NRG CO_2NCEPT - CONFIRMATION OF NOVEL COST-EFFECTIVE EMERGING POST-COMBUSTION TECHNOLOGY

DE-FE0026581 Final Technical Report

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DISCLAIMER

1 Acronyms and Abbreviations

AACEi	Association for the Advancement of Cost Engineering International
ADSIM	Aspen Adsorption
BACT	best available control technology
BC	British Columbia
BDTR	bed durability test rig
BEC	bare erected cost
BFD	block flow diagram
BFW	boiler feed water
BOP	balance of plant
CAMR	Clean Air Mercury Rule
CCF	capital charge factor
CCP	CO_2 capture plant
CCS	carbon capture system
CCUS	carbon capture, utilization, and sequestration
CF	capacity factor
CFD	computational fluid dynamics
CFG	coal flue gas
CL	closed-loop
CO_2	carbon dioxide
CO_2NCEPT	Confirmation of Novel Cost-effective Emerging Post-combustion Technology
COA	chart/code of accounts
COE	cost of electricity
CPR	cycles per revolution
CTE	critical technology element
CWP	cooling water pump
CWS	cooling water system
DBM	design basis memorandum
DCC	direct-contact cooler
DCS	Distributed Control System
DOE	U.S. Department of Energy
DSTS	dynamic seal test station
EAF	equivalent availability factor
EFOR	equivalent forced outage rate
EH&S	environment, health, & safety
EPA	Environmental Protection Agency
EPC	engineering procurement & construction
EPCM	engineering procurement and construction management
Etc.	Etcetera
FD	forced draft
FEED	front-end engineering design
FGD/WFGD	Flue Gas Desulfurizer (Wet FGD)
FOA	Funding Opportunity Announcement 0001190
FOAK	first of a kind
FW	feed water
gpm	gallons per minute
GSU	generator step-up transformer
H&MB	heat and material balance
HEX	heat exchanger
HHV	higher heating value
HP	high pressure
HRG	high resistance grounding
HSE	health, safety, and environmental
HVAC	heating, ventilating, and air conditioning
ID	inside diameter
IGCC	integrated gasification combined cycle
IOU	investor owned utility
IP	intermediate pressure
IPP	independent power producer
kW	kilowatt
kWh	kilowatt-hour
LAER	Lowest Achievable Emissions Rate
LBDTR	Large Bed Durability Test Rig
LHV	Lower Heating Value
LNB	Low NOx Burners
LP	Low Pressure
LTP	long-term plan
MATS	Mercury and Air Toxic Standards
MCC	motor control center
MRC	Merit Review Criteria
MT	Metric Tonne
MW	megawatt
MWe	megawatt equivalent
MWh	megawatt-hour

N_2	nitrogen gas
NETL	National Energy Technology Laboratory
NEPA	National Environmental Policy Act
NGCC	Natural Gas Combined Cycle
NO_x	oxides of nitrogen
NRG	NRG Energy Inc.
NSPS	New Source Performance Standards
NSR	New Source Review
O&M	operations and maintenance
OD	outside diameter
OE	Owner's Engineer
OEM	original equipment manufacturer
OSHA	Occupational Health & Safety Administration
P&ID	piping and instrumentation drawing/diagram
Parish	NRG's WA Parish Generation Station
PC	Pulverized Coal
PDC	Power Distribution Centers
PDU	Process Demonstration Unit
PFD	process flow diagram
PLC	programmable logic controller
PM	Particulate Matter
PMP	Project Management Plan
PRB	Powder River Basin
PRV	pressure reducing valve
psia	pounds per square inch absolute
PSD	Prevention of Significant Deterioration
PV	product of contact pressure and linear surface velocity
PVC	polyvinyl chloride
QGESS	Quality Guidelines for Energy Systems Studies
R&D	research and development
R,D&D	research, development, & demonstration
RAM	rotary adsorption machine
SC	Supercritical
SCR	Selective Catalytic Reduction
SLPM	standard liter per minute
SO_2	sulfur dioxide
SOA	State of the Art
SOPO	statement of project objectives
SO_x	oxides of sulfur
TASC	Total As Spent Cost
TEA	techno-economic analysis
TEG	Triethylene Glycol
TOC	Total Overnight Cost
TPC	Total Plant Cost
tpd	References in this report to tpd are to be interpreted as metric tonnes per day
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
TSA	thermal swing adsorption
TX	Texas
U.S.	United States
VFD	Variable Frequency Drive
VPP	OSHA's Voluntary Protection Program
VTS	VeloxoTherm™ Test Station
WACC	weighted average cost of capital
WAP	W.A. Parish
WBS	Work Breakdown Structure

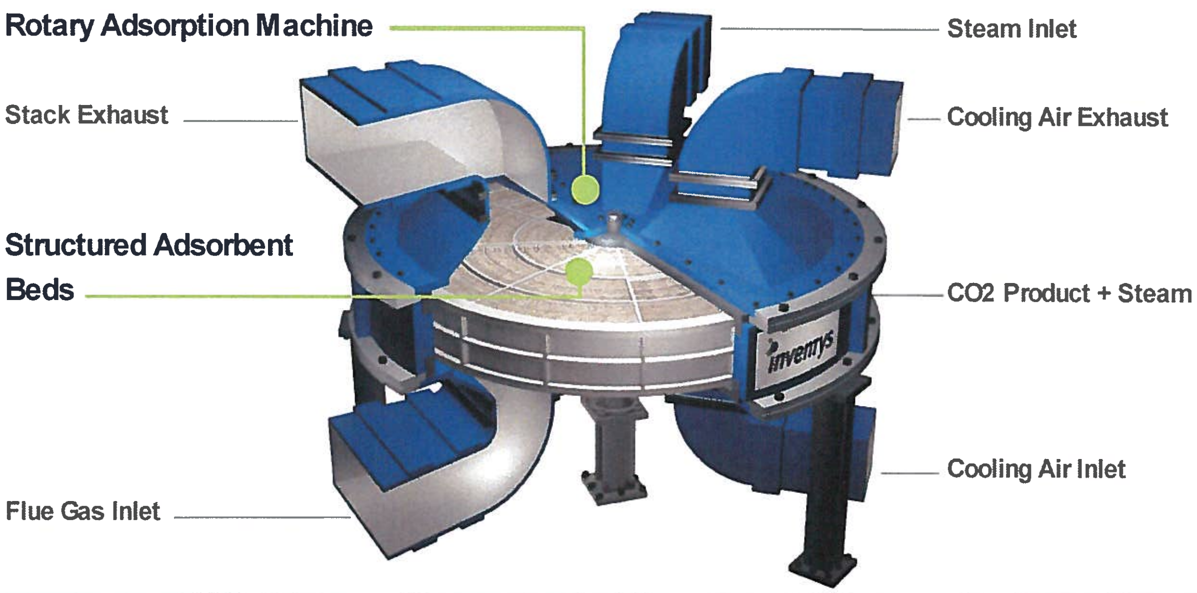
2 Table of Contents

2.1 List of Exhibits

3 Executive Summary

NRG Energy (NRG), as prime recipient, and Inventys as sub-recipient applied for Department of Energy's (DOE's) solicitation DE-FOA-0001190 (the "Solicitation") to develop a Large-Scale Pilot post-combustion CO_2 capture project. The proposed project, titled Confirmation Of Novel Cost-effective Emerging Post-combustion Technology or "CO_2NCEPT", was designed to demonstrate Inventys' VeloxoTherm™ carbon capture technology on a 10 Megawatt equivalent (MWe) or greater slipstream of coal flue gas at one of NRG's Gulf Coast generating stations. VeloxoTherm™ is an adsorption-based technology developed by Inventys. It is comprised of an intensified thermal swing adsorption (TSA) process that uses a patented architecture of structured adsorbent and a novel process design and embodiment to capture CO_2 from industrial flue gas streams. Structured adsorbents possess unique physical and transport properties which serve to greatly improve the performance of gas separation, enabling fast cycle times and small equipment sizes that can deliver attractive capture economics. Exhibit 3-1 provides a simplified graphical representation of a rotary adsorption machine (RAM) concept which lies at the core of the VeloxoTherm™ technology – containing the structured adsorbent and carrying out the rapid cycle TSA process.

Exhibit 3-1: Graphical Representation of VeloxoTherm™ Rotary Adsorption Machine (illustrative only)



Under the award FE0026581 (the "Award"), NRG, with Inventys as sub-recipient, were selected for the performance of tasks and activities related to Phase 1 of the Solicitation, including the development of key deliverables such as:

- The performance of a front-end engineering and design (FEED) study for the Large-Scale Pilot project to arrive at a robust project baseline for the CO_2NCEPT project, including design basis, preliminary design, budget, schedule, and execution plan;
- The development of a technology design and economic analysis report, which presents the results of a techno-economic analysis (TEA) on the VeloxoTherm™ technology as applied in a Full Scale Commercial plant as part of a greenfield ~550 MWe-net supercritical puliverized coal (PC) power-generation facility (the "Phase 1 TEA"); and,
- A comprehensive technology gap analysis ("Phase 1 Gap Analysis") which addresses the current stage of development of the VeloxoTherm™ technology and summarizes the research, development & demonstration, (R,D&D) requirements to close any gaps which exist before full-scale commercial deployment.

The results and conclusions of the analysis and design work completed under the Award significantly helped NRG and Inventys assess and determine the technical, commercial, and economical feasibility of retrofitting the Inventys VeloxoTherm™ post-combustion technology to a coal plant. The numerous design and integration alternatives explored during these studies aided in the refinement of the scope and approach presented herein. These design considerations and recommendations combined with the development of the overall technical specifications, design basis, material balances, equipment lists, utility requirements, process flow diagrams, piping and instrumentation diagrams (P&IDs), and other preliminary engineering deliverables provided a reasonable foundation to obtain equipment bids and generate the conceptual capital cost estimate.

Although this body of work increased confidence around the feasibility and capital cost of the carbon capture system itself, it was concluded that additional work still needs to be completed in various areas of the program before this program could move into Phase 2 (the execution phase of the project) . The modeling work that accompanied the conceptual design efforts during Phase 1 provided indications that the techno-economic targets established by the DOE Funding Opportunity Announcement (FOA) were at risk with the original sorbent material selected for the program, and as a result, NRG and Inventys have determined that the appropriate next steps included additional work around adsorbent selection can work toward the expected step-change in economics and Technology Readiness Level (TRL) this FOA implies.

4 Introduction

To break down the barriers to widespread adoption of carbon capture and to progress towards the DOE's programmatic carbon capture goals, NRG, as prime recipient, and Inventys as sub-recipient applied for DOE solicitation DE-FOA-0001190 (the "Solicitation") to develop a Large-Scale Pilot post-combustion CO_2 capture project. The proposed project, entitled **C**onfirmation **O**f **N**ovel **C**ost-effective **E**merging **P**ost-combustion **T**echnology or "CO_2NCEPT", was designed to demonstrate Inventys' VeloxoTherm™ carbon capture technology on a 10 Megawatt equivalent (MWe) or greater slipstream of coal flue gas atone of NRG's Gulf Coast coal-fired generating stations. VeloxoTherm™ is an adsorption-based technology developed by Inventys. It is comprised of an intensified TSA process that uses a patented architecture of structured adsorbent and a novel process design and embodiment to capture CO_2 from industrial flue gas streams. Structured adsorbents possess unique physical and transport properties which serve to greatly improve the performance of gas separation, enabling fast cycle times and small equipment sizes that deliver attractive capture economics within the VeloxoTherm™ System.

The Solicitation was structured to be performed in two phases, with a detailed application and competitive down select process to proceed from Phase 1 to Phase 2. Under award FE0026581, NRG, with Inventys as sub-recipient, were selected for the performance of tasks and activities to produce the Phase 1 deliverables as required by the Phase 1 statement of project objectives (SOPO). Phase 1 work consisted generally of the development of a design approach and execution plan for Phase 2, including environmental, health and safety risk assessment, the preparation of permit applications and preliminary identification National Environmental Policy Act (NEPA) requirements. The majority of the feasibility and technical analysis for the application of Inventy's technology to coal-fired power generation were captured in three deliverables:

- The performance of a front-end engineering and design (FEED) study for the Large-Scale Pilot project to arrive at a robust project baseline for the CO_2NCEPT project, including design basis, preliminary design, budget, schedule, and execution plan;
- The development of a technology design and economic analysis report, which presents the results of a techno-economic analysis (TEA) on the VeloxoTherm™ technology as applied in a Full Scale Commercial plant as part of a greenfield 550 MWe-net supercritical PC power-generation facility (the "Phase 1 TEA"); and,
- A comprehensive technology gap analysis ("Phase 1 Gap Analysis") which addresses the current stage of development of the VeloxoTherm™ technology and summarizes the R,D&D requirements to close any gaps which may exist before full-scale commercial deployment.

This final scientific and technical report under award FE0026581 presents the results of the work performed for Phase 1, and in particular the conclusions of the design, development and feasibility analysis performed per the FEED work for the large scale pilot, the Phase 1 TEA and the Phase 1 Gap Analysis.

4.1 Objectives, Goals, Expected Results

The overall objective of NRG's CO_2NCEPT Demonstration Project was to establish the scalability, the technical feasibility, and economic viability of Inventys' VeloxoTherm™ post-combustion capture process when applied to a coal-fired boiler flue gas slipstream. The project was to be performed at a scale sufficient to demonstrate commercial readiness of the technology and to accelerate the adoption of post-combustion CO_2 capture technology to the existing coal-fired generation fleet in the U.S.

Specific objectives were as follows:

- Successfully demonstrate a post-combustion capture technology on coal flue gas that achieves 90% CO_2 capture efficiency at a large scale MWe size (10MWe or greater).
- Validate that the CO_2 produced has a purity greater than 95% or identify additional solutions to obtain 95% purity using the Inventys VeloxoTherm™ post combustion carbon capture system.
- Confirm the cost of capture for the Inventys VeloxoTherm™ post combustion carbon capture system which could make step-function progress toward the goal of $40/tonne by 2025.
- Establish the impact of CO_2 capture on the Cost of Electricity (COE) which the project team expects could make a significant move toward the 30% decrease from baseline CO_2 Capture approaches by 2030.

The project was intended to be executed in two phases with a competitive down select to continue from Phase 1 into Phase 2. Each phase represents a distinct aspect of the project execution. The project phases are:

- **Phase 1**: Project Definition / Front End Engineering Design ("FEED") – The objectives of Phase 1 are to develop a design approach and execution plan for Phase 2, and to provide sufficient techno-economic analysis in a Technology Engineering Design and Economic Analysis Report with supporting models and Technical Gap Analysis Report.
- **Phase 2**: Project Life Cycle – The objectives of Phase 2 are to execute the full project through its full life cycle including permitting, design, construction, operation and maintenance, and decommissioning.

5 Technology Overview

5.1 The VeloxoTherm™ Process

VeloxoTherm™ is an adsorption-based technology developed by Inventys. It is comprised of an intensified TSA process that uses a patented architecture of structured adsorbent, novel process design and embodiment to capture CO_2 from industrial flue gas streams. Inventys' in-house developed structured adsorbents are based on a parallel plate contactor design and possess unique physical and transport properties. These properties can serve to greatly improve the performance of gas separation relative to other approaches by enabling fast-cycle times and comparatively small equipment sizes with the VeloxoTherm™ System.

Solid adsorbents, including those applying physisorption, have critical advantages over liquid solvents and other post-combustion capture technologies which can result in lower operating costs due to their relative regeneration energies and a lack of solvent consumption. Solid adsorbents can be made of benign materials, which do not generate waste by-products or fugitive emissions and do not pose significant environmental, health or safety risks.

