi CO_2 capture process for the WCEV Project is scheduled for one year, starting in June 2014 through May 2015. Prior to the testing and demonstration phase, the CO_2 capture system will undergo start-up, commissioning and shakedown between December 2013 and May 2014, using the design solvent, UCARSOL AP 814. Figure 13-1 gives a schedule of the solvent testing period towards the end of Phase 2 of the WCEV Project.

The demonstration period is divided into four three-month quarters, to test the three proposed solvents. During the first and second quarters, the CO_2 capture system will be operated with the Dow UCARSOL AP 814 solvent and Hitachi's proprietary solvent, H3-1. CO_2 removal efficiency, solvent usage and steam consumption, among other parameters, will be monitored. A range of parametric tests will be performed during the test period in order to characterize the solvent at this approximately 50 MW scale, and collect data for process optimization and for upgrading to full-scale operations. Gas and liquid samples will be collected periodically, for system mapping and characterization of the process. Regular and specialty analysis will be performed on the samples collected for different parametric cases.

During the third quarter of the demonstration period, the commercial benchmark solvent, MEA will be tested. Parametric tests similar to those performed in the first six months will be repeated with MEA so as to provide an appropriate reference for comparison of the performance and efficiency of the H3-1 solvent.

H3-1 solvent used in the second quarter will be reclaimed and used as the solvent charge for the final three months of the demonstration period. Long-term process optimization will start during this period, continuing into the last three months of the Project (report writing phase). Any new or repeat tests required for obtaining additional data on the solvent performance and system behavior will also be performed during the final quarter of the demonstration period.

Additionally, a host of materials will be tested and analyzed during each quarter, to determine the corrosion impact of each solvent on the various materials.

Prior to charging with a fresh solvent, the CO_2 capture system will be flushed with demineralized water to avoid any residual effect of the previous solvent on the performance of the fresh solvent to be tested.

No	WCEV DOE Project - Phase 2 **Hitachi Demonstration Schedule**	Projected Test Period Start	 End
I	**WCCS Start-up, Commissioning & Shakedown**	**2-Dec-13**	**31-May-14**
	Flue gas available	14-Feb-14	
II	**Phase 2 Demonstration**	**1-Jun-14**	**31-May-15**
1	**UCARSOL AP 814** Solvent		
	Parametric Tests	1-Jun-14	31-Aug-14
	Specialty analysis and process characterization		
2	**H3-1** Solvent		
	Solvent change & System mapping	Sep-14	
	Parametric Tests	1-Sep-14	30-Nov-14
	Specialty analysis and process characterization		
3	**MEA** Solvent		
	Solvent change & System mapping	Dec-14	
	Parametric Tests	1-Dec-14	28-Feb-15
	Specialty analysis and process characterization		
4	**H3-1** Solvent		
	Solvent change & System mapping	Mar-15	
	Long-term optimization	1-Mar-15	31-Aug-15
	Specialty analysis and process characterization		
5	Materials Analysis for Corrosion	1-Jun-14	31-May-15
III	**Final Topical Report Writing**	**1-Jun-15**	**31-Aug-15**

Figure 13-1: Solvent Testing and Demonstration of Hitachi Carbon Capture System at WCEV during Phase 2

13.2 CO_2 MVA PLAN

The CO_2 used in the WCCS Project demonstration will be scrutinized as laid out in the MVA Plan, using appropriate technologies to ensure that the CO_2 is monitored, verified, and accounted for during the demonstration.

Due to the differences between the reservoirs being targeted for EOR operations (i.e. Niagaran Pinnacle Reefs) and the deep saline aquifer formations (i.e. Bois Blanc Formation), unique MVA Plans have been prepared and will be implemented that focus on the most likely leakage pathways, wellbores, and plume migration, respectively.

13.2.1 MVA Plan for a Typical EOR Target Formation

During the demonstration, at least one EOR target (i.e. depending on the storage capacity of the target) will be utilized to demonstrate that CO_2 can be sequestered safely and in an environmentally friendly manner, while at the same time bolstering oil production in Michigan. Expanding oil producing operations will be good for the Michigan economy as it will preserve and/or create jobs.

Because of the site certainty that can be provided, the demonstration to sequester CO_2 will utilize Core Energy's existing and significant EOR infrastructure and other sites conducive for saline aquifer Storage under Core's control. Utilizing sites under Core's control virtually ensures the likelihood that the demonstration can actually be successfully implemented in accordance with the requirements and time line stipulated by the DOE (Completion of Project by June 2015).

The EOR MVA Plan is tailored to address the unique risks associated with an EOR site. The EOR sites being targeted in the project area (i.e. Niagaran pinnacle reefs) are particularly suited for the Storage of CO_2 as they have demonstrated over the course of geologic time that they can effectively store buoyant fluids (e.g. oil and gas) due to them being definitive geologic traps overlain by well defined and effective cap rock layers. Therefore, the focus of the MVA Plan for EOR sites in the project area will focus in on the most likely leakage pathways—wellbores.

Hands-on experience and involvement with a Phase II Demonstration for the DOE's Carbon Storage Program through the Midwest Regional Carbon Storage Partnership (MRCSP), has provided Core with valuable insights for the preparing of a robust and cost-effective MVA Plan. Helping to implement the actual MVA Plan for the Phase II MRCSP Demonstration supplemented with the DOE's January 2009 Report titled, *"Best Practices for: Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations,"* and other sources of industry information have equipped Core Energy to fulfill this task.

The MVA Plan will incorporate appropriate monitoring techniques from the various recognized categories: atmospheric, near-surface and subsurface monitoring; and will utilize Primary, Secondary or Potential Additional Technologies as deemed necessary and appropriate to meet requirements and fulfill the task.

The EOR MVA Plan will utilize primarily the techniques categorized as primary monitoring technologies (i.e. defined as proven and mature technologies or applications capable of handling the minimum monitoring requirements). Core Energy's experience is consistent with the finding in DOE 2009 Best Practices Report, *"the primary technologies are fully capable of meeting and exceeding the UIC monitoring requirements of 40 CFR § 146 and achieving the MVA goals for geological Storage"*.

However, if deemed necessary, secondary monitoring technologies (i.e. defined as an available technology/protocol that can aid in accounting for injected CO_2 or provide insight into CO_2 behavior that will help refine the use of primary technologies) and/or potential additional monitoring technologies may be utilized.

As a part of utilizing a targeted EOR field in the project area during the demonstration, the following work will be designed and implemented during Phases II of the demonstration:

EOR Target MVA Plan:

It is not the intent of the WCCSP Team to physically purchase a field that would sit idle and strand significant capital for a period of up to 3-5 years with no possibility for a return on investment. Core Energy currently operates seven fields at various stages of CO_2 flooding development and has a plan to add more fields. Core owns significant EOR infrastructure in the project area that will be made available and can easily support a successful demonstration of the WCCSP. Rather if a Phase II Grant is awarded and as the time approaches, a suitable field will be identified and transferred from Core's operations for utilization in the WCCSP demonstration.

Therefore, in developing this MVA Plan, especially the budgetary aspects; it will be assumed that the EOR target will be a field consisting of three wells. A field made up of three wells would fit many of the potential EOR targets in the project area. Furthermore, of Core Energy's seven existing CO_2 floods, five currently have three or less wells in them. Taking this approach is thought to be very realistic and representative of prospective analog fields in the project area.

Pre-injection Phase (initial design, establish baseline conditions, geological characterization, identify risks)**:**

Technologies/Activities during the pre-injection phase of the demonstration will include:

§ **Shooting a 3-D Seismic Survey over the targeted field** – During Phase II, a 3-D seismic survey, the only tool available for accurately mapping the size, shape and boundaries of Niagaran pinnacle reefs—the targeted EOR formation for the demonstration; will be shot

Accurately knowing this information serves multiple purposes related to volumetric estimates of reserves, reservoir modeling and simulation, well placement /utilization, and to meet regulatory requirements (e.g. unitization).

A 3-D seismic survey is conducted by laying out a grid pattern over the subject area to strategically locate source points and receivers. The source to be used for the subject surveys will be small dynamite charges, approximately 1/3-1/2 lbs, buried in small diameter boreholes drilled to a depth of approximately 5’-10’.

The seismic waves generated by the dynamite source points propagate through the various layers of rock at various speeds based on the properties of the rock and fluids contained within them, thus, allowing the underground formations to be accurately mapped.

Only in the very immediate proximity to the source points will any noise and/or minute ground movement be observed. Essentially, the output from the source points is undetectable and the shooting of the seismic surveys will have very little to no impact on the surrounding area.