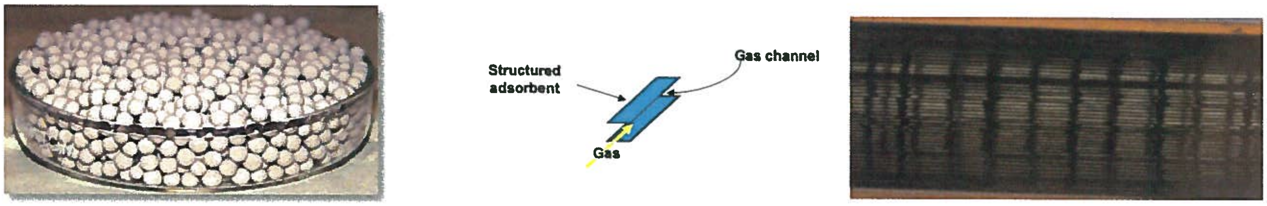
Sorption-based separation processes can be intensified (made to be smaller and more efficient) by increasing the adsorption, regeneration, and desorption frequency of the process. The VeloxoTherm™ Process achieves this intensification, along with the advantages in capture economics, through three key innovations:

1. The use of patented structured adsorbents, as opposed to packed beds;
2. A patented sophisticated TSA cycle; and,
3. Adaptation of proven industrial hardware into a novel rotary embodiment that enables the sophisticated TSA cycle and leverages the properties of structured adsorbents for a compact cost-effective piece of equipment.

5.1.1 Structured Adsorbents

Structured sorbents—sorbents that are organized in a parallel array of flow passages with spacing between the adsorbent layers and a prescribed wall thickness—strike a favorable balance between hydraulic and transport properties in gas separation processes. The hydrodynamic behavior of structured adsorbents follows a linear relationship to superficial gas velocity, resulting in significantly lower pressure loss penalties as compared to packed beds. This relationship is a result of the gas flow regime operating in a laminar condition. Although laminar flow would typically result in a low mass transport coefficient, the short diffusion path length of the structured adsorbent more than compensates for this effect. Exhibit 5-1 highlights a comparison between beaded systems and the VeloxoTherm™ structured adsorbents.

Exhibit 5-1: Granular vs Structured Adsorbents



(Left) Granules of adsorbent, which are normally found in sorption-based gas separation processes. The material in this image has a diameter of approximately 3.5 mm. (Center) Representation of a gas-flow path in a parallel-plate contactor. (Right) Close-up view of the VeloxoTherm™ structured adsorbent.

While the transport properties of granular adsorbents can be improved with smaller diameter granules to achieve a similar short diffusion path length, this is not a practical solution due to fluidization limits. Fluidization in packed bed systems is an operating condition wherein the pressure drop force across the packed bed is equivalent to the downward force of the mass of adsorbent resulting in suspension or entrainment of the granule particles in the gas stream. This is the main cause of process and mechanical failure for packed beds since fluidization results in the relative motion and impact of individual granules causing attrition and the breakdown of the granules themselves. Also, fluidized beds are well known to operate in a homogenous fashion (temperature, concentrations, etc.) which is undesirable in gas separation. In contrast, with higher superficial velocities, structured adsorbents perform progressively better than the granular sorbents. Post-combustion CO_2 capture takes place in high superficial gas velocity environments due to the flue gases having extremely large volume and low pressures. It is in this region of high superficial gas velocities that structured adsorbents demonstrate their superiority and make them well-suited for post-combustion CO_2 capture.

Structured adsorbents are at the core of the VeloxoTherm™ technology, where their advantages related to hydrodynamics, specific surface area, and mass and heat transfer rates enable process intensification. More specifically, the advantages of using structured adsorbents for the separation of low pressure dilute gases can be summarized to include:

- Depending on the selected adsorbent, the ability to use physisorption (van der Waals force) with a solid adsorbent, as opposed to liquid solvents utilizing chemisorption (chemical bonding). Typical binding energy of physisorption is about 0.01–0.1 eV, where chemisorption usually forms bonds with energy of 1–10 eV. Therefore, physisorption significantly lowers regeneration energy and can result in a reduction in operating expenses.
- The application of solid adsorbent materials which are benign and inert, do not generate toxic or corrosive waste by-products, fugitive emissions or have any significant environmental, health or safety impacts.
- Technology, including rapid cycle regeneration, can be more robust in the presence of contaminants (elevated levels of NO_x, and SO_x and particulate matter) relative to chemical solvents; potentially reducing the need for expensive flue gas pre-treatment typical for State of the Art (SOA) systems.
- Leveraging the critical advantages of structured adsorbents enables process intensification, allowing for smaller, less expensive equipment.
- Very low-pressure drop; one to two orders of magnitude lower than that of conventional packed-bed systems.
- Immobilized adsorbent with no fluidization or attrition.
- High geometrical (surface) areas per reactor volume, typically 1.5 to 4 times more than in reactors with granular material.
- High mass and heat transfer efficiency and kinetics due to very short diffusion paths within the structured materials.
- De-coupled mechanical and separation properties of adsorbent, allowing for a more durable structure with optimized adsorption characteristics.
- Engineered thermal properties, including anisotropic heat transfer properties—resistance to heat transfer in the radial direction being substantially greater than the resistance to heat transfer in the axial (gas flow path) direction in the adsorbent structure.
- Very strong performance in adsorption processes in which selectivity (the affinity of the adsorbent for one gas species over another) is impaired by mass-transfer resistances;

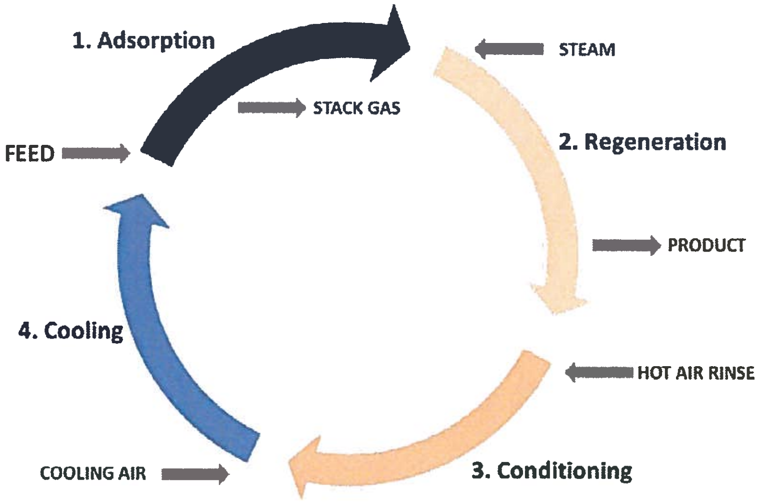
5.1.2 TSA Cycle

To take advantage of the low regeneration energies of using solid sorbents, as well as the tailored hydrodynamic, heat and mass transfer, and mechanical properties of structured adsorbents, an optimized TSA cycle is required. To manage temperature and moisture levels, and minimize energy losses often associated with the thermal-swing cycle sometimes requires more steps beyond the basic adsorption and desorption phases of TSA.

Inventys has developed a TSA cycle for both natural gas and coal flue gas applications and tested this cycle using an engineering-scale pilot on natural gas boilers, coal-fired heaters, and in the field on a coal-fired power plant flue gas slipstream.

The streams associated with the general TSA cycle are illustrated in Exhibit 5-2 where the steam, hot air rinse, and cooling air steps take advantage of the thermal and adsorption properties of the VeloxoTherm™ structured adsorbent to optimize overall energy consumption of the process.

Exhibit 5-2: VeloxoTherm™ Process Cycle Schematic



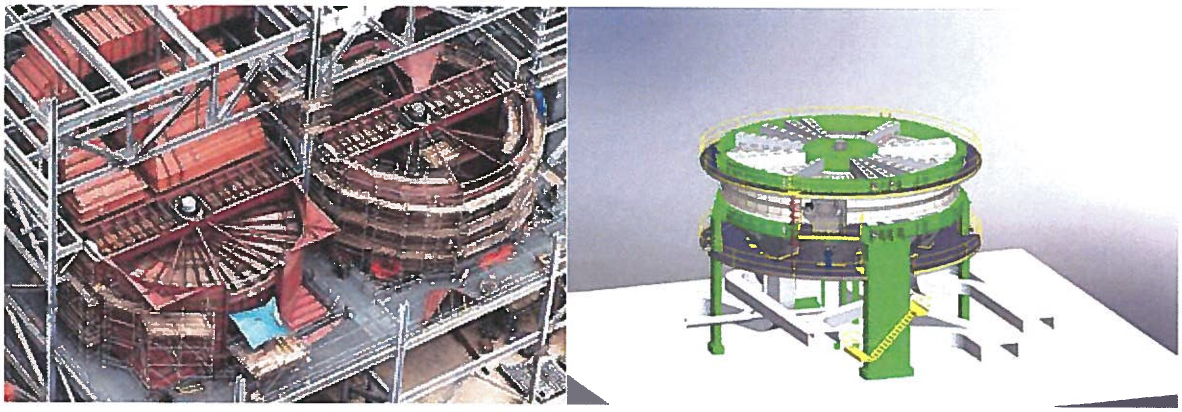
- **Adsorption:** In the Adsorption step, flue gas, in some cases cooled by a direct-contact cooler (DCC), enters the structured adsorbent beds as the feed stream. Stack gas (primarily nitrogen, water vapor) exits the beds, while CO_2 is adsorbed by the structured adsorbent.
- **Regeneration:** After the beds have become "occupied" by CO_2 during the Adsorption step, they rotate to the Regeneration step where low-pressure steam is used to release the CO_2 from the adsorbent, producing a CO_2 product stream of water vapor and CO_2 which can be cooled to knock-out the water and recover a purified CO_2 product.
- **Conditioning:** After steam is used to push out the product stream (Regeneration), a stream of hot air is used to remove any residual water vapor from the adsorbent beds.
- **Cooling:** The last step of the process before the cycle repeats is the Cooling step, where ambient air is used to cool the adsorbent to the optimal temperature for CO_2 adsorption during the next step – **Adsorption**.

5.1.3 Mechanical Embodiment

The core of the process is contained within Inventys' rotary adsorption machine (RAM), which is based on the same mechanical systems found in rotary heat exchangers commonly used in coal-fired plants and operating at the same scale and conditions as in the VeloxoTherm™ process would be. In pulverized coal-fired power plants, rotary heat exchangers are used to recover heat from the boiler flue gas before it's released to the environment. In these preheaters, heat energy is transferred from the hot flue gas to the incoming combustion air by a matrix of heating elements that populate the rotor and act as the medium of heat transfer in the process. The rotor continuously moves the hot elements from the hot flue gas stream into the incoming combustion air. In the VeloxoTherm™ system design, instead of the matrix of heating elements that populate a typical rotary heat exchanger, arrays of the VeloxoTherm™ structured adsorbent beds are used. These beds are then rotated through the different steps of the cyclic TSA process, including flue gas inlet and CO_2 adsorption, steam regeneration with CO_2 production, and adsorbent conditioning.

The TSA cycle based on the primary steps shown in Exhibit 5-2 is implemented in a RAM, the design of which is adapted from rotary air preheaters. Exhibit 5-3 shows a conventional rotary air preheater as implemented in coal-fired power plants, next to the design of the RAM for the Large Scale Pilot considered for this project.

Exhibit 5-3: Rotary Air Preheater (left) vs Rotary Adsorption Machine (right)



The process entails the introduction of flue gas into the RAM, where the CO_2 is adsorbed on to the surface of the structured Adsorbent Beds while the remainder of the flue gas vents to the stack. The CO_2-rich adsorbent then rotates to a sector of the RAM where low-grade steam flows through the Adsorbent Bed releasing a stream of primarily CO_2 and steam. This product stream is then cooled and H_2O is recovered leaving a purified CO_2 product. After steam regeneration, the bed rotates through a sector where hot air removes any remaining moisture and fresh air cools the bed to prepare for the adsorption step again.

The design of conventional rotary heat exchangers found in industry typically use gas sealing designs which do not have the performance characteristics required for the VeloxoTherm™ gas separation process. In the VeloxoTherm™ technology, the different stages of the RAM cycle are separated from each other and from the environment using proprietary seal designs that minimize inter-step leakage rates and maximize product purity. These seal designs represent a novel aspect of the technology, and the risks and technology gaps associated with them are described in Section 6.2.2.

5.2 Phase 1 Process Design for Coal Applications

Inventys' VeloxoTherm™ CO_2 capture technology is generally applicable to post-combustion flue gas sources, including coal fired power plants and natural gas-fired generation units. The process demonstration and testing completed thus far has been performed with the intent to de-risk the technology for multiple applications, including coal. Parallel to the Phase 1 feasibility and design efforts (but not within the scope of the Award), a field demonstration of a small prototype RAM was performed on a coal-fired power plant flue gas. The VeloxoTherm™ process cycle and adsorbent performance targets were refined during the Phase 1 performance period in order to optimize it around the targets of the design basis of the large scale pilot program and Phase 1 TEA using the methodology as outlined below. The achievement of the performance targets for the Large Scale Pilot and Full Scale Commercial RAM designs included identified technology gaps, which were also analyzed within the performance period of the Phase 1 Award.

5.2.1 Modeling Approach

The foundation of the VeloxoTherm™ process model is based on Aspen Adsorption (ADSIM), a finite element simulator developed for dynamic process modeling, process design/optimization, and performance prediction of gas adsorption processes. Aspen Adsorption is capable of simulating rigorous multi-physics adsorption providing simultaneous solutions to processes that involve momentum, heat, and mass transfer phenomena. Inventys-developed proprietary code and techniques were used to represent the unique aspects of the VeloxoTherm™ process within the process model. The VeloxoTherm™ process modeling approach consists of the following three stages:

A. **Preliminary Modeling and Verification:** The first stage involves setting up the process model in a single bed breakthrough configuration using the appropriate properties of the structured adsorbent bed. The outputs of the preliminary modeling are verified against the actual result from the single bed breakthrough test performed on VeloxoTherm™ Test Station (VTS).

B. **VeloxoTherm™ Process Modeling and Verification:** In the second stage of modeling work a dynamic separation process model is put together using the properties of the structured adsorbent bed from Stage 1 and a process cycle for efficient CO_2 capture. The model is then verified against the actual result from the single bed tests performed on the VTS.

C. **VeloxoTherm™ Performance Prediction:** The third stage and final stage involves using the verified model from the previous stage to predict the performance of the VeloxoTherm™ process.

The primary testing and verification tool for the development of the VeloxoTherm™ process is the VTS, a single bed adsorbent and process cycle performance evaluation test station. It can be programmed to perform various process cycles with complex sequences and is used for:

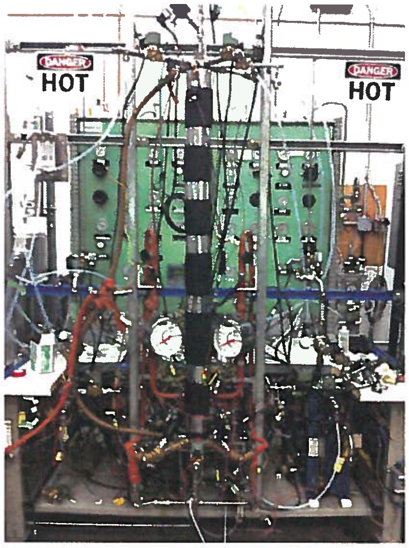
(a) Process cycle development: the test station is capable of performing various process cycle configurations and sequencing by programming the array of solenoids which are attached to the top and bottom bed manifolds and controlled by a programmable logic controller (PLC).

(b) Adsorbent material testing: VTS test station is used to perform pressure drop measurement across the adsorbent bed and adsorption breakthrough capacity tests.

Bed axial thermal profiles were collected to check model fidelity on energy balance. A gas compositions profile was obtained on bed manifolds to obtain mass balance and check model fidelity on mass balance. The test bed has a small mass and large surface area, hence very sensitive to heat loss. Therefore, the bed is insulated and jacketed to reduce heat loss from the bed to the environment. It was found that bed insulation itself is not sufficient to maintain the heat in the bed during the production step. Therefore, polycarbonate housing jacket was designed to surround the external casing of the bed to further reduce heat loss by minimizing the thermal gradient between the bed and its surrounding environment. The axial thermal gradient of the jacket is matched to the bed axial thermal profile to minimize the negative effects of heat loss on the performance of the adsorbent bed.

Large-Scale Pilot or Full-Scale Commercial RAMs will not require thermal jackets around the beds due to the larger thermal mass of the adsorbent beds compared to thermal mass of exposed bed walls.

Exhibit 5-4: VTS, VeloxoTherm^{TM} Test Station for in-house structure bed process testing



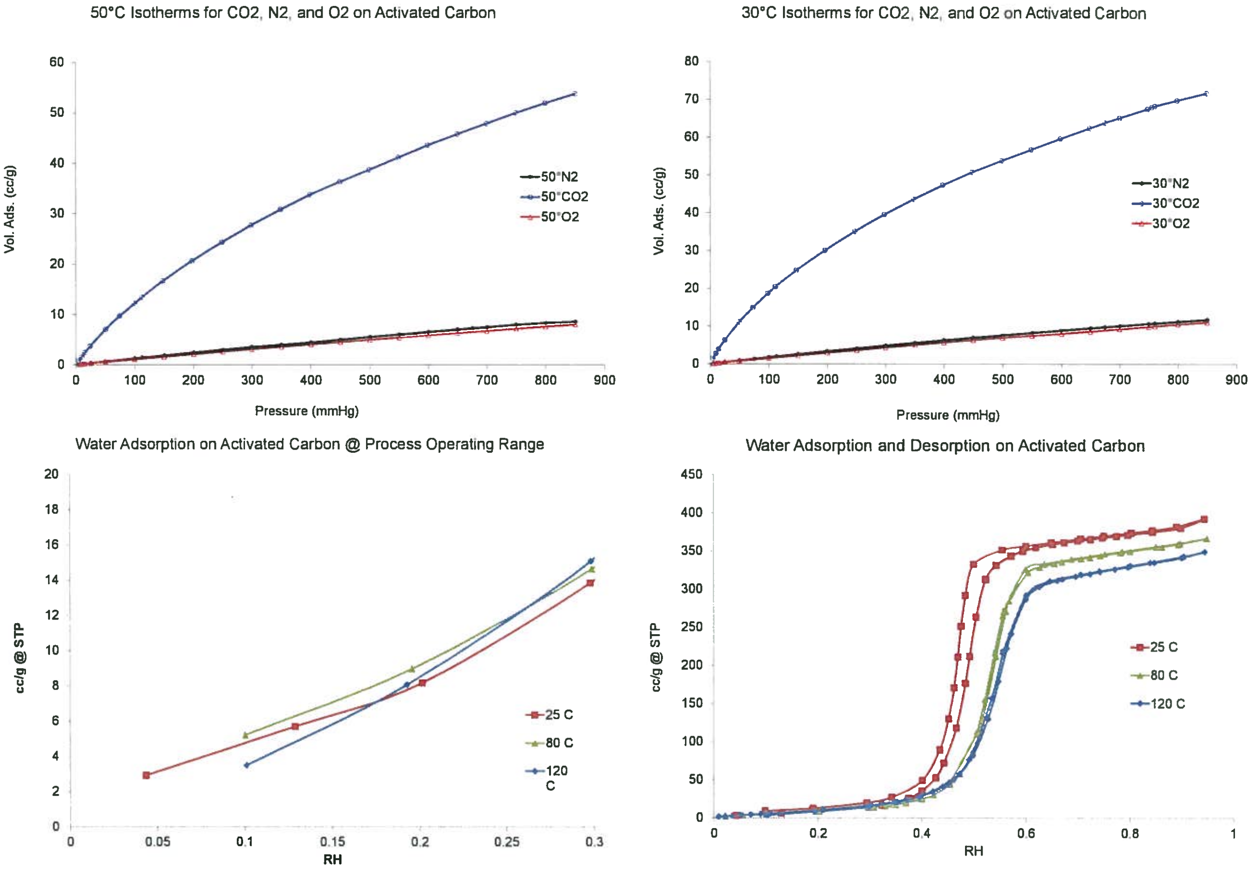
In the preliminary modeling stage, a single-bed breakthrough model was set up using the physical properties of the carbon structured adsorbent beds.

After inputting the adsorbent bed parameters, the model is set up with the cycle design and test bed parameters such as dead volume and estimated heat leakage. Amongst all these inputs in the list above, adsorption isotherm is the most important determining factor that defines the adsorption capacity and performance. Therefore, effort was spent on validating the adsorption isotherm with actual breakthrough bed capacity. For more information on Aspen Adsorption software please refer to training manual published by AspenTech: http://www.aspentech.com/products/aspen-adsim.aspx

5.2.1.1 Adsorption Equilibrium Isotherms

In adsorption processes, surface coverage of adsorbate is a function of adsorptive gas or vapor pressure. This dependency can be observed by collecting equilibrium data in the form of isotherms. This property determines the thermodynamic behavior in adsorption process. Isotherms represent measured adsorption capacity of the adsorbent as a function of gas phase partial pressure at constant temperature. Exhibit 5-5 shows the isotherm data for CO_2, N_2, O_2 and H_2O adsorption on activated carbon.

Exhibit 5-5: Isotherm of various temperatures for N_2, CO_2, O_2, and H_2O on activated carbon

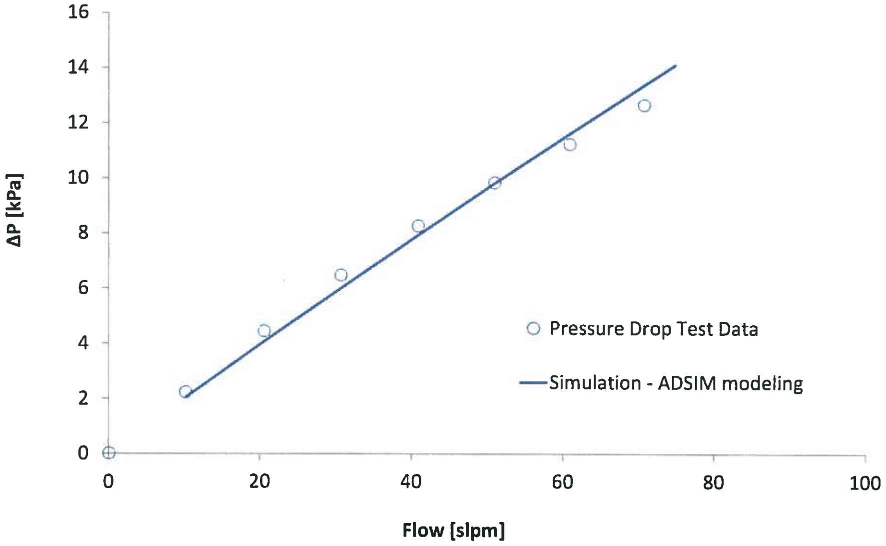


As illustrated above, the equilibrium of CO_2, N_2 and O_2 adsorption on activated carbon was measured at various temperatures of using the volumetric method in an automatic sorptometer, Micromeritics ASAP 2020, up to approximately atmospheric pressure. In general, adsorption capacity at equilibrium decreases with increasing temperature. Otherwise, the equilibrium of H_2O adsorption on activated carbon was measured at various temperatures using the gravimetric technique in a magnetic suspension microbalance, approximately up to saturation.

5.2.1.2 Bed Pressure Drop Model

Bed pressure drop data was collected by passing nitrogen through structured adsorbent bed at approximately 25°C and 15 pounds per square inch absolute (psia) over a flow range of 20 to 90 standard liter per minute (SLPM). The Darcy's law coefficient in the model was then tuned to match the bed pressure drop trend observed in the test.

Exhibit 5-6: Bed pressure drop data - testing vs modeling



5.2.1.3 *Breakthrough Process Modeling*

The adsorbent bed was pre-treated by passing hot nitrogen for about an hour, followed by cooling nitrogen at 25°C (77°F) until bed temperatures stabilized. Then the experimental breakthrough curves were obtained by passing a premade gas mixture at various flow rates through the structured adsorbent bed at approximately 30°C (86°F) and 15 psia. The breakthrough process was simulated at the same conditions as the test. Exhibit 5-7 shows the breakthrough test and simulation results for the adsorbent bed and Exhibit 5-8 shows the bed temperatures and simulation results at locations within the adsorbent bed along its length. A considerable thermal peak can be seen passing through the adsorbent bed.

Exhibit 5-7: CO_2 Breakthrough Test and Modeling Result

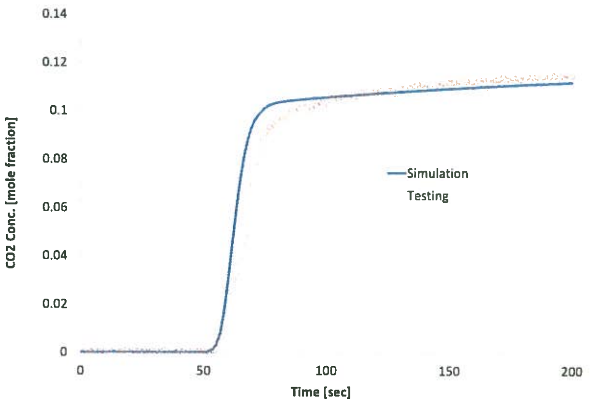
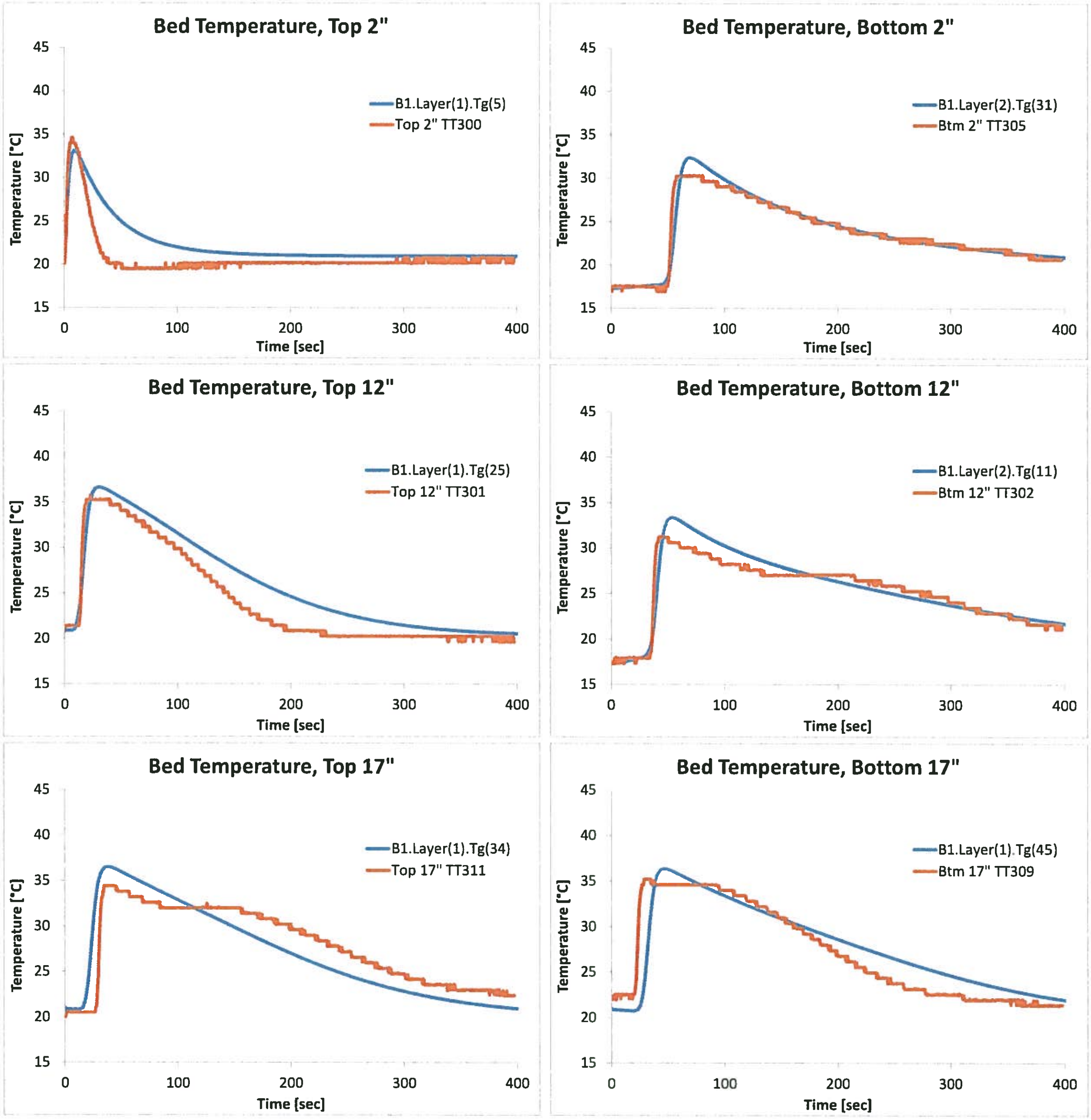


Exhibit 5-8: Breakthrough – testing vs. modeling for CO_2 concentration and bed axial temperature profile



Adsorption breakthrough results are a symmetrical "S" shape concentration profile for ideal processes with very small axial dispersion and very fast heat and mass transfer rates. The structured adsorbent is known to have very high mass transfer rate and very low dispersion coefficient. However, according to temperature measurements, the heat profile in adsorbent beds is not near isothermal during the breakthrough process. This is in accordance with experience that the heat of adsorption increases the bed temperature during the breakthrough test. In actual test conditions the heat transfer phenomenon follows a rigorous model. In other words, the temperature profile in the bed is not constant during the breakthrough process. The heat generated by the adsorption of CO_2 cannot exit the bed without raising the temperature of the adsorbent downstream. This transient axial thermal profile will cause lower adsorption capacity downstream due to higher local temperatures which skews the shape of breakthrough curve as seen in Exhibit 5-8.

The results confirmed the model follows similar trends in concentration and temperature response times. Despite the slight gap between the measured data and modeling results, which were related to process control challenges, measurement delay, and the distance between flow and pressure/temperature instruments, the models are considered predictive.

5.2.2 Performance Targets & Identified Gaps

The VeloxoTherm™ TSA cycle performance is measured through the use of key parameters that describe CO_2 product quality and impact the economic performance of the technology. These key performance metrics are:

- **Product Purity** – The VeloxoTherm™ process is capable of producing CO_2 purities of 95%+, however there are energy consumption and cost trade-offs. The DOE's target of 95% CO_2 purity in the product stream was adopted by Inventys in its design basis for both the Large Scale Pilot and Full Scale Commercial plants.
- **CO_2 Recovery** – CO_2 recovery can be optimized by incorporating feed recycle and reflux steps, although at the cost of incremental capital and operating expense. These steps allow for the process to be tuned to recycle CO_2 containing streams back into the process rather than discharge into the environment. In alignment with DOE programmatic goals, the overall CO_2 recovery target for the Large Scale Pilot and Full Scale Commercial cycles are 90%.
- **Productivity** – This performance metric is a measure of the amount of gas a system can process per unit control volume of active material in a specific amount of time. For the CO_2 capture system described the performance metric of interest is the tonnes of pure CO_2 product generated per day for every m^3 of adsorbent (TPD/m^3). Hence this defines the physical size of the CO_2 capture system for a desired amount of product flow or CO_2 removal and is directly related to the capital costs of the RAM.
- **Steam Ratio** – VeloxoTherm™ can use low energy steam in order to assist in the regeneration of the structured adsorbent beds and as a "sweep fluid" to assist in pushing the product CO_2 out of the bed's channels. By measuring the mass of steam required (at a given condition) per mass of CO_2 recovered as purified product, together with the condition of the steam, the energy consumption of cycle can be optimized;
- **Pressure drop**– The pressure drop characteristics of the structured adsorbent are an important measure of the momentum balance of the system and the fan energy required to drive the process.

In order to develop the performance targets for both the Large Scale Pilot (Phase 2 program) and the Full Scale Commercial design basis used in the Phase 1 TEA, a structured adsorbent bed was designed, fabricated and tested on the VTS using the coal flue gas conditions. An ADSIM dynamic simulation was done to validate the model and verify the performance of the process. The model was then used in conjunction with identified structured adsorbent bed development and cycle design targets to predict the targeted performance of the process for the purposes of the Phase 1 TEA. Exhibit 5-9 outlines the performance targets set for the design basis of the Phase 1 TEA (Full Scale Commercial) and the preliminary feasibility study for the Large Scale Pilot.