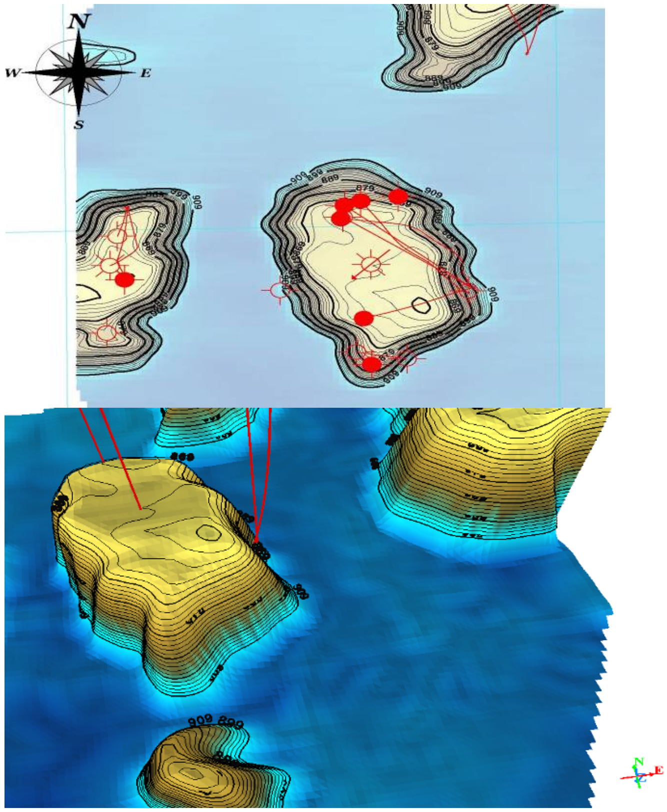


Figure 13-2: 3-D Seismic Survey Depiction of a "typical" Three Well EOR Target Field in the Project Area

- **Conducting a field review and history of development for the field –** During Phase II, information available from state of Michigan records or other sources, if available, will be reviewed and used to develop a complete history of development and production for the field.

- **Conducting a wellbore inventory of all wells in the area of review (AoR) based on available data (using EPA UIC Class II Well criteria)** – During Phase II, all wellbores in the AoR will be inventoried to assess the adequacy of their condition by ensuring that they have been constructed in a manner that meets the criteria for obtaining an EPA UIC Class II Injection Permit (i.e. the class of permit that regulates the injection for CO_2 EOR projects). A remedial action plan will be developed and implemented for all wellbores that do not meet the subject criteria, so that a Class II permit can be secured.

  Again, because the Niagaran pinnacle reefs being targeted for EOR are known to be superb containers for holding buoyant fluids over geologic time, the focus of the MVA plan will be on wellbores—the most likely leakage pathway.

- **Conducting a review of logs in the field and preparing necessary cross-sections, maps, etc.** – During Phase II, available well logs will be reviewed to help characterize the geology and reservoir of the EOR target. As needed to aid in the project, the logs will be placed into a cross-section for use and reference.

- **Calculating a material balance for all fluids/gases withdrawn from the field** – During Phase II, the reservoir voidage (i.e. volume in reservoir barrels) of the withdrawn fluids/gas from primary production will be calculated to allow for a determination of the volume of CO_2 necessary for initial fill-up prior to establishing production.

- **Identifying necessary permits** – During Phase I, the permits necessary for operating an EOR project have been identified drawing on Core Energy's extensive experience in this area. During Phase II, the permit(s) will be applied for and obtained.

- **Measuring current reservoir pressure** – During Phase II, current (pre-flood) reservoir pressure will be measured using downhole pressure gauges. The pre-flood pressure can then be compared with pressures taken at later times in the evolution of the flood to depict changes in the conditions in the reservoir.

- **Sampling current fluids in the reservoir** – During Phase II, current (pre-flood) fluids will be obtained and analyzed. The samples can then be compared with samples taken at later times in the evolution of the flood to depict changes in composition that may aid in better understanding the conditions in the reservoir.

- **Running cased hole logging services to identify fluids in reservoir and cap rock** – During Phase II, pulsed neutron and carbon/oxygen type logs (e.g. Baker Atlas' RPM-C GasView) will be run across the EOR target zone and the cap rock layers above to establish baseline conditions for saturation, fluids/gas in pore space, porosity, and lithology. This baseline case will then be used to compare with subsequent runs to demonstrate that the CO_2 has been sequestered in the target formation and/or to identify leakage pathways along the wellbore that could then be remediated.

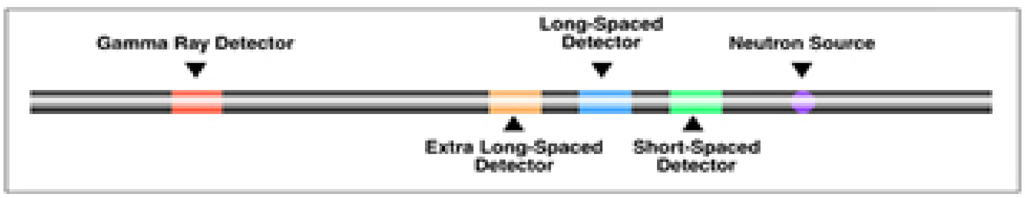
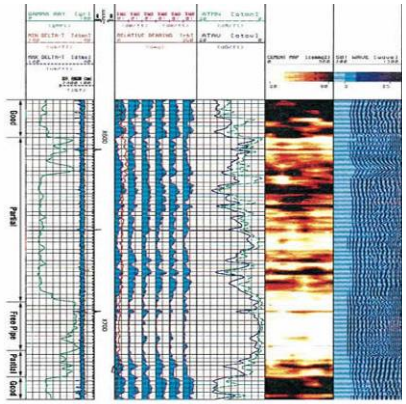


Figure 13-3: 3-D Baker Atlas Gas View Log

[The three high-resolution detectors in the RPM-C instrument are arranged to receive both capture and inelastic gamma rays and to sample the neutron-gamma transport over a longer baseline than conventional tools.]

- **Running latest generation cement bond logs to evaluate cement bonding** – During Phase II, a second generation cement bond log (e.g. Baker Atlas' Segmented Bond Tool) would be run to determine the quality of bonding in all wells to be used in EOR operations. If any cement bonding issues are identified that warrant repair, then a remediation plan would be developed and implemented.



Baker Atlas Segmented Bond Tool: The SBT log identifies a wide range of cement bond conditions as indicated for the interval X580 to X740. Partial bonding is identified from X600 – 88 and X714 – 28, but there is sufficient cement present to provide hydraulic isolation.

Figure 13-4: Baker Atlas Segmented Bond Tool

[The SBT log identifies a wide range of cement bond conditions as indicated for the interval X580 to X740. Partial bonding is identified from X600 – 88 and X714 – 28, but there is sufficient cement present to provide hydraulic isolation.]

§ **Running casing inspection logs to determine current condition of casing** – During Phase II, casing inspection logs (e.g. Baker Atlas' MicroVertilog: Magnetic Flux Leakage Inspection) would be run in all wells to be used in EOR operations to determine the physical condition of the long casing strings to be utilized during injection/production. If any casing integrity issues are identified that warrant repair, then a remediation plan would be developed and implemented.

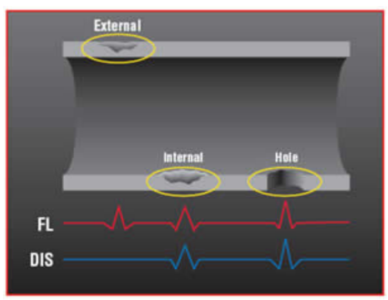


Figure 13-5: Baker Atlas Segmented Bond Tool

§ **Mechanical integrity testing (MIT) of wellbores to be utilized in demonstration – During Phase II, any wells that will be utilized for injection of CO2 would have a Mechanical Integrity Test (MIT) performed in accordance with EPA UIC requirements.**

§ **Developing a plan designed to correct any deficiencies discovered by the work/tests performed** – During Phase II, any wellbore deficiencies that are discovered as a result of reviews, data collection, logging operations, etc., will have a remediation plan developed and implemented to correct identified deficiencies.

§ **Identifying surface and downhole equipment that will be used during the operating phase (e.g. injection, production, taking of measurements, monitoring for leakage)** – During Phase I, surface and downhole equipment for a typical three well EOR field has been identified. The equipment has been selected based on Core Energy's experience with seven other fields in the area and to meet EPA Class II UIC Rules and the requirements of other agencies with jurisdictional oversight (e.g. Michigan DNRE). During Phase II the equipment would be purchased and installed.