Exhibit 5-9: Predicted Performance

	Large Scale Pilot	Full Scale Commercial
Product CO_2% (dry)	95	95
Recovery [%]	90	90
Productivity [T/D/m^3]	5.0 [1]	5.0
Steam Ratio	1.5	1.14
Pressure Drop [kPa]	10	10
Bed density [kg/m3]	570	570
Void Fraction	0.39	0.39
Steam Pressure [kPa]	101	50
Regen Pressure [kPa absolute]	101	30

[1] Productivity of 3.5 was used during Phase 1 FEED activities to develop project baseline

In performing the process model development and optimization used to arrive at the targeted performance outlined in Exhibit 5-9 for coal flue gas applications, Inventys identified technology gaps between VTS tested bed performance and the targets. Exhibit 5-10 outlines the single bed data from VTS testing compared with the verified model prediction using ADSIM calibrated using the same.

Exhibit 5-10: Model Validated VTS Testing vs Predicted Performance

	Single Bed Data	Model Verification
Case	VTS Test	VTS Model
Product CO_2% (dry)	95	95
Recovery [%]	80	80
Productivity [T/D/m^3]	5.0	5.0
Steam Ratio	3.00	3.01
Pressure Drop [kPa]	10	10
Bed density [kg/m3]	275	275
Void Fraction	0.43	0.43
Steam Pressure [kPa]	101	98
Regen Pressure [kPa absolute]	60	60

Achieving the targets laid out for the Full Scale Commercial unit evaluated in the Phase 1 TEA and closing the performance gaps compared to the VTS test data outlined in Exhibit 5-10 was based on a strategy comprised of the following which are described further below:

- **Implementing a vacuum cycle:** The use of a vacuum relative to atmospheric on the product and reflux out steps, making the cycle a vacuum-assisted rapid cycle TSA process to reduce the steam ratio and improve other performance metrics.

- **Increasing the bed adsorbent density:** The initial structured adsorbent bed design bulk density was determined to be short by 40% relative to that estimated to be required for delivering specified performance in CO_2 recovery, productivity, and steam ratio.

Gap Closure: Vacuum Assisted TSA Cycle

A vacuum assisted rapid cycle temperature swing process cycle was developed for the coal application and particularly designed to take advantage of a recently developed hydrophobic version of carbon-based adsorbent from a supplier of adsorbents to Inventys. The cycle was designed specifically for coal flue gas temperatures consistent with the outlet of a wet flue gas desulphurization (FGD) and optimized with respect to levels of CO_2, N_2, O_2 and H_2O in the applicable design basis flue gas stream. The cycle was modeled on the ADSIM dynamic platform to obtain the duration for each step and an absolute pressure of 30 kPa on both reflux out and product streams was specified (approximately a 10 psig vacuum relative to a standard atmosphere). As a result, the steam steps (reflux out and product) happen at a lower pressure, reducing water adsorption, and preliminary modeling showed the ability for this strategy to reduce the steam ratio and move toward closing the performance gaps related to the process targets for the Phase 1 TEA (in concert with the increase in adsorbent bed bulk density discussed below). According to the ideal gas law, the drop in pressure also reduces steam temperature, thereby lowering the steam grade required from the power plant. The bed temperature has a peak temperature of 95°C (203°F) during steam steps compared to a previous value between 120-130°C (248- 266°F). The vacuum assisted TSA cycle also considered pressure equalization steps to minimize pressure losses and operating costs related to vacuum suction and gas compression.

Gap Closure: Structured Adsorbent Bed Density

A fundamental advantage of Inventys' structured adsorbent technology is the ability to tailor the adsorbent bed density, voidage and pressure drop with more degrees of freedom than is the case for packed bed or beaded systems. During the Phase 1 design and verification activities, increasing the bulk density of the structured adsorbent beds was identified as a critical strategy for closing performance gaps relative to test platform results and Phase 1 TEA targets. By increasing the bulk density of the structured adsorbent beds, the effective CO_2 capacity of the bed is increased and the overall performance metrics, such as steam ratio can improve.

Bed bulk density and voidage are determined by channel height, adsorbent sheet thickness and packing density within the coated adsorbent sheet. The more tightly particles are packed within the coated sheet, the higher the bulk density and the lower the voidage. This is desired as more adsorption sites will be available within a fixed bed volume without affecting bed pressure drop.

The ideal calculation of bulk density and voidage assumes adsorbent layers are perfectly smooth on the surface and are evenly layered giving perfectly consistent channel height within the structure. In reality, however, this is not true; other factors such as surface void and uneven bed compression must be considered. Most of all, fractional void within an adsorbent sheet (i.e. pockets inside the coating) must be taken into account. The fractional void within a coating sheet is adjusted to match the calculated adsorbent loading to the measured loading.

It is important to distinguish the two density numbers – *bed adsorbent density* includes active material only (adsorbent activated at 140°C or 284°F), and *bed bulk density* includes active material and non-active material (binder and substrate). Bed bulk density will always be higher than bed adsorbent density. Non-active material in the bed does not assist the separation process; it will increase the overall mass and take up thermal energy from the process. The primary goal is to increase bed adsorbent density (active material only) while minimizing the non-active material. In another words, the two density numbers should be as close as possible.

Exhibit 5-11 summarizes the calculated bulk density and voidage of our current and targeted structured adsorbent bed. This is achieved by using slightly thicker, smoother, and denser coating with less structural material, and minimum binder content. The fractional void inside could be easily reduced to 12% by better milling process and optimizing particle size without any negative effect on adsorption kinetics.

Exhibit 5-11: Bed density and voidage of current and target adsorbent beds

	Current	Target	Delta
Coating thickness [mil]	10	13	+3
Spacer height [mil]	10	8	-2
Substrate base weight [g/ft^2]	1.5	0.75	-0.75
Binder content	5%	3%	-2%
Fraction void inside coating	0.32	0.12	-0.20
Bed ads. density* [kg/m^3]	275	570	+295
Bed bulk density† [kg/m^3]	360	620	+260
Bed voidage	0.43	0.35	-0.08

*includes active material only, i.e. adsorbent activated at 140°C/284°F

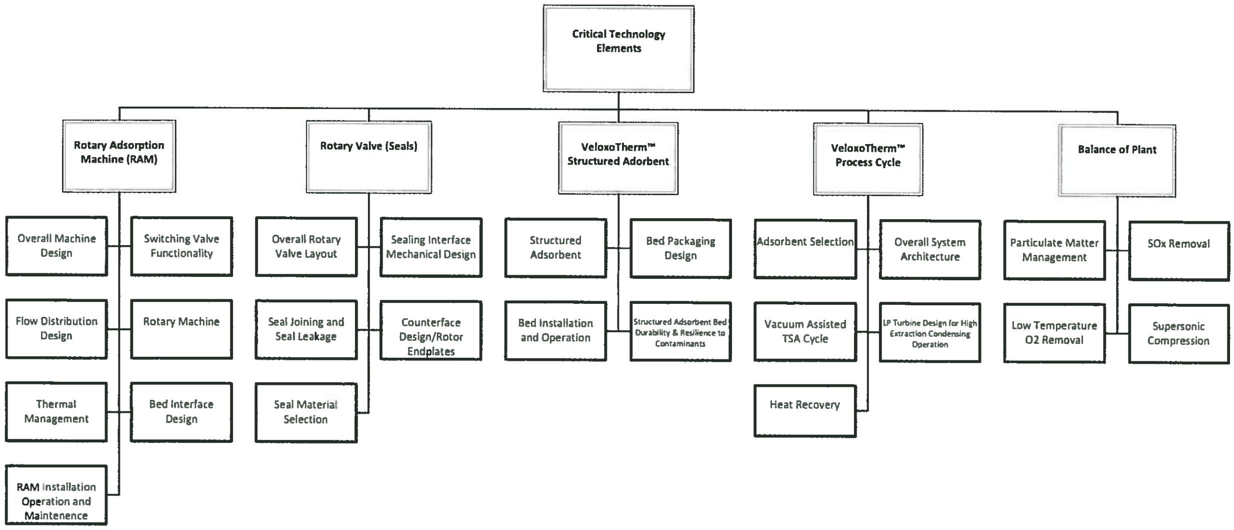
†includes active and non-active materials, i.e. adsorbent activated at 140°C, binder and substrate

6 Technology Gap Analysis

As part of the Phase 1 performance, a technology gap analysis (Phase 1 Gap Analysis) was developed and documented in detail as part of the preliminary submission of NRG's and Inventys' Phase 2 Application pursuant to the Solicitation. The Phase 1 Gap Analysis represented a study of the current state of development of all of the major/critical process components of the VeloxoTherm™ advanced CO_2-capture technology, along with an analysis of the research, development, and demonstration needs required to fully develop the technology to commercialization.

In order to present a detailed analysis of the status of the VeloxoTherm™ technology and outline the development required to bring the technology to commercial status, it was necessary to break the technology up into major subsystems/components and design elements that are critical to the performance and success of the process. In creating the Phase 1 Gap Analysis, Inventys relied in part on the language and methodology of the DOE's *Technology Readiness Assessment Guide* (DOE G 413.3-4A, 2011) (TRA) for the purposes of consistent nomenclature. To discuss specific technology gaps in a consistent manner, we used the concept of critical technology elements (CTEs) from the DOE's TRA guide to define the technology components and/or subsystems. In general, we have used a flowsheet or system approach to defining CTEs, as opposed to a work breakdown schedule (WBS). Where process and system integration over multiple unit operations or pieces of equipment is critical to overall performance of the technology, then such process or system integration concepts were also identified as CTEs. The CTEs identified for the VeloxoTherm™ process are summarized in Exhibit 6-1.

Exhibit 6-1: Critical Technology elements identified as part of the Phase 1 Gap Analysis organized by functional area within the VeloxoTherm™ process



For the purposes of this final technical report, the results of the Phase 1 Gap Analysis are presented and summarized at a "sub-system" level, for the following major technology components:

A. Rotary Adsorption Machine
B. Rotary Valve (Seals)
C. Structured Adsorbent Beds
D. Process Cycle & Performance
E. Balance of Plant (capture system)

6.1 Technology Readiness

Inventys validated certain CTEs in field testing, with engineering scale equipment and laboratory testing of CTE sub-components. The Inventys engineering-scale demonstration plant is a fully autonomous system which was operated in unattended mode on site at NRG's WA Parish Electric Generating Station operating on coal flue gas supplied from the baghouse of Unit #7. Unit #7 is a 613 MW (gross) plant which combusts low-sulfur coal originating from the Powder River Basin (PRB). As Unit #7 does not have an FGD, the flue gases entering the demonstration unit had elevated levels of SO_2. Through March 31st, 2016 the demonstration unit operated in excess of 500 hours on coal flue gas and demonstrated an ability to deliver >90 mol% pure CO_2. Stable operation was observed with respect to the performance of the demonstration plant.

Inventys has further validated elements of the technology in tests conducted in-house and at third party testing facilities. A summary of the validation tests can be found in Exhibit 6-2.

Exhibit 6-2: Design Validation Test Summary

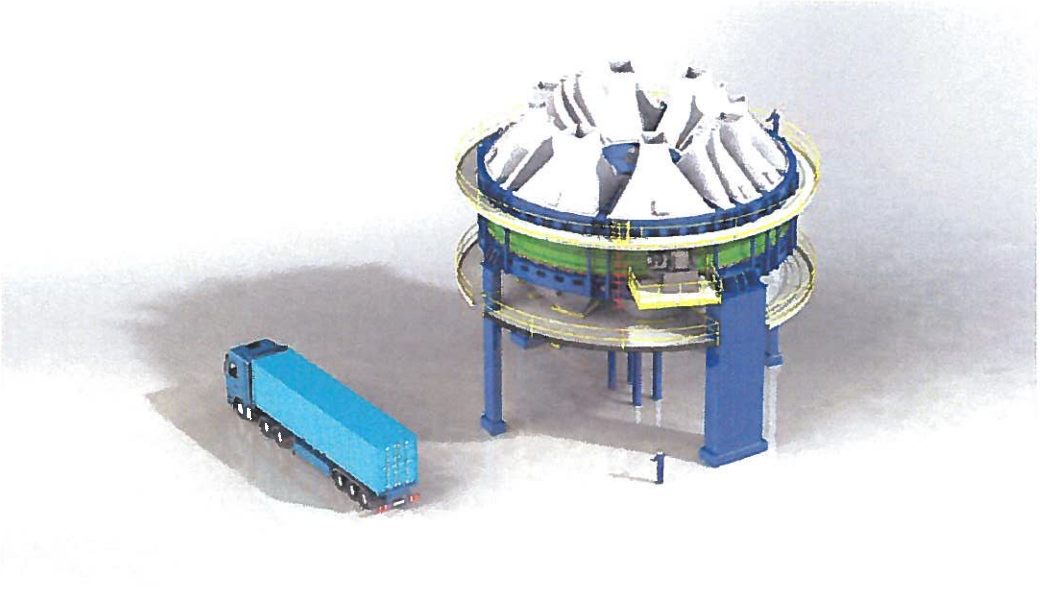
Description	Equipment	Location	Outcomes
Coal-Fired Flue Gas – Field Demonstration	Engineering Scale Demo Unit	NRG — WA Parish	Objectives to confirm process stability and durability while operating under real coal-fired power plant conditions are being met.
Coal Fired Flue Gas – In-House Testing	Engineering Scale Demo Unit	In-house	Investigated resilience of Inventys Demo Unit to contaminants in coal flue gas. Demonstrated stable performance over 156 hours of cumulative testing. Confirmed effectiveness of the caustic dosing system to reduce SO_x contaminants for sites that do not have FGD equipment already in place.
Natural Gas Fired Flue Gas In-House Testing	Engineering Scale Demo Unit	In-house	The Inventys Demo Unit was tested with natural gas fired coal flue gas for over 2,000 hours. The equipment demonstrated resilience to elevated NO_x levels, i.e. 72 ppm. The rotary valve seal design and materials proved to be effective over the duration of the tests and many of the same elements were identified for the Large Scale Pilot seal design.
Adsorbent Sheet Acid Exposure Test	Wet lab	In-house	Adsorbent sheets immersed acid solutions (50 wt% sulfuric acid and 25 wt% sulfuric/25 wt% nitric acid) for 1 month showed constant CO_2 adsorption capacity and tensile strength
Adsorbent Sheets Contaminant Exposure	Exposure Chamber	External	Adsorbent Sheets exposed to high concentration SO_x were shown to have their CO_2 adsorption capacity fully restored after 100 hours of operation in the VeloxoTherm™ cycle.
Seal Material Contaminant Exposure	Exposure Chamber and Seal Material Gas Exposure Test Rig	External and In-house	A number of commercially available seal materials were tested by a third party testing facility and in-house to validate the hard and soft seal material selections for the Large Scale Pilot and Full Scale Commercial RAM units.
Large Scale Seal Material & Design Validation	Large Scale Dynamic Seal Test Station (DSTS)	In-house	The DSTS was commissioned in Feb-2016 and is capable of producing results that are directly applicable to the seal designs for the Large Scale Pilot and Full Scale Commercial Plants. The test station is capable of matching the PV (contact pressure x linear velocity) required for the large diameter RAM units required for commercial plants.
Adsorbent Bed Durability	Bed Durability Test Rig (BDTR)	In-house	The test conditions in the BDTR allow flow conditions (temperature swing, pressure drop and gas velocity) for the Large Scale Pilot to be simulated on adsorbent beds that have sub-scale dimensions, i.e. length and cross-sectional area
Adsorbent Materials & Process Cycle Tests	VTS & Process Demonstration Unit (PDU)	In-house	The VTS & PDU test rigs allow Inventys to rapidly test and verify adsorbent material, adsorbent bed and process cycle designs. Data from these test rigs is used to verify predicted results from Inventys' proprietary adsorbent and cycle simulation models.
Adsorbent Bed Durability	Large Bed Durability Test Rig (LBDTR)	In-house	The LBDTR gives Inventys the ability to test up to two adsorbent beds under accelerated conditions. The flow conditions are comparable to the flow conditions of the Large Scale Pilot Plant. Adsorbent beds are tested periodically to CO_2 adsorption capacity and weight. At end of life, tests are performed to check mechanical strength.