§ **Developing a plan to flood the reservoir with CO_2 (sequestering it) that utilizes existing wellbores whenever possible, but incorporating new wellbores as deemed necessary (i.e. reservoir model/simulation)** – During Phase II, as a result of the 3-D seismic survey, field review, wellbore inventory, review of logs and cross-sections, reservoir voidage, logging operations, etc., a detailed flooding plan will be developed for implementation.

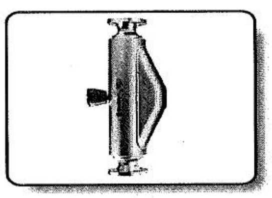
Operating Phase (Injection of CO_2 into sinks)**:**

Technologies/Activities during the operating phase of the demonstration will include:

§ **Wellbores will be constructed and operated to meet all EPA requirements (e.g. MIT, Class II EPA UIC Permits)**.

§ **Data will be reported to EPA and other regulatory agencies per requirements.**

§ **Accurate measurement of the CO_2 injected into the field using mass flow meters** – During Phase II, Coriolis mass flow meters will be utilized to measure volumes of CO_2 injected into the wells/field. Published mass flow accuracy for Micro Motion's F-Series meters is ±0.10%.



F-Series
High performance compact drainable Coriolis meter

- Best flow and density measurement in a compact, drainable flow meter
- Broadest range of application coverage
- Superior reliability and safety

Accuracy – Liquids and slurries

	Flow accuracy(1)		Temperature	Density, values in g/cm³ (kg/m³)(1)
	Mass	Volume		
ELITE	±0.05%(2)	±0.05%(2)	±1 °C	±0.0002 (±0.2)(2)
F-Series	±0.10%	±0.15%	±1 °C	±0.001 (±1.0)
H-Series	±0.10%	±0.15%	±1 °C	±0.001 (±1.0)
T-Series	±0.15%	±0.25%	±1 °C	±0.002 (±2.0)
R-Series	±0.50%	±0.50%	±1 °C	—
LF-Series	±0.50%	±0.50%	±1 °C	±0.005 (±5.0)
7835	—	—	—	±0.0001 (±0.1)
7845/7847	—	—	—	±0.0001 (±0.1)
7826/7828	—	—	—	±0.001 (±1.0)

(1) Flow rate accuracies are base percentages. For total accuracy see the box on page 7. Stated accuracy includes the combined effects of repeatability, linearity, and hysteresis. Specifications for ELITE ±0.0002 g/cm³ (±0.2 kg/m³) density accuracy are based on reference conditions of water at 68 to 140 °F (20 to 60 °C) and 15 to 30 psig (1 to 2 bar). All other specifications are based on reference conditions of water at 68 to 77 °F (20 to 25 °C) and 15 to 30 psig (1 to 2 bar).

(2) The accuracy for some ELITE sensor models may differ. Consult the ELITE Product Data Sheet for details.

§ **Accurate measurement of the CO_2 and other produced fluids using typical oil field metering systems.**

§ **Accurate continuous measurement of surface (e.g. injection and annulus) and periodic downhole pressures during injection and production** – During Phase II injection and for a period following, surface injection pressure and temperature will be measured and recorded continuously to develop a history. The data will be used in determining reservoir injectivity, ensuring conditions of EPA UIC Permit are adhered to, and diagnosing operational matters.

The annular pressures between the injection/production tubing and long-string casing and the long-string casing and intermediate casing will be monitored daily as a diagnostic step to further aid in detecting wellbore integrity issues.

At pre-determined injection volumes (e.g. 1/3 and 2/3 of estimated fill-up volume), injection will be temporarily shut-down to allow for bottom hole pressure data to be collected and analyzed for use in both reservoir understanding and to aid in leak detection.

§ **Periodic sampling of produced fluids (gases) to compare with baseline samples** – During Phase II injection, fluid/gas samples will be taken at least two times (e.g. corresponding with downhole pressure surveys and at the conclusion of fill-up) to identify and track composition and discern changes and/or trends.

§ **Periodic running of cased hole logging services to compare with baseline run** – During Phase II injection, at the midway point and then again at the end of the demonstration injection period; again run pulsed neutron and carbon/oxygen type logs (e.g. Baker Atlas' RPM-C GasView) across the EOR target zone and the cap rock layers above to compare with the baseline log run pre-injection.

If any leakage of CO_2 is identified, a plan to remediate the leakage pathway will be developed and implemented.

§ **CO_2 monitoring equipment will be placed at the injection wellheads to detect surface leaks related to injection operations** – During Phase II injection, CO_2 detectors will be placed at the wellheads of injection wells, due to their having an elevated risk of leakage during the injection phase.

The detectors will continuously monitor the atmospheric CO_2 concentrations. If any rapid or significant increase over the normal or background atmospheric CO_2 concentration is detected, an alarm will be triggered which dispatches a field operator to the site and/or automatically shuts the injection system in, thus, stopping the flow of CO_2.

Closure Phase (Injection ceased, wells plugged and abandoned, equipment and facilities removed, sites restored)**:**

It should be noted that injection operations will most likely continue on for a considerable amount of time beyond the WCCS P Phase II demonstration, therefore, these things will not likely occur during the life of the DOE project. They are being shown only to illustrate the types of activities that would typically be performed during the closure phase of an MVA Plan.

Technologies/Activities during the closure phase of the demonstration will/may include:

§ Final volume of CO_2 sequestered will be documented, reported and kept on file.
§ Final measurement of reservoir pressures to compare with material balance for volume of CO_2 injected and volumes of oil, gas and water produced.
§ Final sampling of all produced fluids (gases) to compare with baseline and operating samples.
§ Running of final cased hole logging services to compare with baseline and operating phase runs.
§ Running of final casing inspection logs to compare with baseline run.

- § Wells will be plugged in accordance with the requirements of all regulatory agencies that have jurisdictional oversight (e.g. EPA, DNRE).
- § Equipment and facilities will be removed from wells and locations restored.

Post-Closure Phase (ongoing monitoring to demonstrate that Storage has occurred and it's safe to discontinue further monitoring)**:**

Again, it is noted that EOR operations will most likely continue on for a considerable amount of time beyond the WCCSP Phase II demonstration, therefore, these things will not likely occur during the life of the project. They are being shown only to illustrate the types of activities that would typically be performed during the post-closure phase of an MVA Plan.

Technologies/Activities during the post-closure phase of the demonstration will/may include:

- § Periodic visual checking of well sites to look for leaks and impact on vegetation.
- § Other post-closure monitoring requirements that may be prescribed by regulatory agencies who have oversight. These types of regulations are a work in progress.

13.2.2 MVA Plan for a Typical Deep Saline Aquifer

During the WCCSP demonstration, at least one deep saline aquifer site (i.e. depending on the projected storage capacity of EOR targets and additional saline aquifers) will be utilized to demonstrate that CO_2 can be sequestered into a deep saline aquifer safely and in an environmentally friendly manner.

Because of the site certainty that can be provided, the demonstration to sequester CO_2 will utilize Core Energy's existing and significant infrastructure, use sites under Core Energy's control, and target saline aquifers that demonstrated the ability to sequester CO_2 at a commercial scale during a recent MRCSP/DOE Carbon Storage Program Phase II Demonstration. Utilizing sites under Core's control and targeting formations with a demonstrated ability to sequester $CO_{2,}$ virtually ensures the likelihood that the demonstration can actually be successfully implemented in accordance with the requirements and time line stip

The Saline Aquifer MVA Plan will be tailored to address the unique risks associated with a deep saline aquifer site. Through work already done during the MRCSP/DOE Phase II Demonstration, the deep saline aquifer to be targeted is known to be overlain by well defined and effective cap rock layers, but without a definitive structural geologic trap. Therefore, the focus of the MVA Plan for the saline aquifer site(s) in the project area will focus in on tracking the migration of the plume.

Hands-on experience and involvement with the aforementioned Phase II MRCSP/DOE Demonstration, has provided Core with valuable insights to inform the preparation of a robust and cost-effective MVA Plan. Helping to implement the actual MVA plan used in the Phase II DOE Demonstration supplemented with the DOE's January 2009 Report titled, *"Best Practices for: Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations,"* and other sources of industry information have equipped Core Energy to fulfill this task.

The saline aquifer MVA Plan will incorporate appropriate monitoring techniques from the various recognized categories: atmospheric, near-surface and subsurface monitoring; and will utilize Primary, Secondary or Potential Additional Technologies; as required to meet requirements and fulfill the task.

Since during the subject demonstration little to no research and development will occur (the focus of the potential additional monitoring technologies), the MVA Plan will utilize mostly those categorized as primary monitoring technologies (i.e. defined as proven and mature technologies or applications capable of handling the minimum monitoring requirements). Core's experience is consistent with the finding in DOE 2009 Best Practices Report, *"the primary technologies are fully capable of meeting and exceeding the UIC monitoring requirements of 40 CFR § 146 and achieving the MVA goals for geological Storage"*.

However, if deemed necessary, secondary monitoring technologies (i.e. defined as an available technology/protocol that can aid in accounting for injected CO_2 or provide insight into CO_2 behavior that will help refine the use of primary technologies) and/or potential additional monitoring technologies may be utilized.

As a part of the plan to target a deep saline aquifer for sequestering CO_2 in the project area during the demonstration, the following work will be designed and implemented during Phase II of the demonstration:

Saline Aquifer MVA Plan:

Core Energy currently owns and/or operates two wellbores that penetrate to the Bass Island Formation, a part of the geologic stratigraphic column that exists in the project area and that contains one of the saline aquifers being targeted in the project area—the Bois Blanc Formation. The wells are currently being held in a temporary abandonment status and are very good candidates for use as deep saline aquifer Storage targets for the WCCSP.

The Bois Blanc Formation, as a part of the MRCSP Phase II CO_2 Storage Demonstration, in July 2009 demonstrated the ability to safely sequester CO_2 at commercial rates. The volume of CO_2 injected during the Phase II Demonstration was 50,000± metric tons and the formation easily accepted the CO_2 at injection rates exceeding 600 metric tons per day (the capacity of the infrastructure used in the demonstration). The data obtained during the Phase II Demonstration indicated that the Bois Blanc Formation has the capacity for accepting significantly more CO_2 on a daily basis as the formation was not stressed at the infrastructure restrained rate of 600 metric tons per day. Though the reports for the MRCSP/DOE Phase II Demonstration are not yet finalized, estimates are that the Bois Blanc Formation could accept CO_2 at injection rates in excess of 1,000 metric tons per day.

The continuous nature of the targeted Bois Blanc Formation in the area, Core's owning of the surface land, and a wellbore that penetrates the target aquifer, the large storage volume of the target aquifer (as calculated by Western Michigan University), and the demonstrated ability of the target aquifer to accept CO_2 at commercial daily rates in a well only 2 miles away, make the proposed site a very suitable and viable location to serve as the secondary option for sequestering CO_2 to supplement the primary Storage effort for the WCCSP--EOR targets.

The development of this Saline Aquifer MVA Plan, especially the budgetary aspects will be developed assuming the utilization of an existing Core Energy owned surface location and wellbore currently drilled and cased through the Bois Blanc Formation.

Pre-injection Phase (initial design, establish baseline conditions, geological characterization, identify risks)**:**

Technologies/Activities during the pre-injection phase of the demonstration will/may include:

§ **Aquifer simulation work will be conducted using existing analog work (e.g. from MRCSP/DOE Phase II Demonstration), if available, or develop a new simulation to predict plume size to inform area of review (AoR).** - During Phase II, an AoR will be established by using reservoir work already done by the MRCSP on a well only two miles away by estimating the distance that the CO_2 plume will travel as a function of the volume of CO_2 to be injected.

§ **Shooting a 2-D regional seismic survey or using existing data if available.** – During Phase II, 2-D seismic data will be either purchased or shot, depending upon the availability of quality data in the vicinity. Because the targeted saline aquifer, Bois Blanc Formation, is quite homogeneous, large in its regional extent and does not possess a definitive structural trap; it is important to determine that there are no major faults in the AoR that may serve as leakage pathways through the otherwise known to be well defined and effective cap rock layers.

§ **Shooting a 3-D seismic survey over the tentative site area(s) or using existing data if available and able to provide quality data.** – During Phase II, an initial (to establish baseline conditions) and then at least one subsequent 3-D seismic survey would be shot over the area of review (i.e. estimated by aquifer simulation for the outer edge of the CO_2 plume). A 3-D seismic survey does not directly measure the presence of CO_2 in an aquifer.

The repeated surveys do, however, measure the change in rock and fluid properties of an aquifer caused when naturally occurring brines are displaced by the injected CO_2. The changes observed from survey to survey are attributed to the presence of CO_2, thus, allowing the plume to be mapped.

The grid pattern, source points, receivers and other parameters will be duplicated for each survey to ensure that any changes observed in the surveys are a result of the CO_2 plume and not surface or other factors.

§ **Conducting a wellbore inventory of all wells in the AoR based on available data (EPA UIC Class V or VI Well criteria will be used for construction).** – During Phase II, all wellbores in the area of review will be inventoried to assess the adequacy of their condition to ensure that they have been constructed in a manner that meets the criteria for obtaining an EPA UIC Class V or Class VI Injection Permit (i.e. the class of permits that regulate the injection of CO_2 for the purposes of geologic Storage). A remedial action plan will be developed and implemented for all wellbores that do not meet the subject criteria, so that a Class V or VI permit can be secured. It should be noted that the Class VI Rules have not yet been finalized by the EPA and may not be until 2011.

Because saline aquifers tend not to be definitive structural traps capable of containing buoyant fluids, in addition to wellbores being potential leakage pathways, the tracking of the CO2 plume will be an additional area of focus for the Saline Aquifer MVA Plan.

§ **Conducting a review of logs available in the area of review and preparing necessary cross-sections, maps, etc.** - During Phase II, available well logs will be reviewed to help characterize the geology and characteristics of the saline aquifer in the AoR. To aid in the project and to demonstrate the regional similarity of the targeted saline aquifer, the logs will be placed into a cross-section for use and reference.

§ **Identifying necessary permits.** - The permits necessary for operating a CO_2 geologic Storage project have been identified. During Phase 2, the permits will be applied for and obtained.

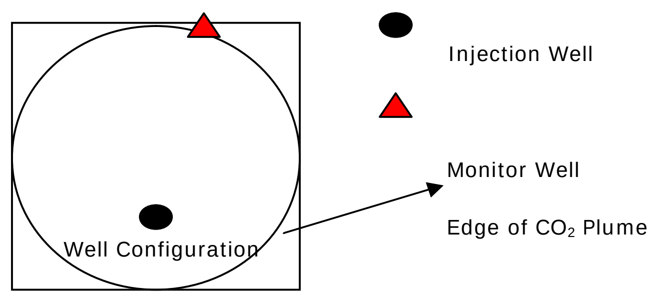
§ **Drill and complete new wells or convert existing wellbores, if available, for use as injection wells using EPA UIC Class V or VI Well construction criteria.** During Phase II, the existing well that is temporarily abandoned will be permitted and constructed to meet the

EPA requirements for use in the WCCSP demonstration, as a Class V or Class VI UIC Injection Well.

§ **Drill monitor well for use in monitoring actual performance of injection and to revise simulation.** During Phase II, an aquifer monitoring well will be drilled at a distance to be determined by the aquifer simulation work aforementioned.

Monitoring wells provide an avenue to perform fluid sampling and geophysical monitoring techniques (e.g. cross-well seismic, wireline logging, downhole microseismic monitoring), information necessary to monitor the characteristics and movement of the CO_2 being transported through the aquifer.

As a part of drilling of the aquifer monitor well, the target interval (e.g. Bois Blanc Formation) will be cored analyzed and a suite of open hole logs will be run to measure formation characteristics and properties (e.g. identify fluids in the reservoir, identify the presence of bedding planes and fractures). This data will serve to more thoroughly characterize the formation as a commercial Storage target.



§ **Crosswell seismic surveys between injection well and monitor well.** – During Phase II, cross-well seismic surveys will be run pre-injection to establish a baseline, at the midway point of injection and then again at the conclusion of injection.

Cross-well seismic is another geophysical technique that allows the distribution of CO_2 in a saline aquifer to monitored and tracked over time. The technique requires at least two wells, one for the use of seismic sources that generate seismic waves and the other for a series of receivers that record the waves created by the sources. A two well survey yields a 2-dimensional “slice” of data between the source and receiver wells.

The data can be processed in a variety of ways to aid in monitoring the presence of CO_2. A change in velocity from one survey to the next would generally be interpreted as evidence of CO_2 being present. Wave amplitude is another seismic attribute that may indicate the presence of CO_2. More sophisticated analysis may involve frequency attributes involving signal processing transforms.

Because of the proximity of the sources and receivers to the injection interval, the resolution of the seismic data is much better than data obtained from surface seismic surveys. Using successive cross-well surveys should allow for the detection of a CO_2 plume to with a high degree of accuracy (e.g. 10’±).