6.2 Technology Gap Identification and R,D&D Requirements

6.2.1 Rotary Adsorption Machine

The purpose of the RAM is to perform the VeloxoTherm™ process cycle in a rotating device that houses the proprietary adsorbent beds. Each adsorbent bed is exposed to sequential steps in the gas separation process as it rotates between a series of seals, together creating a continuous rotary switching valve. In the Large-Scale Pilot project (>10Mwe), the RAM was designed to take the form of a single ~15m-diameter rotating wheel, whereas the Full-Scale Commercial embodiment of the RAM envisioned a series of 30m-diameter machines of similar form. Exhibit 6-3 shows the exterior form of a Large-Scale Pilot RAM designed for a target CO_2 processing capacity of approximately 500 tpd.

Exhibit 6-3: Exterior of Large-Scale Pilot RAM



The RAM design is based on the 100+ year old rotary heat exchanger design. Rotary heat exchangers approaching 30m diameter are produced by mature global manufacturers and have been known to be in service for more than 30 years in utility, petrochemical and process gas industries.

As the RAM is scaled to larger sizes, it is anticipated that practical limitations will be encountered with respect to physical size. Some of these limitations and risks include:

- Maximum diameter associated with manufacturing capability, transportation to site and site assembly
- Rotor imbalances as process loads and thermal stresses act over larger moments, potentially resulting in eccentric bearing loads
- Bed dimensions which exceed manufacturing capabilities, installation and handling requirements or mechanical durability characteristics
- Unit lengths of seal assemblies in the radial direction which suffer adverse impacts from differential wear rates, as well as concerns around unsupported stiffness and manufacturability

As these limitations were identified and quantified, design approaches transitioned from a pure scale-up strategy toward a modular or building-block strategy. This design strategy moves the risks associated with very large scale RAM embodiments away from technical scale-up risks and more toward modular cost risks in the short term. Exhibit 6-4 summarizes identified gaps and limitations of the overall RAM design as well as approaches identified to close these gaps through a large scale piloting program or subsequent R,D&D related prior to commercial development.

Exhibit 6-4: Technology Gap Identification – Rotary Adsorption Machine

Technology Gap	Description	Gap Closure and R,D&D Requirements
Rotor Imbalances and deflection	Differential loads from process gases and thermal stresses which vary between asymmetric cycle steps, timing, flows & temperatures can result in imbalances and deflections.	Multiple process cycles in each revolution of the rotor was incorporated into the conceptual design of the RAM for both the Large Scale Pilot and Full Scale Commercial machines. This results in balanced and symmetrical process and thermal loads on the machine, as well as the following ancillary benefits: • Reduced rotation speed and reduced seal wear rate • Smaller transition ducting reducing span loadings and duct pressure forces • Smaller modular adsorbent bed characteristic dimensions Confirming this approach and closing the gap will require demonstration of the design at Large Pilot scale.
Switching Valve Functionality	The primary purpose of the RAM device is to implement the VeloxoTherm™ process cycle in a rotating machine. To do this, the rotating bed openings on the top and bottom of the rotor must combine with the seal openings in the correct sequence, with the correct process step timing. As well, in order to maximize the packing density of the adsorbent material within the RAM device, this switching valve function should occur in trapezoidal sectors for large machines – to date Inventys has only demonstrated circular ports.	Trapezoidal-shape valve switching is proven in industry. Direct process verification using circular port switching for VeloxoTherm™ together with industry experience with trapezoidal-shape valve switching has been evaluated as indicating manageable scale-up associated risks. Demonstration of the switching valve functionality at the Large Pilot scale would test this design and de-risk it for Full Commercial scales.
Flow Distribution Design	Flow distribution design for the RAM consists both of managing pressure drop balances between the ducting for the multiple cycles per revolution, as well as the assurance of a uniform velocity distribution across the faces of the adsorbent beds. Flow transition ducting is designed to produce the required velocity field at the inlet of each step.	Flow distribution requirements are unique for each machine design; however design techniques used to meet requirements are standard in industry. Preliminary computational fluid dynamics (CFD) analysis for the Large Scale Pilot of the flow transition ducting showed the expected effectiveness of a three dimensional grid of flow directing vanes to produce a uniform velocity field at the bed faces. With respect to pressure balancing between multiple cycles, conceptual design included symmetry in elements such as ducting corners and preliminary CFD analysis confirmed pressure drop variations within allowable process limits. The approach for gap closure and risk mitigation during detailed design of the Large Scale Pilot includes detailed CFD analysis and standard design practices such as those used for heating, ventilation, and air-conditioning (HVAC) systems.

Technology Gap	Description	Gap Closure and R,D&D Requirements
Thermal Management	Potential gaps between predicted thermal inertia and behavior of the RAM compared with actual performance in the field. In particular confirmation of the steady state operating temperatures of various elements and actual thermal growth & stress risers vs sealing requirements.	Temperature profiles and effectiveness of design methods for thermal management has been demonstrated on the Engineering-Scale RAM and predictive tools have been developed. An instrument slip ring will be installed on the rotor and instruments will be installed to monitor temperature at various positions on stator and rotor. Design will incorporate thermal expansion gaps with degrees of mechanical freedom to prevent stress risers and buckling.
RAM Installation, Operation, and Maintenance	Actual torque loads and variability, controllability of rotation speed, and maintenance intervals and servicing requirements can only be verified by operation at larger scale.	Demonstration at the Large Pilot scale will verify expected performance based on analog rotary heat exchangers and smaller scale RAM designs. Surplus motor capacity and dual variable frequency drive (VFD) control incorporated into design to ensure controllability and design margin for torque requirements. RAM design includes numerous access ports, bed removal access with overhead crane, and other design elements to facilitate access and replacement of beds, sealing elements, and other components.

6.2.2 Rotary Valve (Seals)

The function of the rotary valve is to control gas flow into and out of the RAM as well as implement the prescribed TSA cycle, providing for gas containment for each process step while minimizing design complexity and therefore fabrication and anticipated operating costs. In order to achieve the required seal performance for certain process steps in the VeloxoTherm™ cycle, Inventys has developed proprietary seal designs which function as a form of rotary valve (implementing the TSA cycle steps). These seals line the perimeter of each process step at the interface of the rotor (which holds the adsorbent beds) and the flow transition ducting, and are assembled using a modular design to allow scalability and local serviceability. Important performance parameters associated with the rotary valve/seal design include:

- Sealing performance in the form of inter-step leakage rates, and leakage rates to the environment
- Seal lifetime and durability
- Thermal mass and minimization of heat loss from the process
- Power consumption and torque loads on the rotary machine

Inventys operates a large scale DSTS that is capable of producing experimental data that is directly applicable to seal designs for scales up to machines that are 30m in diameter. Testing programs using the DSTS, conceptual design activities, and reliance on previous industry experience were used during Phase 1 to develop seal concepts for both the Large Scale Pilot and the Full Scale Commercial design considered in the Phase 1 TEA. Exhibit 6-5 provides a summary of some critical R,D&D gaps and scale-up risks associated with these seal designs.

Exhibit 6-5: Technology Gap Identification – Rotary Valve (Seals)

Technology Gap	Description	Gap Closure and R,D&D Requirements
Leakage Rates under process vacuum conditions.	Static and dynamic testing of Inventys' seal designs for both small pilot and larger RAM purposes has been at near-atmospheric pressures with pressure differentials across seal elements on the order of 3 - 5 psig. The adsorbent and TSA cycle energy performance targets as shown in the Phase 1 TEA, however, require larger pressure differentials between TSA cycle steps and across sealing surfaces, including some steps that operate significantly below atmospheric pressure. In order to economically achieve significant vacuum pressure within the RAM, the seal designs will be required to meet a lower allowable leakage rate specification. In the very large physical scales of the RAM device, achieving very low leakage rates could result in a number of design challenges, risks, process integrity, and feasibility issues.	Conceptual design strategies for vacuum operation need to be developed and tested, which could include the different mechanical designs, the use of blanket CO_2. Gap closure will require development of new testing programs and apparatus, and significant risks remain unmitigated as at the date of this report related to vacuum operation of the seals. Industry experience exists for rotary valve seals in rapid cycle pressure swing adsorption technologies, however the applicability of these design concepts to the large machine sizes of the VeloxoTherm™ technology remain unverified. In addition, the general mechanical design concept for the RAM will need to be evaluated for suitability under new loading conditions arising from vacuum operation. This is not anticipated to represent a significant risk, however the design evaluation must be completed and adjustments to the design concept will be made as required.
Seal Deflections	As the RAM is scaled up from current equipment to the Large Scale Pilot and Full Scale Commercial scales, the length of sealing segments increases and bending or deflection of the seals in the radial direction could occur.	The seal design was divided into segmented tracks, allowing the individual seal components to be supported at regular radial intervals, minimizing any seal bending over the adsorbent beds. In addition, finite element analysis was completed using input loading from the DSTS. Final loads from the Large Scale Pilot are a critical design validation step for Full Scale Commercial designs.
Differential Seal Wear	As the radius of the RAM increases, the linear velocity experienced by the sealing elements at the inner diameter (ID) and outer diameter (OD) of the rotary valve become increasingly divergent, resulting in differential wear rates of the seals and the potential for degradation of seal performance over time.	The seal design included a segmented strategy with multiple radial seal elements, limiting the variation in linear velocity between the ID and OD of any individual seal unit.
Seal Material Selection	During the Phase 1 performance period, the materials of construction for the elements of the seal design to be applied to the coal flue gas application at Large Pilot Scale and Full Scale Commercial scales underwent a formal selection process and accelerated exposure testing to the types of gas species and contaminants present in design basis coal flue gases. The wear rate of these seal materials and their mechanical durability under long term operation with particulate matter present at the levels expected for coal flue gas were not determined however.	The design of the rotary valve and seals for the Large Scale Pilot unit includes elements which allow for detailed inspection and ongoing monitoring to determine wear rates. The design also allows for quick replacement of the seal materials themselves, should wear rates exceed expectations.

6.2.3 Structured Adsorbent Beds

At the core of the VeloxoTherm™ technology, is Inventys' parallel-plate structured adsorbent media, which is incorporated into Adsorbent Beds and installed into the RAM; together with the rotary valve promoting the primary CO_2 separation. Inventys uses in-house manufacturing equipment to turn adsorbent powder supplied by independent vendors into bulk structured adsorbent media that is comprised of parallel stacked sheets of adsorbent material. This bulk structured adsorbent media is then cut into the design bed dimensions and shape, sealed and insulated on all sides except the two ends which allow for process streams to enter and exit. This sealed and insulated adsorbent structure is then packaged into a metal housing to create the full Adsorbent Bed which is carefully installed into the RAM. The Adsorbent Beds design and manufacturing process is a comprehensive and careful undertaking, from selecting the properties of the fundamental adsorption media and parallel-plate contactor design through to the mechanical assembly unit itself, there are a number of properties, performance parameters and characteristics that are critical to the overall design:

- Adsorbent Structural considerations- A fundamental advantage of the structured adsorbent design over a packed bed design is the ability to tailor sheet thicknesses and particle packing density within the sheet, as well as channel height and bed length – this determines Bed density, voidage, permeability, pressure drop and mass and heat transfer kinetics.
- Adsorbent Material(s) considerations- The selection and design of bed packaging materials are subject to the requirements imposed by coal flue gas contaminants and the composition of process streams and thermal mass and behavior of bed packaging can have an impact on the process performance
- Adsorbent Durability considerations - Coal flue gas has contaminants and particulate matter that can be a durability and resilience challenge for the structured adsorbent media

VeloxoTherm™ Structured Adsorbent provides enough design flexibility to tailor the adsorbent material and process cycle for specific gas separations. The adsorbent manufacturing process allows design features to be tightly controlled and repeatable. This provides control over process gas conditions and separation efficiencies, i.e. pressure drop, flow velocity and heat management.

Recent efforts at Inventys and by third parties have shown that Inventys adsorbents and adsorbent structures are resilient to the primary contaminants in coal flue gases, i.e. SO_x, NO_x and particulate matter (PM). It was found that SO_x contaminants can be desorbed from the adsorbents by the VeloxoTherm™ cycle and other periodic maintenance type processes, e.g. water washing.

The Inventys adsorbent structures are also proving to be durable under in-house accelerated testing, in-house acid immersion testing and field testing with coal-fired fuel gas. Efforts will continue to further validate designs and remedy any issues that are uncovered during testing of typical contaminants found in coal flue gas. Exhibit 6-6 summarizes some of the current gaps with existing adsorbent media and how these gaps are being evaluated.

Exhibit 6-6: Technology Gap Identification – Structured Adsorbent Beds

Technology Gap	Description	Gap Closure and R,D&D Requirements
Structured Adsorbent bulk density.	Structured Adsorbent bulk density is required to increase in order to achieve process performance targets consistent with the Phase 1 TEA. Bed bulk density and voidage are determined by channel height, adsorbent sheet thickness and packing density within the coated adsorbent sheet. The more tightly particles are packed within the coated sheet, the higher the bulk density and the lower the voidage.	A structured adsorbent bed manufacturing process was designed to increase the adsorbent density of the bulk bed. This involves using a coating procedure that increases thickness, reduces surface roughness and irregularities and increases coating density, while using less structural material and binder/additive content. It has been determined that a better adsorbent size reduction process with optimized particle sizes could reduce coating fractional void by 12% without negatively impacting adsorption kinetics.
Permeability of the Adsorbent Beds.	The pressure drop through the Adsorbent Bed is a function of the permeability of the bed, flow rate of the gas & its viscosity and the cross-sectional area length of the beds. Meeting the performance targets established for the Phase 1 TEA requires achieving the Adsorbent bed bulk density targets while minimizing adverse impacts to the pressure drops through the system.	By specifying a structured adsorbent parallel plate contactor design that involves increasing the density of the coated sheets, as well as increased thickness it was determined that the adverse impact on permeability of increasing the bulk density of the Adsorbent bed could be mitigated to a certain degree. The degree to which the pressure drop may increase when the higher density beds are constructed is to be established during the Phase 1 performance period.
Bed packaging design for resilience and thermal footprint.	The packaging and mechanical housing of the Adsorbent Beds will be subject to pressure cycling, temperature cycling and dynamic exposure to steam and moisture. In addition, the dynamic thermal footprint of the packaging material will have an impact on the performance of the TSA cycle.	A number of design elements in the bed packaging design have been incorporated to reduce risk, including: • Structural design which includes curved sides and tensile strapping to manage process pressures • Selection of process-exposed sealing material which minimizes moisture absorption • Selection of packaging material that thermally isolates the structured adsorbent Additional gap closure and R,D&D work identified for parallel efforts to the performance of Phase 2 include optimizing the thickness of the packaging material to reduce its thermal footprint and the development of moisture-resistant hybrid designs for the sealing mechanism of the bed packaging.
Resilience of adsorbent media to coal flue gas contaminants.	The adsorbent media used in the Adsorbent Beds has undergone process testing on actual coal flue gas, as well as accelerated exposure testing to certain contaminants, including SOx and sulfuric acid. Long term resilience to particulate matter, SOx, NOx, and other coal flue gas contaminants requires extended operation such as that planned for the Large Scale Pilot project.	Long term operation of the Large Scale Pilot was identified as the key gap closure strategy for demonstrating Adsorbent Bed resilience to contaminants in order to de-risk commercial applications of the VeloxoTherm™ technology. In addition, gap closure and risk mitigation include: • Reliance on standard upstream particulate removal unit operations such as a baghouse for coal power plants • For the Large Scale Pilot, the Direct Contact Cooler will have caustic dosing capability to reduce SOx levels if required • As a parallel activity, the small pilot (engineering-scale) RAM will be used to accumulate operating hours on coal-generated flue gases.