§ **Drill wells in the vadose zone to determine baseline USDW Parameters.** - Phase II well inventory review, wellbores in the AoR are identified to have been constructed or plugged in a manner that adds significant risk to the USDW’s, then at least one Drinking Water Monitoring Well will be drilled, sampled to establish baseline conditions, and periodically sampled during injection to detect if any changes in water chemistry occur over time resulting from CO_2 coming into contact with the USDW. For the sake of the Phase II Budget, one such well has been included.

§ **Measuring initial aquifer pressure.** – During Phase II, initial (pre-injection) aquifer pressure will be measured using downhole pressure gauges. The pre-injection pressure can then be compared with pressures taken at later times in the evolution of the demonstration to depict changes in the conditions in the aquifer.

§ **Initial sampling fluids in the aquifer.** During Phase II, initial (pre-injection) aquifer fluids from the injection and aquifer monitor wells will be obtained and analyzed. The samples can then be compared with samples taken at later times in the evolution of the demonstration to depict changes in composition that may aid in better understanding the conditions in the aquifer.

§ **Running cased hole logging services to identify fluids in reservoir and cap rock** – During Phase II, pulsed neutron and carbon/oxygen type logs (e.g. Baker Atlas' RPM-C GasView) will be run in the injection and aquifer monitor across the targeted injection zone and the cap rock layers above to establish baseline conditions for saturation, fluids/gas in pore space, porosity, and lithology. This baseline case will then be used to compare with subsequent runs to demonstrate that the CO2 has been sequestered in the target formation and/or to identify leakage pathways along the wellbore that could then be remediated.

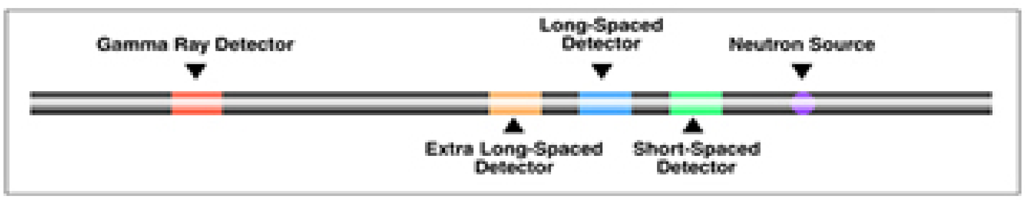
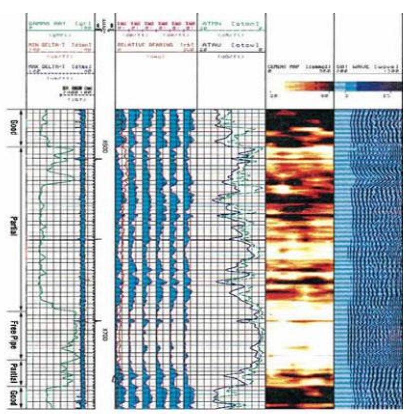


Figure 13-3: 3-D Baker Atlas Gas View Log

[The three high-resolution detectors in the RPM-C instrument are arranged to receive both capture and inelastic gamma rays and to sample the neutron-gamma transport over a longer baseline than conventional tools.]

§ **Running latest generation cement bond logs to evaluate cement bonding** – During Phase II, a second generation cement bond log (e.g. Baker Atlas' Segmented Bond Tool) will be run to determine the quality of bonding in all wells to be used in injection or monitoring operations. If any cement bonding issues are identified that warrant repair, then a remediation plan would be developed and implemented



Baker Atlas Segmented Bond Tool: The SBT log identifies a wide range of cement bond conditions as indicated for the interval X580 to X740. Partial bonding is identified from X600 – 88 and X714 – 28, but there is sufficient cement present to provide hydraulic isolation.

Figure 13-4: Baker Atlas Segmented Bond Tool (SBT)

[The SBT log identifies a wide range of cement bond conditions as indicated for the interval X580 to X740. Partial bonding is identified from X600 – 88 and X714 – 28, but there is sufficient cement present to provide hydraulic isolation.]

§ **Running casing inspection logs to determine current condition of casing** – During Phase II, casing inspection logs (e.g. Baker Atlas' MicroVertilog: Magnetic Flux Leakage Inspection) would be run in all wells to be used in injection and monitoring operations to determine the physical condition of the long casing strings to be utilized during injection/production. If any casing integrity issues are identified that warrant repair, then a remediation plan would be developed and implemented.

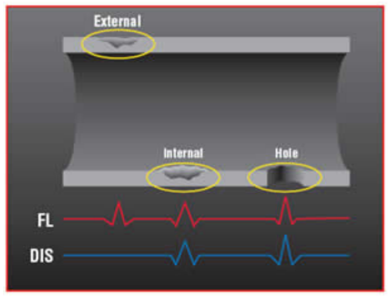


Figure 13-5: Baker Atlas Segmented Bond Tool

§ **Mechanical integrity testing (MIT) of wellbores to be utilized in demonstration –** During Phase II, any wells that will be utilized for injection of CO_2 would have a Mechanical Integrity Test (MIT) performed in accordance with EPA UIC requirements.

§ **Developing a plan designed to correct any deficiencies discovered by the work/tests performed** – During Phase II, any wellbore deficiencies that are discovered as a result of reviews, data collection, logging operations, etc., will have a remediation plan developed and implemented to correct identified deficiencies.

§ **Identifying surface and downhole equipment that will be used during the operating phase (e.g. injection, production, taking of measurements, monitoring for leakage)** – During Phase I, surface and downhole equipment for a typical three well EOR field has been identified. The concept has been developed based on Core Energy's experience with seven other fields in the area and to meet EPA Class II UIC Rules and the requirements of other agencies with jurisdictional oversight (e.g. Michigan DNRE). During Phase II the equipment would be purchased and installed.

§ **Identifying surface and downhole equipment that will be used during operating phase (e.g injection, taking of measurements, monitoring for leakage) -** During Phase I, surface and downhole equipment for one injection well, one injection aquifer monitoring well, and one drinking water monitoring well has been identified and budgeted. The conceptual design has been developed based on Core Energy's experience with EPA requirements gained during the MRCSP's Phasee II Demonstration and will meet EPA Class IV or VI UIC Rules and the requirements of other agencies with jurisdictional oversight (e.g. Michigan DNRE). During Phase II the equipment would be purchased and installed.

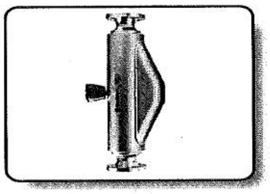
Operating:

Technologies/Activities during the operating phase of the demonstration will include:

- **Wellbores will be constructed and operated to meet all EPA requirements (e.g. MIT, Class II EPA UIC Permits)**.

- **Data will be reported to EPA and other regulatory agencies per requirements.**

- **Accurate measurement of the CO_2 injected into the field using mass flow meters** – During Phase II, Coriolis mass flow meters will be utilized to measure volumes of CO_2 injected into the wells/field. Published mass flow accuracy for Micro Motion's F-Series meters is ±0.10%.



F-Series
High performance compact drainable Coriolis meter

- Best flow and density measurement in a compact, drainable flow meter
- Broadest range of application coverage
- Superior reliability and safety

Accuracy – Liquids and slurries

	Flow accuracy(1)			
	Mass	Volume	Temperature	Density, values in g/cm³ (kg/m³)(1)
ELITE	±0.05%(2)	±0.05%(2)	±1 °C	±0.0002 (±0.2)(2)
F-Series	±0.10%	±0.15%	±1 °C	±0.001 (±1.0)
H-Series	±0.10%	±0.15%	±1 °C	±0.001 (±1.0)
T-Series	±0.15%	±0.25%	±1 °C	±0.002 (±2.0)
R-Series	±0.50%	±0.50%	±1 °C	—
LF-Series	±0.50%	±0.50%	±1 °C	±0.005 (±5.0)
7835	—	—	—	±0.0001 (±0.1)
7845/7847	—	—	—	±0.0001 (±0.1)
7826/7828	—	—	—	±0.001 (±1.0)

(1) Flow rate accuracies are base percentages. For total accuracy see the box on page 7. Stated accuracy includes the combined effects of repeatability, linearity, and hysteresis. Specifications for ELITE ±0.0002 g/cm³ (±0.2 kg/m³) density accuracy are based on reference conditions of water at 68 to 140 °F (20 to 60 °C) and 15 to 30 psig (1 to 2 bar). All other specifications are based on reference conditions of water at 68 to 77 °F (20 to 25 °C) and 15 to 30 psig (1 to 2 bar).

(2) The accuracy for some ELITE sensor models may differ. Consult the ELITE Product Data Sheet for details.