6.2.4 Process Cycle & Performance

The VeloxoTherm™ process uses an advanced TSA cycle, leveraging Inventys' structured adsorbents with the integration of the unique process cycle in the design of the RAM. The VeloxoTherm™ TSA cycle contains steps for adsorption, regeneration, conditioning, and cooling. The VeloxoTherm™ process is verified and validated by an iterative approach between modeling and testing. The verified model allows Inventys to accurately predict process parameters in equipment ranging from engineering scale prototypes to full scale commercial. The design, verification and optimization of the Veloxotherm™ TSA cycle for coal flue gases was necessary in order to arrive at performance targets for design basis utilized in the Phase 1 TEA is described in Section 7. Key strategies involved in the cycle design and overall integrated process design for meeting performance targets include:

- Vacuum Assist: The cycle design for the commercial application specifies process pressure during the regeneration and conditioning steps to be below atmospheric. This will reduce the overall energy consumption by reducing the water loading and steam ratio and increasing the CO_2 working capacity and adsorbent productivity.
- Steam Supply: The VeloxoTherm™ process cycle requires low energy steam for regeneration of the structured adsorbent beds. For the full scale commercial plant, Inventys will extract steam from the low pressure turbine of the coal-fired power plant at vacuum conditions. This reduces the parasitic load on the power plant from steam extraction.
- Heat integration: The VeloxoTherm™ process cycle requires heat for the conditioning step. The heat required for this step can be supplied through a natural gas fired heater or from integration with power plant systems. Inventys has considered some strategies for optimal heat integration with the power plant. These strategies involve standard heat integration practices and conventional industrial equipment.

Exhibit 6-7 summarizes some of the gaps in the process cycle requiring further investigation.

Exhibit 6-7: Technology Gap Identification – Process Cycle & Performance

Technology Gap	Description	Gap Closure and R,D&D Requirements
Vacuum Assisted TSA Cycle	In addition increasing the bulk density of the Adsorbent Beds, during Phase 1 a vacuum-assisted TSA cycle was modeled in order to meeting performance targets utilized for the Phase 1 TEA analysis. This is discussed more fully in Section 7; however this strategy involves a pressure of ~30 kPa absolute on the product and reflux-out steps of the TSA cycle in order to reduce the energy consumption from regeneration steam used in the process (i.e. steam ratio).	During the Phase 1 performance period, testing programs for the VTS were specified in order to confirm expected performance impacts of the vacuum-assisted strategy in concert with increased Adsorbent Bed bulk density.
Adsorbent selection	In order to improve the overall energy consumption and performance of the VeloxoTherm™ technology for coal flue gas applications, the incorporation of different adsorbent materials into the VeloxoTherm™ structured adsorbent technology can be pursued.	Parallel efforts to the scope of work under the Solicitation include the investigation of various adsorbents and collaboration with adsorbent vendors to develop tailored materials. Accelerated exposure testing and the use of Inventys' modeling, testing, and validation and verification methodology can enable these adsorbents to be rapidly deployed into existing equipment with manageable risk profiles.

Technology Gap	Description	Gap Closure and R,D&D Requirements
Low Pressure (LP) Turbine Design for High Extraction Condensing Operation	The process design presented in the Phase 1 TEA analysis incorporates the use of direct extraction steam from the host power plant's low pressure turbine, resulting in a high extraction flow on a condensing turbine.	Engagement with power industry engineering firms and steam turbine original equipment manufacturers (OEMs) has been identified as a key parallel activity in order to optimize steam extraction strategies and obtain detailed cost and performance mapping data.
Heat Recovery	The VeloxoTherm™ TSA cycle specified for coal flue gas applications includes the use of a heated ambient air stream (Hot Air Rinse) to assist in conditioning the Adsorbent Beds during the TSA cycle. The source of heat for this stream in the Phase 1 TEA has been identified as from the CO_2 compression train if supersonic compression technology with high pressure ratios is utilized.	Conceptual modeling during the Phase 1 TEA demonstrated the ability for supersonic compression strategies for product CO_2 compression to be capable providing the estimated heat requirements for the Hot Air Rinse stream. Detailed modeling and experimental validation of the compression technology is required to confirm this strategy. Absent the use of waste from CO_2 compression, however, the use of fired heaters or integration with other host site waste heat sources can be used. Incremental fuel or utility costs would need to be assessed to determine impacts on capture economics.

6.2.5 Balance of Plant

The balance of plant (BOP) for the full scale commercial and large scale pilot plants utilize commercially available equipment that is commonly utilized in power generating, petrochemical plant and gas processing plants globally. This includes items such as cooling towers, heat exchangers (shell-and-tube and plate-frame), knockout vessels, pumps, fans and dehydration equipment, control systems and electrical equipment.

A direct contact cooler (DCC) was specified for the Large Scale Pilot design basis contemplated for Phase 2 work, as there is no upstream FGD and incoming flue gas temperatures would be too high for the TSA cycle. The vacuum-assisted TSA cycle designed for the Full Scale Commercial plant in the Phase 1 TEA however assumes the existence of an upstream FGD and was therefore optimized for the expected outlet temperatures of this FGD without a DCC. The DCC for the Large Scale Pilot was designed to provide a secondary functional benefit, similar to the FGD, i.e. reduce SO_x and PM levels entering the RAM. This was demonstrated in the operation of the engineering scale pilot unit at the NRG WA Parish facility.

CO_2 compression and O_2 removal was not included in the scope for the Large Scale Pilot, while for the Full Scale Commercial plant the compression technology included in the Phase 1 TEA leverages supersonic CO_2 compression technology currently under development in industry.

Exhibit 6-8 below summarizes a few of the significant differences between the Large Scale Pilot vs. the Full Scale Commercial approach.

Exhibit 6-8: Differences in assumptions between the Large Scale Pilot Demonstration vs. Full Scale Commercial TEA

Item	Basis	Assumption
Particulate Matter Management	Process testing of the RAM and adsorbent beds on coal flue gas from a PC power plant slipstream has been short term in nature, and balance of plant equipment upstream of the RAM are also subject to impacts from the presence of particulate matter.	For the Large Scale Pilot, a DCC has been specified which will include a solids removal and sludge handling design specification for the vendor. Extended operation of the engineering scale RAM on flue gas from a coal-fired generation plant, along with detailed measurement of particle size distributions at the inlet and outlet of the beds, as well as analysis of process performance and Adsorbent Bed autopsies will provide important indications of risks from particulate matter. The design of the RAM for the Large Scale Pilot considered for Phase 2 execution includes the ability to quickly inspect and replace adsorbent beds should particulate matter result in degradation.
SOx Removal	The Large Scale Pilot has been designed for a coal flue gas slipstream that does not have upstream sulfur emissions control equipment (such as an FGD).	The DCC designed for the Large Scale Pilot includes a caustic dosing loop for SOx removal with a PH control strategy. This was tested on coal flue gas with the engineering scale RAM and demonstrated the ability to handle very similar flue gases to that specified for the Large Scale Pilot, reducing SO_2 levels to below 40ppm, which was a level that did not show any process performance degradation of the RAM during the test program. The Phase 1 TEA design basis includes an upstream FGD which is expected to provide sufficient SOx removal.
CO_2 Product Oxygen Removal	The atmospheric VeloxoTherm™ TSA cycle produces a CO_2 product stream with <1% O_2 by volume which meets the DOE's sequestration specification, but not the EOR specification.	For the Large Scale Pilot, if CO_2 compression is considered as an addition to scope during Phase 2, initial modeling showed that a low-temperature O_2 removal strategy could be implemented in the compression train to meet a <100ppmv specification. The introduction of a vacuum to the product step of the Vacuum-Assisted TSA cycle designed for the Phase 1 TEA analysis was initially expected to result in meeting the O_2 product quality specification for EOR, however this will be tested through experiments on the VTS to confirm the product oxygen content during the Phase 1performance period.
CO_2 Compression Equipment Selection	For the Phase 1 TEA, supersonic compression technology was considered given certain economic and waste heat integration advantages. This technology has yet to reach fully commercial technology readiness levels.	Full scale demonstration of supersonic compression technology by an industry vendor is expected to occur in parallel R,D&D programs during the Phase 2 performance period. Conventional compression could utilized instead, resulting in adjustments to the Phase 1 TEA that could have significant economic impacts to estimated capture costs.

7 Phase 1 Techno-Economic Analysis & Evaluation

Included in the deliverables of the FE0026581 award was a Technology Engineering Design and Economic Analysis Report ("Phase 1 TEA") in order to describe the design, performance, and economics of the VeloxoTherm™ technology for full scale commercial applications. In particular, the Phase 1 TEA was intended to determine VeloxoTherm™'s potential for meeting the DOE's Carbon Capture Program performance goals of a 90% CO_2 capture rate with >95% CO_2 purity at a cost of $40/tonne of CO_2 captured by 2025. The methodology in this analysis and reports that are referred to throughout were based on the DOE's report series termed as "Cost and Performance Baseline for Fossil Energy Plants" which have been produced in several volumes and revisions (the "Baseline Studies").

7.1 Technical Approach

The Phase 1 TEA was prepared in accordance with the methodology outlined by the Baseline Study presented in "Cost and Performance Baseline for Fossil Energy Plants – Volume 1: Bituminous Coal and Natural Gas to Electricity (Rev 2a, September 2013)"[1] (the "Reference Baseline Report"). Additional consideration has been given to Attachment 3 of Appendix 3 of the FOA governing the Solicitation as well as the various applicable Quality Guidelines for Energy Systems Studies (QGESS) published by National Energy Technology Laboratory (NETL). The general approach consists of the conceptual design, cost estimation and economic analysis of a new greenfield power plant. This plant is designed both without CO_2 capture (the "No Capture Case"), and with CO_2 Capture (the "Capture Case"), both plants are designed with the same net power exported to the grid, with the gross fuel consumption and scale of the Capture Case increased to compensate for the parasitic loads associated with the CO_2 capture process in order to maintain the same net power export in both cases. The primary economic performance metric then becomes the Cost of Electricity (COE), with the cost of CO_2 capture then implied by comparing the COE and CO_2 capture/MWh of the Capture Case and No Capture Case on an equivalent net power export basis. The DOE Baseline Studies provide the No Capture Case's and reference Capture Cases for different power plants using the SOA capture technology for the reference Capture Case. The reference Capture Case can then be used in developing an advanced technology capture case, while the reference No Capture Case is used for COE, thermal performance and cost of capture calculations on a comparative basis.

7.1.1 Reference Cases & Baseline Studies

In this report, the reference No Capture Case is Case 11 (550 MW supercritical pulverized coal power plant, 550 MW net), from the Reference Baseline Report while the reference Capture Case is Case 12 (550 MW supercritical, PC power plant, 550 MWe net, with the Fluor Econamine amine-based CO_2 capture technology).

Exhibit 7-1: Reference Cases and Novel Case Summary

	Case 11	Case 12	Case 12V
	Reference No Capture Case	Reference Capture Case	Novel Capture Case
Unit Cycle	Pulverized Coal	Pulverized Coal	Pulverized Coal
Fuel	Illinois No. 6 Bituminous	Illinois No. 6 Bituminous	Illinois No. 6 Bituminous
Site	Midwest USA Greenfield	Midwest USA Greenfield	Midwest USA Greenfield

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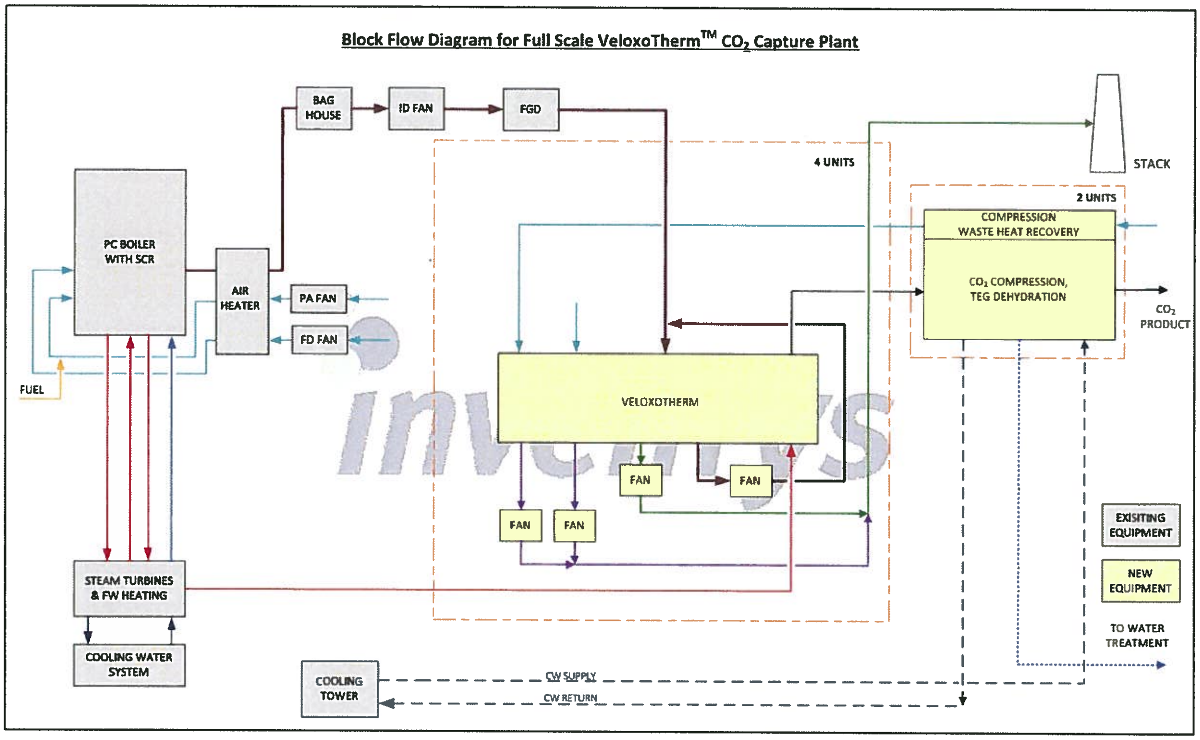
[1] (DOE/NETL, 2013)

	Case 11	Case 12	Case 12V
	Reference No Capture Case	Reference Capture Case	Novel Capture Case
Cost Basis	Jun-2011	Jun-2011	Jun-2011
Capacity Factor	85%	85%	85%
Net Power Export	550 MW	550 MW	560 MW
Steam Cycle (psig/F/F)	3500 psig/ 1100°F/1100°F	3500 psig/ 1100°F/1100°F	3500 psig/ 1100°F/1100°F
Oxidant	Air	Air	Air
Sulfur Removal	Wet FGD/Gypsum	Wet FGD/Gypsum	Wet FGD/Gypsum
PM Control	Baghouse	Baghouse	Baghouse
NOx Control	LNB w/OFA & SCR	LNB w/OFA & SCR	LNB w/OFA & SCR
CO_2 Removal	None	Fluor Econamine	Inventys VeloxoTherm Process
CO_2 Recovery	0%	90%	90%
CO_2 Product	None	99.85% @ 2215 psia	95.3% @ 2215 psia
Purpose	Used to calculate relative increase in COE for CO_2 Capture Costs	Used as design reference for novel case, and for scaling capital cost estimates for power plant	Evaluation of VeloxoTherm™ technology relative to DOE programmatic goals and comparison to SOA technologies

7.1.2 Process Overview & Scope of Analysis

The scope of the Phase 1 TEA considers the battery limits of a full greenfield supercritical pulverized coal power plant, integrated with the Veloxotherm™ advanced carbon capture technology. Exhibit 7-2 provides a Block Flow Diagram (BFD) describing the power plant w/carbon capture that is analyzed in this TEA as Case 12V.