- **Accurate continuous measurement of surface (e.g. injection and annulus) and periodic downhole pressures during injection** – During Phase II injection and for a period following, surface injection pressure and temperature will be measured and recorded continuously to develop a history. The data will be used in determining reservoir injectivity, ensuring conditions of EPA UIC Permit are adhered to, and diagnosing operational matters.

  The annular pressures between the injection/production tubing and long-string casing and the long-string casing and intermediate casing will be monitored daily as a diagnostic step to further aid in detecting wellbore integrity issues.

  At pre-determined injection volumes (e.g. 1/2 and conclusion of the estimated fill-up volume), injection will be temporarily shut-down to allow for bottom hole pressure data to be collected and analyzed for use in both reservoir understanding and to aid in leak detection.

- **Crosswell seismic survey between injection well and monitor well(s) to compare with baseline conditions**. - During the Phase II injection period, a cross-well seismic survey will be run at the approximate mid-way point of injection for comparison with the baseline survey run pre-injection as a way to monitor and track the movement of the CO_2 plume.

- **Periodic sampling of all fluids/gases (e.g. injectant, saline aquifer brine, USDW's (gases) to compare with baseline samples** – During Phase II injection, fluid samples will be taken at least two times (e.g. corresponding with downhole pressure surveys or other down times) and at the conclusion of injection to identify and track brine composition and discern changes and/or trends.

  Periodic running of cased hole logging services to compare with baseline run – Phase II injection, at the midway point and then again at the end of the demonstration injection period; pulsed neutron and carbon/oxygen type logs (e.g. Baker Atlas' RPM-C GasView) will again be run in the injection and aquifer monitoring wells across the target injection zone and the cap rock layers above to compare with the baseline log run pre-injection.

  If any leakage of CO2 is identified, injection will cease and a plan to remediate the leakage pathway will be developed and implemented.

  CO_2 monitoring equipment will be placed at the injection wellheads to detect surface leaks related to injection operations – During Phase II injection, CO_2 detectors will be placed at the wellhead of the injection well, due to their having an elevated risk of leakage during the injection phase.

  The detectors will continuously monitor the atmospheric CO_2 concentrations. If any rapid or significant increase over the normal or background atmospheric CO_2 concentration is detected, an alarm will be triggered which dispatches a field operator to the site and/or automatically shuts the injection system in, thus, stopping the flow of CO_2.

Closure Phase

It should be noted that demonstration period for the WCCSP ends in 2015, prior to the Storage well evaluation work being completed. The Phase II Budget will include funding to complete the Closure and Post-closure Phase MVA technologies/activities to ensure that all necessary data has been collected, reported, filed; and the wells are plugged in accordance with the conditions of the permits and/or other regulatory requirements.

Technologies/Activities during the closure phase of the demonstration will include:

- Final volume of CO_2 sequestered will be documented and reported.
- Final measurement of reservoir pressures and detailing of how fast pressure falls off back to or near baseline conditions.
- Final sampling of all fluids/gases to compare with baseline and operating samples.
- Final Cross-well seismic survey to compare with baseline and operating phase surveys.
- Running of final cased hole logging services to compare with baseline and operating phase runs.
- Running of final casing inspection logs to compare with baseline run.
- Wells will plugged in accordance with the requirements of all regulatory agencies that have jurisdictional oversight (e.g. EPA, MDEQ).
- Equipment and facilities will be removed from wells and locations restored.

Post-Closure

Again, it is noted that Storage operations will most likely continue on for a period of time beyond the WCCSP Phase II Demonstration. To make certain that operations related to the geological

Storage of CO2 into a deep saline aquifer are closed out properly, the Phase II Budget will include funding to complete the Post-closure Phase MVA technologies/activities

Activities during the post-closure phase of the demonstration, if any occur, will include:

§ Periodic visual checking of well sites to look for leaks and impact on vegetation.

14 FULL-SCALE CCS INTEGRATION AND FUTURE APPLICATION OF THE TECHNOLOGY

14.1 FULL-SCALE CO_2 CAPTURE AND COMPRESSION – ADVANCED INTEGRATION CONCEPTS

Aside from using the best solvent with the lowest energy requirement, the overall net efficiency of a power plant with CO_2 Capture and Compression can be maximized by optimizing the use of available heat sources and heat sinks across the entire plant system including the CO_2 Capture and Compression scope. Today's state-of-the-art thermal power plants achieve high efficiencies by raising steam temperature (and pressure) to the highest possible values allowed by available materials, and by recovering as much low grade heat as economically feasible for preheating combustion air and turbine condensate or boiler feed water. However, in general, the boiler/AQCS systems and the steam cycle are optimized independently and efficiency optimization under consideration of the overall system is generally not performed. The introduction of post-combustion CO_2 Capture and Compression changes this approach completely. The heat requirement of the CO_2 capture system is very large, almost entirely low grade (used for solvent regeneration to keep the stripper at a temperature of about 100 – 120^{o}C, 212-250^{o}F). If this low grade heat is provided solely from an LP turbine steam extraction, the LP stage steam flow will be reduced by as much as 50%, resulting in large reduction of power output. Therefore, integrating post-combustion CO_2 capture demands a system-wide re-optimization of heat management in the plant.

The Wolverine CO_2 Capture and Compression plant is a slipstream demonstration facility treating approximately 17% of the flue gas from a 300 MWe power train. As such the energy requirement for CO_2 capture will only have limited impact on the performance of the steam turbine and the overall plant. Therefore, some of the integration measures discussed here are not required for the Wolverine slipstream demonstration project. However, these integration measures are critical to reduce the cost of CO_2 Capture and Compression at full scale application. Most of these integrating measures can be accurately simulated using Hitachi's design programs for turbine, boiler and AQCS equipment, as well as plant system analysis tools such as THERMOFLEX and ASPEN Plus.

Hitachi's ability to achieve optimized plant integration is derived from its world class technologies as a leading global supplier of complete thermal power plants. Specifically, Hitachi's vast experience as a supplier of boilers, steam turbines and air quality control systems and as a plant system integrator provides an ideal knowledge base for optimization of heat management for the overall plant. The following aspects need to be evaluated on a plant specific basis for the optimized integration in the context of CO_2 Capture and Compression (as illustrated in Figure 14-1).

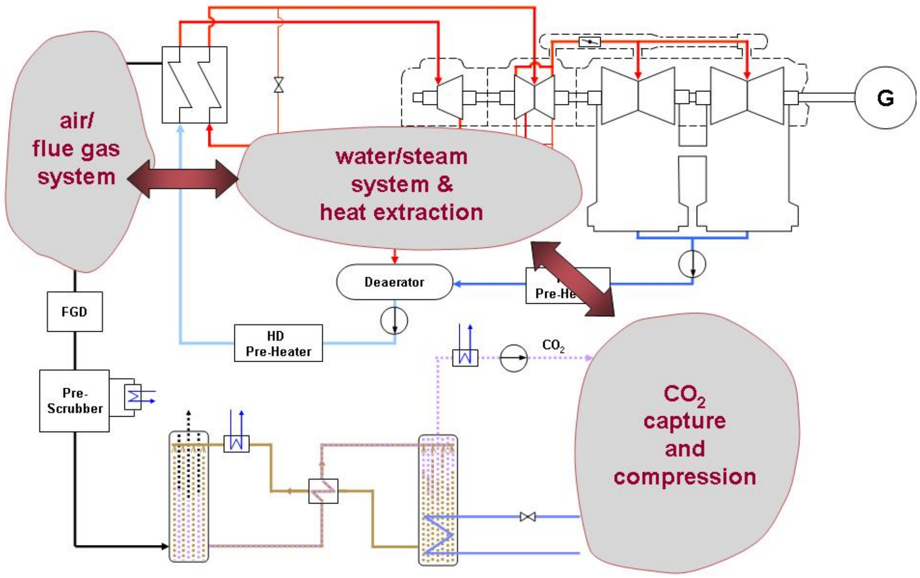


Figure 14-1: Areas for Plant System Heat Optimization

1. Steam Turbine - CO_2 stripper integration: Steam extraction points, processing of extracted steam and return of condensate/flash steam from the CCS island, and turbine modifications.
2. Balance between preheating of combustion air and/or drying of high moisture fuels and heating for solvent regeneration.
3. Balance between preheating of turbine condensate / boiler feed water and heating of the stripper.
4. Utilization of waste heat from CO_2 compression.
5. Choice between two stage SO_2 removal (main scrubber plus prescrubber) and single stage high performance SO_2 scrubbing to reduce energy consumption, operating and capital costs.
6. Use of Hitachi's patented Clean Energy Recuperator (CER) to recover low grade flue gas energy for turbine condensate heating or for amine regeneration.

14.2 ADVANCED APPROACH FOR THERMAL INTEGRATION

In a conventional approach, the steam for desorption is extracted at the hot or cold reheat steam line (1) or the crossover pipe (2) between the IP and LP turbine (Figure 14-2). As a result, very high losses in plant efficiency cannot be avoided. This conventional approach for CO_2 capture process implementation will have a power plant net efficiency loss of about 13.1% points if an MEA-based process with a specific regeneration heat of 3600 kJ/kgCO_2 is used. An additional loss of efficiency of about 2.8% points due to CO_2 compression has to be added, assuming that the CO_2 is compressed to 200 bar at 30°C (2900 psi at 80°F). The basis for the efficiency comparison is an 800 MWe power plant. The reference plant has a single reheat steam cycle with a main steam temperature of 596°C (1105°F) and reheat temperature of 608°C

(1126°F), which represents the state-of-the-art supercritical pulverized coal-fired power plants. When firing a bituminous coal, the plant has a net efficiency of 46.9% LHV, without CO_2 Capture and Compression. It should be noted that this reference plant, located in Europe, uses very high steam conditions and also several special design features for heat recovery. Therefore, it has higher efficiency than typical new plants in the US. However, the efficiency penalties discussed here are applicable to plants in the US.

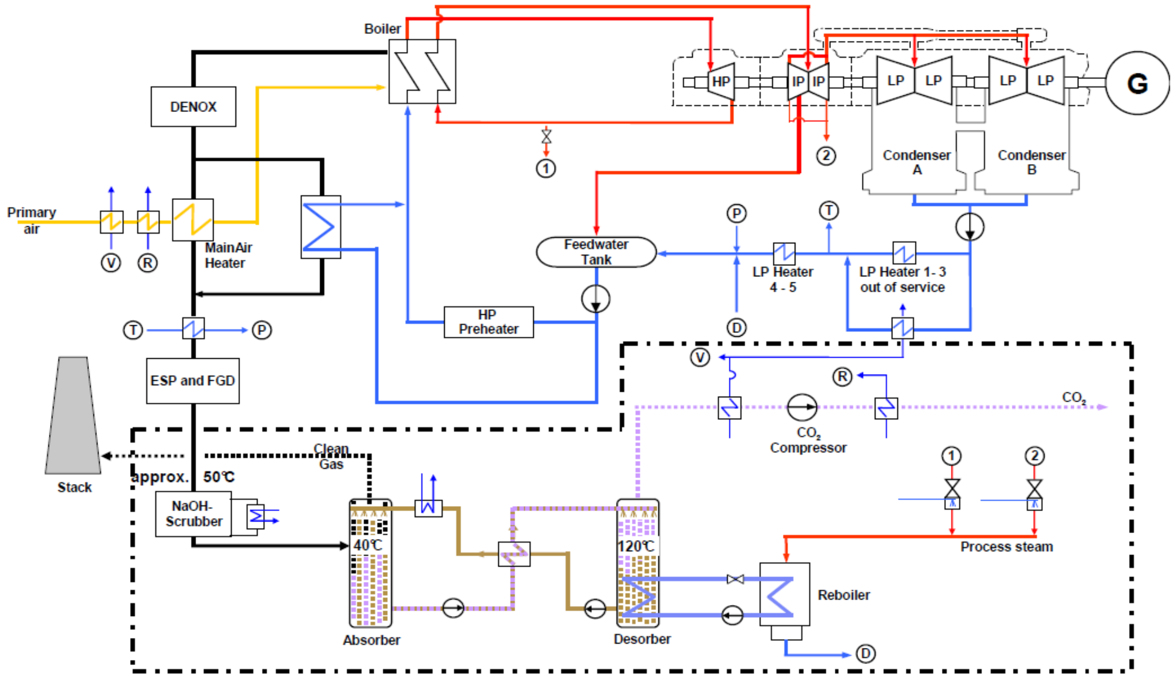


Figure 14-2: Optimized Water-Steam Cycle with CCS Process Integration

To reduce the efficiency penalty by CO_2 Capture and Compression, an optimization of the plant overall process is needed, i.e., all heat sinks of the CO_2 Capture and Compression system need to be introduced at an optimum location of the steam cycle so that no energy is wasted. This can be accomplished by integration of the condensate and the cooling water from the CO_2 Capture and Compression process into the water steam cycle as well as the steam extraction from the steam turbine for reboiler heating. Figure 14-2 shows an optimized water steam cycle of a power plant, which includes the following modifications of the water steam cycle:

- Condensate from the reboiler heating steam is reintegrated into the main condensate line downstream of the condensate preheater No. 5.
- A part of the heat transferred by the CO_2 Capture and Compression system to the cooling water can be recovered to warm up the condensate upstream of the feedwater tank / de-aerator. As a result, the LP heaters No. 1-3 can be bypassed and unloaded, which results in increased steam cycle efficiency.
- A part of the waste heat from the CO_2 cooling at the stripper outlet (V) and the waste heat of the CO_2 compressor (R) can be used for air preheating before entering the main air heater. Since these waste heats are used for air preheating, a part of the flue gas heat can be shifted to the feedwater line by using a heat exchanger in parallel to the main air heater. The remaining heat amount of the flue gas downstream of the main air heater can be used for main condensate preheating (P), for instance utilizing the Clean Energy Recuperator (CER).

- The thermodynamically preferred location for the steam extraction is the crossover pipe (2) between the IP- and LP- steam turbine. This extraction can be partially switched to the cold reheat steam line (1) to increase the pressure of the extraction steam, if and when necessary.

14.3 STEAM TURBINE MODIFICATIONS

Large amount of heat required for solvent regeneration necessitates modifications to the standard steam turbine design. For 90% CO_2 separation about 25-30% of the live steam flow or approximately 60% of the exhaust steam flow has to be extracted. Depending on the steam extraction arrangement at the steam turbine, the following design considerations are required.

Regardless of whether the steam is extracted from the crossover line between IP- and LP- steam turbines, the reheat steam lines or both, the blades of the HP- and IP-turbine must be designed for the increased pressure/enthalpy drop across all stages. The casted outer casing of the IP- turbine must be designed according to the increased mass flow of the steam extraction for the CO_2 Capture and Compression process. The LP turbine must be able to accommodate large flow variations due to the process steam extractions (in some cases, the steam turbine will also have to be able to continue operation with no process steam extractions, when the CCS is not in operation.) The length of the last stage blades (LSB) of the LP- turbines must be optimized according to the new exhaust steam flow requirement (which is less with CO_2 Capture and Storage). Operation with CO_2 Capture and Compression will require shorter LSBs to avoid excessive exhaust losses due to ventilation and low load operation. Optionally a crossover valve between the IP- and LP-turbines can be used to reach the required steam pressure for the supply of the heat quantity for the CCS process. The crossover valve maintains a constant steam pressure on IP- turbine outlet and the extraction stub, which would minimize the modifications required for HP and IP turbine design. However, the crossover valve itself creates its own design challenges that need to be considered. Moreover, throttling losses of the crossover valve will decrease the cycle efficiency.

The above mentioned design requirements can be considered in the planning phase for new power plants. In case of existing plants, the required modifications at the steam turbine for the steam extraction can be executed with a turbine retrofit.

14.4 IMPACT ON NET PLANT EFFICIENCY

Figure 14-3 shows a comparison of the net plant efficiencies without and with CO_2 Capture and Compression, using MEA and H3-1 solvents for retrofitting an 800 MWe supercritical power plant (600°C/1112°F main steam temperature). The reference plant without CO_2 Capture and Compression has a net plant efficiency of 46.9%LHV. With an MEA-based conventional CO_2 Capture plant, the total efficiency penalty is 15.9% points. With the advanced integration approach described above, this loss of net efficiency is reduced to only 7.8% points for H3-1 based process and 7.5% points for an optimized process based on next generation solvent (NGS) with regeneration energy of 2500 kJ/kgCO_2 (including CO_2 compression to 200 bar / 2900 psia). As part of Phase 2 work of the proposed slipstream demonstration plant at the WCEV facility, a conceptual design study for retrofitting the entire flue gas stream with CO_2 Capture and Compression will be performed to define the optimum system integration for the 300 MWe power train.