Exhibit 7-2: Case 12V (VeloxoTherm) Block Flow Diagram



The target sizing parameter for this analysis was a net power exported of 550 MW, however in developing the analysis and process simulations used for Case 12V, iterations were required between a proprietary dynamic simulation in ADSIM and the Aspen Plus (Aspen+) steady state simulation tool. As a result, completion of the Phase 1 TEA actually resulted in a net power export of 560 MW for Case 12V. The DOE methodology used in the Baseline Studies is based on the unitized COE and how they differ between Capture Cases and No Capture Cases. This allows for technologies such as coal gasification and natural gas combined cycle plants to be compared on a like-for-like basis, and as a result it compensates for the fact that Case 12V has a net power export of 560 MW, vs the target of 550 MW.

Major unit operations of the power plant and CO_2 capture system described by Exhibit 7-2 can be broken into the following categories:

- **Power Plant:** PC Boiler, Steam Turbines and Feed Water (FW) Heating, Boiler Air Heater, Selective Catalytic Reduction (SCR), Baghouse, WFGD, cooling water system, water treatment and ancillaries etc.
- **CO_2 Capture System:** The VeloxoTherm™ rapid cycle TSA based CO_2 capture technology, from the exit of the WFGD and inlet of the RAM and including the fans, heat exchangers and vessels required to produce separated CO_2 to the CO_2 drying and compression train.
- **CO_2 Compression:** The CO_2 product stream from the RAM is first compressed to ~1 atm pressure and then fed to a supersonic compression train, which together with a glycol dehydration system, heat exchangers and knockout vessels, produces pipeline grade supercritical CO_2 suitable for pipeline transportation to an enhanced oil recovery or sequestration site

- **VeloxoTherm™ Integration:** The primary integration concepts involving the VeloxoTherm™ carbon capture process and the other unit operations identified in Exhibit 7-2 include the use of extraction steam from the steam turbine cycle, and the recovery of heat from the supersonic compression train in order to heat the hot air rinse process stream require by the RAM for the TSA cycle

The system boundaries which are used for the scope of the process flowsheet, simulation and cost estimation can be described as:

- Delivered coal entering the power plant, through to the high pressure, high-purity CO_2 stream that crosses the plant boundary
- Combustion, secondary and primary air intake
- Flue gas to stack
- Net electricity sent to electric grid
- Raw make-up water
- Waste streams generated by the power plant, including the CO_2 capture system, are adequately treated on-site prior to discharge or disposal

The scope of this analysis, and the associated capital and operating cost estimation, considers all unit operations, equipment and utilities implied by the above system boundaries, as well as the full project lifecycle for greenfield construction from a free and level site. The project scope, for cost estimation purposes is limited to inside the "fence line", and the scope stops at the high side terminals of the Generator Step-up Transformers (GSUs). Examples of items that outside the fence-line and outside of the scope of this analysis are:

- New access roads and railroad tracks
- Upgrades to existing roads to accommodate increased traffic
- Makeup water pipe outside the fence-line
- Landfill for on-site waste (slag) disposal
- Natural gas line for backup fuel provisions
- Plant switchyard
- Electrical transmission lines & substation

In addition, the project scope does not address items that would be associated with a site other than a generic mid-western greenfield site and does not include:

- Piles or caissons
- Rock removal
- Excessive dewatering
- Expansive soil considerations
- Extreme temperature considerations
- Hazardous or contaminated soils
- Demolition or relocation of existing structures
- Leasing of offsite land for parking or laydown
- Busing of craft to site
- Costs of offsite storage

7.1.3 Target Power Plant Performance Metrics

The primary figure of merit used in this TEA and referred to by the Reference Baseline Report is the first year COE. The COE is the revenue received by the generator per net MWh during the power plant's first year of operation, assuming that the COE escalates thereafter at a nominal annual rate equal to the general inflation rate. The COE is calculated so as to cover all nominal cash operating costs and expenses to produce the electricity, as well as to provide the profit to the generator that is required recover the capital invested, and a return on that capital equal to the generator's weighted average cost of capital (WACC). The first year of operation breakeven COE is a primary figure of merit for evaluating the economics in the DOE Baseline Studies.

The primary economic metric relative to the DOE's programmatic goals is the first year cost of CO_2 captured. Because of the use of a reference No Capture Case with the same net power-exported and power plant design as the reference and novel Capture Cases, the CO_2 captured cost is calculated by dividing the increase in COE, $/MWh between the Capture Case and the No Capture by the amount of CO_2 captured per MWh of net power exported.

Other figures of merit for performance analysis include:

- **Net Plant Efficiency** – The amount of net power exported to the grid divided by the amount of thermal energy input from the fuel (coal), which can be calculated on a higher heating value (HHV) or lower heating value (LHV) basis of the fuel feedstock. Units are a percentage (%).
- **Net Plant Heat Rate** – Essentially the inverse of Net Plant Efficiency, this is the amount of thermal energy input from the coal (on either a LHV or HHV basis) divided by the net power exported to the grid. Presented in units of btu/kWh or kJ/kWh.

7.1.4 Process Modeling

For Case 12V, an Aspen Plus® (Aspen+) steady state simulation was developed for the entire scope of analysis, power plant, steam cycle, CO_2 separation and compression described. The Aspen+ simulation was used to generate material and energy balances, which are in turn used to provide a design basis for items in the major equipment list.

In preparing this analysis, Inventys used the methodology, guidelines and assumptions which have been developed by the NETL for these purposes. NETL has conducted systems analysis studies that require a large number of inputs, from ambient conditions to modeling parameters for Aspen Plus™ process blocks. These have been reported in the both the 2012 (Ref [1]) and 2014 (Ref [2]) versions of the DOE/NETL QGESS document "Process Modeling Design Parameters" as well as the Reference Baseline Report (Ref [3]), and have been applied, as required, to this study to develop an accurate baseline model of a Supercritical (SC) Pulverized Coal (PC) Plant (Case 11) The baseline model has been used to develop the Case 12V model for a SC PC plant with the addition of the CO_2 capture and compression using the VeloxoTherm™ process.

7.1.4.1 Property Methods

A summary of property methods used for modeling various sections of energy systems in Aspen Plus™ is shown in Exhibit 7-3. These property methods are as detailed by the NETL in Ref [2].

Exhibit 7-3: Property Methods used for Case 12V Analysis

Section	Property Method
Coal Boiler	Peng Robinson
Steam Turbine	Steam Tables (STEAM-NBS)
CO_2 Capture	Peng Robinson
CO_2 Compression	Lee-Kessler-Plöcker

The gas side modeling for the boiler system used the Peng-Robinson equation of state.

Steam turbines, and the steam side of coal boilers, were modeled using steam table property values. The steam table is the standard for water based systems, and uses an enthalpy reference state of the triple point of water at 32.02°F and 0.089 psia. Aspen recommends the steam table (STEAM-NBS) property method for pure water and steam, and for the free-water phase, when present. The STEAM-NBS property method is based on the 1984 NBS/NRC steam table correlations for thermodynamic properties. These properties minimize continuity problems that occur at the boundaries between regions of the P-T space that can lead to Aspen model convergence problems. Because the steam tables are a common source of enthalpy data, all enthalpy values in this study were adjusted to the reference conditions as stated.

The CO_2 capture process used the PENG-ROB equation of state which is suitable in high temperature and high pressure regions.

The CO_2 compression used the Lee-Kesler-Plöcker (LK-PLOCK) equation of state based on discussions with CO_2 compression vendors concerning the performance predictability of various equation of state models. The LK-PLOCK property method is consistent in the critical region.

7.1.4.2 Rotary Adsorption Machine & Dynamic TSA Process Modeling

The VeloxoTherm™ rapid cycle TSA process cannot be modeled using steady state simulation packages, as modeling it requires predicting complex dynamic and transient mass and energy transfer behavior and kinetics. The core TSA cycle is instead modeled in ADSIM, which is capable of simulating rigorous multi-physics adsorption and providing simultaneous solutions to process that involve momentum, heat and mass transfer phenomena. Once correctly modeled, the ADSIM simulation for a given TSA cycle design will reach “cyclic steady-state” and the mass and energy balance can be transferred into an Aspen+ steady state simulation to design the overall VeloxoTherm™ process and integrate it with the overall integrated plant. A description of the basic process that was used to develop a verified and accurate predictive dynamic simulation of the VeloxoTherm™ cycle is provided back in Section 5.2

7.2 Design Basis

Inventys adopted the same evaluation basis for Case 12V as presented for the reference Capture Case (Case 12) in the Reference Baseline Report.

As per the reference Capture Case, Case 12 is based on a generic plant site in Midwestern U.S., with ambient conditions and site characteristics as presented in Exhibit 7-4 and Exhibit 7-5. The ambient conditions are the same as ISO conditions.

Exhibit 7-4: Site Ambient Conditions

Parameter	Value
Elevation, (ft)	0
Barometric Pressure, MPa (psia)	0.10 (14.696)
Design Ambient Temperature, Dry Bulb, °C	15 (59)
Design Ambient Temperature, Wet	11 (51.5)
Design Ambient Relative Humidity, %	60

Exhibit 7-5: Site Characteristics

Parameter	Value
Location	Greenfield, Midwestern USA
Topography	Level
Size, acres	300 (PC/IGCC), 100 (NGCC)
Transportation	Rail
Ash/Slag Disposal	Off Site
Water	Municipal (50%) / Groundwater (50%)
Access	Land locked, having access by rail and highway
CO_2 Storage	Compressed to 15.3 MPa (2,215 psia), transported 80 kilometers (50 miles) and sequestered in a saline formation at a depth of 1,239 m (4,055 ft)

The design coal for this study is Illinois No. 6 with the characteristics presented in Exhibit 7-6.

Exhibit 7-6: Design Coal

Rank	Bituminous	
Seam	Illinois No. 6 (Herrin)	
Source	**Old Ben Mine**	
Proximate Analysis (weight %) (Note A)		
	As Received	**Dry**
Moisture	11.12	0
Ash	9.7	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
Total	100	100
Sulfur	2.51	2.82
HHV, kJ/kg	27,113	30,506
HHV, Btu/lb	11,666	13,126
LHV, kJ/kg	26,151	29,544
LHV, Btu/lb	11,252	12,712
Ultimate Analysis (weight %)		
	As Received	**Dry**
Moisture	11.12	0
Carbon	63.75	71.72

Rank	Bituminous	
Seam	Illinois No. 6 (Herrin)	
Source	Old Ben Mine	
Proximate Analysis (weight %) (Note A)		
	As Received	Dry
Hydrogen	4.5	5.06
Nitrogen	1.25	1.41
Chlorine	0.29	0.33
Sulfur	2.51	2.82
Ash	9.7	10.91
Oxygen (Note B)	6.88	7.75
Total	100	100

A. The proximate analysis assumes sulfur as volatile matter

B. By difference

The environmental targets for this Phase 1 TEA were based on those described by the Reference Baseline Report specified by the FOA, and as such are based on the corresponding analysis presented in the Reference Baseline Report. Specifically, this analysis was performed with regard to New Source Performance Standards (NSPS) current at that time, as well as Best Available Control Technology (BACT), and New Source Review (NSR), Prevention of Significant Deterioration (PSD) processes as well as attainment areas for Lowest Achievable Emission Rate (LAER). It is of note, that at the time of the publishing of the Reference Baseline Report, no active legislation was in place regarding acceptable mercury emission levels, as the Clean Air Mercury Rule (CAMR) had been vacated and the new Mercury and Air Toxic Standards (MATS) was not in force. Exhibit 7-7 presents the relevant environmental performance targets adhered to in this analysis, along with a comparison of the NSPS and performance targets between the Reference Baseline Report and Revision 3 of Volume 1 of the Baseline Studies published in summer 2015 (2015 Baseline Report).

Exhibit 7-7: Air Emission Targets (PC)

Pollutant	NSPS (New Units)		Performance Targets			Control Technology
	2015 Baseline (incl. MATS)	Reference Baseline	2015 Baseline (incl. MATS)	Reference Baseline	This Analysis	
SO_2	1.00 lb/MWh-gross	1.4 lb/MWh-gross	1.00 lb/MWh-gross	0.085 lb/MMBtu	**0.085 lb/MMBtu**	Low NOX burners, overfire air and SCR
NOx	0.7 lb/MWh-gross	1.00 lb/MWh-gross	0.7 lb/MWh-gross	0.07 lb/MMBtu	**0.07 lb/MMBtu**	Wet limestone scrubber
PM (Filterable)	0.09 lb/MWh-gross	0.015 lb/MMBtu	0.09 lb/MWh-gross	0.013 lb/MMBtu	**0.013 lb/MMBtu**	Fabric filter
Hg	$3x10^{-6}$ lb/MWh-gross	na	$3x10^{-6}$ lb/MWh-gross	1.14 lb/Tbtu	**1.14 lb/Tbtu**	Co-benefit capture
HCl	0.01 lb/MWh-gross	na	0.01 lb/MWh-gross	na	**na**	none

The greenfield SC PC coal-fired power plant with CO_2 capture using VeloxoTherm™ considered by Case 12V has been designed using a steady state Aspen+ simulation.

7.3 Common Process Areas

In the Reference Baseline Report, process areas that are common to all the PC cases are described in detail which will not be repeated here, Exhibit 7-8 highlights the process areas common to all PC cases in the Reference Baseline Report, and highlights which process areas have design elements that have been adjusted to accommodate the VeloxoTherm™ CO_2 capture process. Where the only impact to the PC common area is due to scale differences between Case 12 and Case 12V, the reader should refer to Section 4.1 of the Reference Baseline Report. PC common process areas that have been altered are described in more detail that follows.

Exhibit 7-8: Impacts to PC Common Process Areas

PC Common Area	Impact of VeloxoTherm™ vs. Case 12
Coal and Sorbent Receiving and Unloading	Scale Only
Steam Generator and Ancillaries	Scale Only
NO_X Control System	Scale Only
Particulate Control	Scale Only
Mercury Removal	Scale Only
Flue Gas Desulfurization	Scale Only
Power Generation	Extraction flow from LP turbine to supply regeneration steam for CO_2 capture system – significant reduction in condenser duty as well from extraction strategy and fresh boiler feedwater (BFW) makeup
BOP – Condensate	Scale Only, unless process condensate recovered from VeloxoTherm™
BOP – Feedwater	Increased BFW makeup required unless recovered from VeloxoTherm™ process condensate
BOP - Main & Reheat Steam	Scale Only
BOP - Extraction Steam	Extraction for CO_2 capture considered separately, Scale Only
BOP - Circulating Water System	VeloxoTherm™ has significantly lower cooling loads than the SOA capture technology, and steam extraction along with fresh BFW makeup reduces condenser duty significantly
BOP - Ash Handling System	Scale Only
BOP - Ducting and Stack	Scale Only
BOP - Waste Treatment & Plant Services	Scale Only

7.3.1 Power Generation

The steam turbine used in Case 12 and Case 12V is a tandem compound type, consisting of HP-IP-two LP (double flow) sections enclosed in three casings, designed for condensing single reheat operation, and equipped with non-automatic extractions and four-flow exhaust. The turbine drives a hydrogen-cooled generator. The turbine has DC motor-operated lube oil pumps, and main lube oil pumps, which are driven off the turbine shaft. The exhaust pressure is 50.8 cm (2 in) Hg in the single pressure condenser. As in Case 12, there are seven extraction points, with existing extraction points on the LP turbine used to accommodate the regeneration steam used by VeloxoTherm™.

The extraction steam used for the regeneration steam required by the VeloxoTherm™ process is extracted after the second stage of each LP (LP2) turbine flow paths, at a condition of 0.132 MPa and 145°C/293°F (55,335 kg/h), and after the third stage of the LP turbine (LP3) at a condition of 0.058 MPa and 85°C/185°F (534,710 kg/h). The LP3 steam is the larger flow and is used as an attemperator stream, mixed with the extraction from LP2 and passed through a pressure reducing valve (PRV) before being delivered to the RAM at 40 kPa and 80°C/176°F. This extraction strategy takes advantage of the low energy steam required by the VeloxoTherm™ solid adsorbent and vacuum TSA cycle to minimize the parasitic load to the power plant.