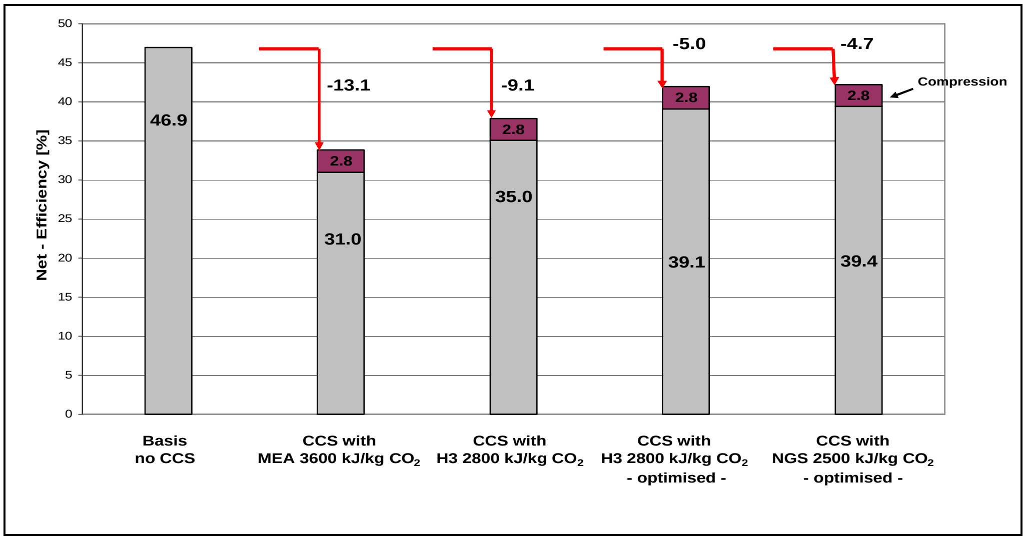


Figure 14-3: Influence of CCS Plant on Overall Net Efficiency with 90% CO_2 Removal

15 CONCLUSIONS

The Wolverine Carbon Capture and Storage Project preliminary design has been sized to produce 1,000 metric tons per day of CO_2 for subsequent compression, transportation and injection for EOR and/or geologic Storage operations. Specifically, the WCCS Project will employ a CO_2 capture system using Hitachi's advanced amine-based solvent technology to capture and sequester 90% of the CO_2 from the treated flue gas stream. The WCCS project will remove 300,000 metric tons per year of CO2 from the flue gas from the Wolverine Clean Energy Venture (WCEV) Unit 1 (300 MW CFB Boiler) ID Fan outlet flue. The concept will be the first ever CO_2 capture process integrated with low emission Circulated Fluidized Bed technology.

The host to the CO_2 capture and compression system is the WCEV project. The WCEV project is a 600 MW clean coal plant near Rogers City, Michigan, with two (2) subcritical 300 MW CFB boilers feeding two (2) 300 MW steam turbines. Based in Rogers City, Michigan, the WCEV plant is designed as a low emissions base load plant to serve Michigan. The WCEV project is located within the limits of an active limestone quarry southeast of Rogers City, Michigan in Presque Isle County.

The Hitachi post-combustion CO_2 capture concept is designed to achieve 90% capture with large cost savings and efficiency improvement over current amine scrubbing technologies. Capture system steam consumption is improved by roughly 30% when operated with the Hitachi solvent as compared to commercial solvents. A testing plan has been developed to confirm this performance improvement and associated reduction in operational costs during the demonstration period of the project. Hitachi developed details of the mechanical, structural, electrical, instrumentation and controls aspects of the CO_2 capture island, and worked with Wolverine and BREI to integrate with the balance of the plant. Various energy optimization concepts and utility requirements, for the integration of the CCS system with the power station, were developed along with CO_2 compression as a joint effort with BREI.

The host to the CO_2 Storage site is Core Energy. Core Energy currently owns and operates a significant CO_2 EOR infrastructure in the vicinity to the site. This infrastructure provides a great deal of flexibility as to where the CO_2 can be delivered for the primary purpose of EOR and the secondary purpose of deep saline aquifer Storage. CO_2 storage capacities and recoverable oil reserves have been quantified by Western Michigan University to document the geological potential for expanded Storage in the project area. Since the project period is constrained by the timeline set forth in the Recovery Act, the demonstration period must conclude after slightly more than a year of operation. Due to the small volume of CO_2 that will be injected during the project period, the primary destination for CO_2 will be Enhanced Oil Recovery targets. As time progresses well beyond the demonstration period and if the CO_2 capture capacity at the plant is expanded, there is ample capacity in the Bois Blanc Formation and the St. Peter Sandstone to support the CO_2 volumes generated from the Power Plant.

A conceptual design and cost estimate was developed for the advanced CO_2 capture and compression concept, CO_2 pipeline and CO_2 storage to support development of the project. A CO_2 storage injection, monitoring, verification and accounting plan has been developed to measure and document the CO_2 that is sequestered during the injection period. The plan incorporates baseline evaluation of the storage site(s), monitoring of ongoing injection operations and accounting of fluids injected over the project period. The commercial demonstration will document the movement of CO_2 in the geologic formations to support future growth in this emerging field.

Core Energy, in collaboration with FTCH has identified a preferred 54± mile CO_2 pipeline route to transport the CO_2 from the proposed CO_2 capture project to the storage site. This pipeline follows an existing pipeline corridor, which greatly improves the probability for obtaining the rights of way required for pipeline construction. A conceptual design of this pipeline has been developed and cost estimates were developed to support project budget and schedule.

An "Environmental Information Volume" (EIV) was prepared to provide information regarding the environmental aspects of the proposed Wolverine Carbon Capture and Storage Project to identify and plan for all of the necessary permits required for the Project.

A project capital cost estimate was developed. Working with various US manufacturers, Hitachi obtained design and price estimates of major common components, including vessel packing and its auxiliaries, reboiler, heat exchangers, tanks, pumps, instruments, and control equipment. Material quantity takeoffs and installation labor was estimated from conceptual design drawings that were developed for that purpose. Cost estimates for the design and supply of the CO_2 capture island were developed and integrated with the overall Project estimate. An operation and maintenance cost estimate for the project was developed. The cost estimate includes the cost of fixed and variable operation costs for the plant and has taken into consideration that the plant is proposed as a demonstration facility for the first year.

A project teaming structure has been developed to support the implementation of this project. If implemented, the project will support the development of new technology, a growth in public confidence in CO_2 transportation and storage and specifically, the expansion of Enhanced Oil Recovery operations in Michigan. In addition, this project may be used as a building block for further CO_2 capture, compression, transportation and Storage projects.

16 ACKNOWLEDGEMENTS

The Wolverine CCS Project team is grateful for the opportunity and funding provided by US DOE to participate in the Phase I study of the CCS project. Wolverine acknowledges the contributions of the team members who have contributed to the project and for providing significant input to this report.

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17 REFERENCES

1. Chapel, D. G.; Mariz, C. L. and Ernest, J. Recovery of CO2 from Flue Gases: Commercial Trends. 1999. Presented at the Canadian Society of Chemical Engineers annual meeting October 4-6, Saskatchewan, Canada

2. Yeh, J. T; Pennline, H. W.; Resnik, K. P. and Rygle, K. Absorption and Regeneration Studies for CO2 Capture by Aqueous Ammonia. 2004. Presentation at the Third Annual Conference on Carbon Capture & Storage May 3-6, Alexandria, VA

3. Zare Aliabadi, Hassan, Mirzaei, Somaye. Using Mixed Amine Solution for Gas Sweetening. 2009. World Academy of Science, Engineering and Technology, Issue 58.

Appendix A

List of Acronyms and Abbreviations

AQCS	Air Quality Control System
BREI	Burns and Roe Enterprises Incorporated
CCS	Carbon Capture and Storage
CE	Core Energy
CER	Clean Energy Recuperator
CFB	Circulating Fluidzed Bed
CO_2	Carbon Dioxide
EERC	Energy and Environmental Research Center
EIV	Environmental Information Volume
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
FGD	Flue Gas Desulfurization
FTCH	Fishbeck Thompson Carr and Huber
GGH	Gas-Gas-Heater
MDEA	Methyl Diethanolamine
MEA	Monoethanolamine
MMP	Minimum Miscibility Pressure
MMSCFD	Million Standard Cubic Feet Per Day
MRCSP	Midwest Regional Carbon Storage Partnership
MTD	Metric Tonnes per Day
MVA	Monitoring Verification and Accounting
NETL	National Energy Technology Laboratory
ROW	Right of Way
SDA	Spray Dryer Absorber
SNCR	Selective Non Catalytic Reduction
U.S. DOE	United States Department of Energy
UIC	Underground Injection Control
WCCS	Wolverine Carbon Capture and Storage Project
WCEV	Wolverine Clean Energy Venture
WMU	Western Michigan University