As in Case 12, the condenser is two-shell, transverse, single pressure with divided waterbox for each shell. Because the extraction steam from the LP turbine is used in direct contact with the adsorbent media in the RAM and exits the VeloxoTherm™ process primarily through the hot rinse stream vent to stack, the load on the condenser is significantly reduced when compared to a no capture case (Case 11). The fresh makeup BFW required to replace the extraction steam for VeloxoTherm™ is supplied at 30°C to the condenser hotwell, achieving the reduction in condenser duty (even relative to Case 12 which returns regeneration condensate to the deaerator).

7.3.2 Balance of Plant

From a BOP perspective, Case 12V is equivalent to Case 12 described in the Reference Baseline Report in most respects. Where the use of the novel VeloxoTherm™ technology significantly impacts the scale, load or operation of a BOP unit operation it is discussed below.

7.3.2.1 Condensate

The function of the condensate system is to pump condensate from the condenser hotwell to the deaerator, through the gland steam condenser and the LP FW heaters. Each system consists of one main condenser; two variable speed electric motor-driven vertical condensate pumps each sized for 50 percent capacity; one gland steam condenser; four LP heaters; and one deaerator with storage tank. As the extraction steam for the VeloxoTherm™ process is made up with fresh BFW supplied to the condenser hotwell, there is no alteration to the condensate and FW heater system design (other than the adjusted mass and energy balance for the scale of Case 12V).

7.3.2.2 Extraction Steam

The function of the extraction steam system is to convey steam from turbine extraction points through the following routes:

- From HP turbine exhaust (cold reheat) to heater 7 and 8
- From IP turbine extraction to heater 6 and the deaerator (heater 5)
- From LP turbine extraction to heaters 1, 2, 3, and 4

The steam extraction strategy for incorporating the VeloxoTherm™ CO_2 capture process maintained the same steam extraction strategy for the feedwater heaters. The enthalpies, temperatures and pressures for the feedwater extraction streams remain the same as for the No Capture Case (Case 11).

7.3.2.3 Circulating Water System

It is assumed that the plant is serviced by a public water facility and has access to groundwater for use as makeup cooling water with minimal pretreatment. All filtration and treatment of the circulating water are conducted on site. A mechanical draft, wood frame, counter-flow cooling tower is provided for the circulating water heat sink. Two 50 percent cooling water pumps (CWPs) are provided. The cooling water system (CWS) provides cooling water to the condenser, the auxiliary cooling water system, and the carbon capture and compression system.

The auxiliary cooling water system is a closed-loop (CL) system. Plate and frame heat exchangers with circulating water as the cooling medium are provided. This system provides cooling water to the lube oil coolers, turbine generator, boiler feed pumps, etc. All pumps, vacuum breakers, air release valves, instruments, controls, etc. are included for a complete operable system.

The introduction of the VeloxoTherm™ capture process does not impose any interstage cooling loads, such as those seen for the SOA CO_2 capture process described in the reference Capture Case as the cooling load for the TSA cycle is provided via ambient air. This results in a reduction in cooling load for Case 12V relative to Case 12 and a significant reduction in the circulating water mass flow and cooling tower duty when compared to Case 12. As in Case 12, the CO_2 compression train does require interstage cooling. Waste heat from the supersonic compression train specified in Case 12V is integrated with the VeloxoTherm™ hot air rinse stream, however, resulting in incrementally less interstage cooling than would be required for the conventional compression scenario presented in Case 12.

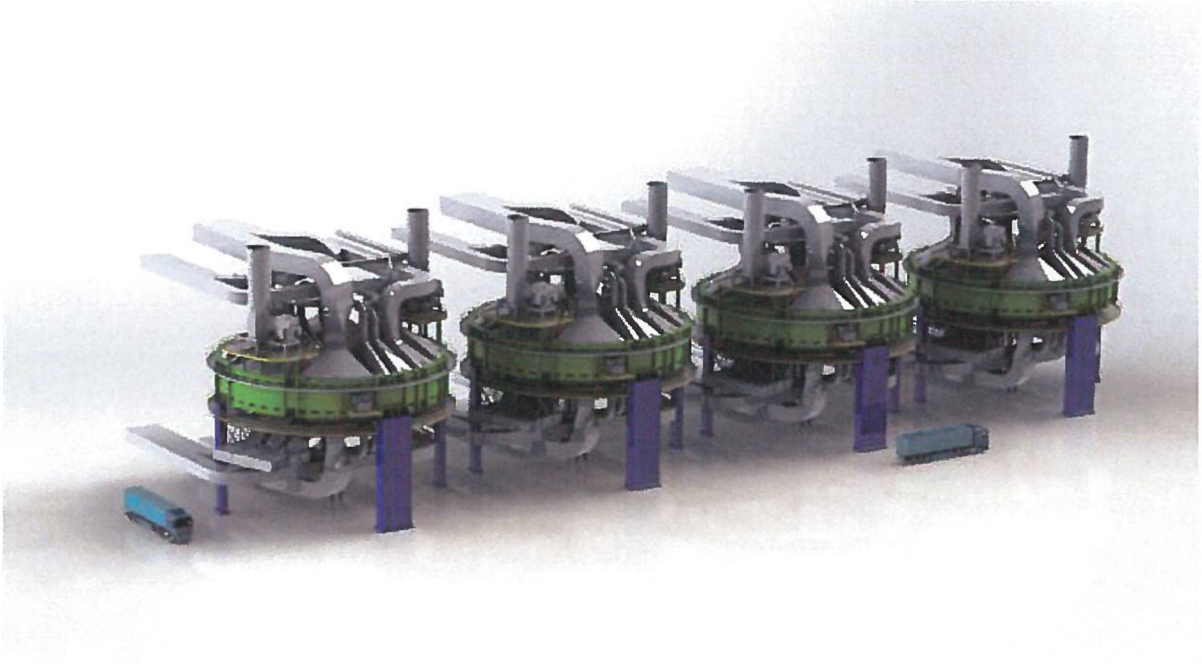
7.4 VeloxoTherm™ Carbon Dioxide Removal System

The VeloxoTherm™ process is a TSA cycle, which consists of a series of process steps which pass flue gas, regeneration steam and conditioning air through the structured adsorbent beds in a specific order. The first step of the process entails the introduction of flue gas into the structured adsorbent beds, where the CO_2 is adsorbed on to the surface of the structured adsorbent beds while the remainder of the flue gas vents to the stack. The CO_2-rich adsorbent bed then rotates to a sector of the process where low-grade steam (80°C/176°F, 40 kPa), extracted from the LP turbine, flows through the adsorbent bed releasing a stream of primarily CO_2 and steam. This product stream is produced at a vacuum condition of 30 kPa absolute (in order to promote the desorption of CO_2 and reduce steam consumption) and is then cooled and H_2O is recovered leaving a purified CO_2 product for compression and drying. After steam regeneration, the bed rotates through a sector where hot air removes any remaining moisture and fresh air cools the bed to prepare for the adsorption step again.

The VeloxoTherm™ TSA cyclic process is implemented in a rotating and continuous fashion through the design of the RAM. The RAM design is based on the same mechanical systems found in rotary heat exchangers, such as Ljungström® style air pre-heaters, that are already used in coal-fired power plants and operating at the same scale and conditions as in the VeloxoTherm™ process. The purpose of the RAM is to perform the VeloxoTherm™ process cycle in a rotating device that houses the proprietary adsorbent beds. Each adsorbent bed is exposed to sequential steps in the gas separation process as it rotates between a series of stator-mounted seals, together creating a continuous rotary switching valve. In the VeloxoTherm™ system design, instead of the matrix of heating elements that populate a typical rotary heat exchanger, contains arrays of the VeloxoTherm™ structured adsorbent beds. These beds are then rotated through the different steps of the cyclic TSA process.

For the purposes of the Phase 1 TEA, Inventys worked with Arvos, which manufactures the Ljungström® Air Preheater, to design a 30m diameter RAM for the Full Scale Commercial VeloxoTherm™ plant specifically used for the 550 MWe SC PC greenfield Case 12V. Exhibit 7-9 shows a 3-D rendering of the four (4) 30m diameter RAMs that have been designed for the Case 12V capture plant which is based on the conceptual design work completed during Phase 1 with Arvos. This RAM design, and the associated ducting transitions, was based on using two (2) TSA cycles per revolution (CPR). The use of 2 CPR allows the RAM to avoid pressure loading and thermal asymmetry associated with a 1 CPR design. This avoids large radial bearing loads and significant rotor deflections, as well as provides for longer seal life as a result of lower velocity of the seals, smaller bed modules and smaller transition ducts (easier flow distribution).

Exhibit 7-9: General Arrangement of VeloxoTherm™ RAMs for Case 12V (550MWe SC PC Installation)



7.4.1 RAM Design Approach

The Phase 1 Gap Analysis includes a detailed description of the design approach used during Phase 1 for the Full Scale Commercial RAM design used in Case 12V. This approach included working closely with Arvos in adopting their existing Ljungström® designs and having Arvos prepare a FEED study memorandum. Exhibit 7-10 outlines the primary individual sub-assemblies of the RAM that will be supplied by the preheater OEM, and Exhibit 7-10 summarizes the design approach used during Phase 1 for specifying the RAM for this Phase 1 TEA.

Exhibit 7-10: Phase 1 Design Approach for RAM used in Case 12V

RAM Component	Design Approach for Phase 1 TEA
Guide Bearing Assembly	Arvos conceptual design & drawings complete
Support Bearing Assembly	Arvos conceptual design & drawings complete
Peripheral Rotor Drive and Pin Rack System	Arvos conceptual design & drawings complete
Upper & Lower Pocket Ring Structures	Arvos conceptual design & drawings complete
Rotor Post and Support Trunnion Assembly	Arvos conceptual design & drawings complete
Pinned Connection of Rotor Modules to Rotor Post	Arvos conceptual design & drawings complete

RAM Component	Design Approach for Phase 1 TEA
Rotor Module Design and Rotor Construction	Arvos conceptual design & drawings complete
Center Support Application	Arvos conceptual design & drawings complete
Upper and Lower Circular Ring Center Structures	Inventys and Arvos, conceptual drawings complete
Upper and Lower Spoke Structures	Inventys and Arvos, conceptual drawings complete
Proprietary seal and rotary valve design	Inventys proprietary design, sized for Full Scale Commercial unit during Phase 1 for TEA purposes
Structured Adsorbent Bed Modules	Inventys proprietary design, completed for Full Scale Commercial during Phase 1
Flow Transition Ducting	Preliminary CFD completed during Phase 1, sizing and internals specified

7.4.2 RAM Sizing and Target Performance Specification

Machine sizing was based on a productivity factor of the structured adsorbent, bed length, and a safety margin applied to account for inefficiency of rotary valve and losses in packing density of adsorbent structure within the rotor. Adsorbent productivity measures the amount of CO_2 product that can be produced from a given bulk volume of structured adsorbent bed, and dictates the size of the RAM. Considerations must be made, however, to account for pressure drop across the RAM to minimize the parasitic load of the capture plant, as the pressure drop through the structured adsorbent bed increases with bed length. The RAM for Case 12V was sized based on a 10 kPa maximum pressure drop across the RAM for each process flow stream. The RAM sectors were sized based on a maximum of 8 kPa pressure drop for each stream thus leaving 2 kPa pressure drop allotted for the design of the RAM inlet/outlet duct transitions.

Exhibit 7-11 below provides a summary of the rating/sizing metrics for the RAMs targeted for Case 12V and used in the design basis. It is important to note that these figures of merit and rating parameters included performance targets for the VeloxoTherm™ adsorption process which incorporate certain identified technology gaps (density and vacuum assist) and R,D&D requirements highlighted in Section 5.2.2. As a result, the Phase 1 TEA represents targeted vs demonstrated performance, consistent with progressing on a pathway towards meeting DOE's programmatic goals for post-combustion capture economics.

Exhibit 7-11: RAM Sizing and Target Performance Rating for Case 12V

Rating Metric	Units	Case 12V Value	Description
Productivity	TPD/M3	5	A fundamental property of the TSA cycle and structured adsorbent - determines the volume of adsorbent required for the targeted CO2 production
Bed Length	m	1.5	Optimized for pressure drop vs RAM diameter for given adsorbent volume
Diameter	m	30	Currently demonstrated diameter for rotary air preheaters
Pressure Drop	kPa	10	Function of bed length and structured adsorbent design
No of RAMs	No.	4	Based on the currently demonstrated diameter for rotary air preheaters, maximum length for pressure drop considerations and productivity factor
Steam Ratio	kg/kg CO2	1.14	Based on vacuum TSA cycle designed for Phase 1 TEA and simulated with verified dynamic simulation
Rotation Speed	RPM	~0.15 - 0.3	The rotation speed is dictated by the duration of the TSA cycle, and the selection of 2 cycles per revolution for the design philosophy
Motor	hp	2x200 hp	Running safety factor of 1.351 for one motor (2x100% design)

7.4.3 Compression

The compression solution evaluated as part of this TEA leverages supersonic CO_2 compression R&D funded under DOE NETL contracts DE-FE-0000493 "Ramgen Supersonic Shock Wave Compression ... Technology" and DE-FE0026727 "Advanced CO_2 Compression with Supersonic Technology'. Aerodynamic and mechanical compression selection work was completed by technology developer of supersonic compression equipment for a nominal 13,000 TPD flue gas stream to align with the initial approximate scale of Case 12V (expected to be analogous in scale to DOE Case 12 for a 550 MW coal fired power plant). This compression technology was originally evaluated to provide the compression from the Carbon Capture Plant at discharge pressure of 14.7 psia to 2215 psia in two stages. As the Full Scale Commercial TSA cycle for the Phase 1 TEA was refined to include vacuum on the CO_2 production step, further evaluations were done to use the supersonic compression on the CO_2 product stream for the vacuum TSA process at 4.35 psia and compress to 2215 psia for injection into a pipeline.

For our discussion here we have labeled the compression stages as LP (Low Pressure, low vacuum to about 32 psia), IP (Intermediate pressure, from atmospheric to around 275 psia) and HP (High Pressure, above about 275 psia)

7.4.3.1 Supersonic CO_2 Compression Background

One of the key objectives of DOE contract DE-FE-0000493 was to design, build and demonstrated via test a supersonic CO_2 compressor that can accomplish a 10:1 pressure ratio in a single rotating inducer. Traditional subsonic compression technologies generally have pressure ratios of 2.2:1 or lower in a single impeller. The tested supersonic compressor was sized to compress in excess of 3,500 tonnes of CO_2 per day or the equivalent of 90 percent capture of a 200 MW coal-fired power plant slip stream. In December 2015, the test phase was concluded with the unit exceeding the 10:1 pressure ratio, delivering CO_2 at pipeline pressure.

One of the key objectives of contract DE-FE0026727 is to design, build and test a pilot scale, supersonic CO_2 compressor, applicable to new or existing coal-based electric generating plant. This project focuses on completing the testing of the existing HP development compressor discussed above (completed Dec 2015) and the design, manufacture and test of a corresponding LP compressor.

The HP compressor was tested and the LP compressor will be tested to confirm projected operating characteristics and performance levels are on track to meet the DOE's Carbon Capture and Storage goals for development of a pathway to achieve a deployment at a cost of \$40/tonne of CO_2 captured, excluding transportation and storage.

7.4.3.2 Case 12V Compressor Selection

This TEA is based on a TSA cycle design which produces a CO_2 stream at 4.35 psia ready for compression. Five (5) LP supersonic compressors will take the gas to 32 psia, two IP supersonic compressors will increase the pressure to 275 psia and the final 2 HP supersonic compressors will take the gas to 2215 psia. The additional waste heat available will be used to partially offset the compressor operating cost by integration with the RAM balance of plant systems and possibly the coal fired power plant.

The vacuum RAM design is based on the work done for the initial atmospheric TSA Cycle which produced a product stream at 14.6 psia. By moving to a vacuum design for the CO_2 product step, the parasitic load from steam consumption could be significantly reduced. These savings would outweigh the cost of the added compression required for a 4.35 to 2215 psia supersonic compression train.

A waste heat integration study was also completed, and recovering the mid-grade heat of the supersonic compressors via the hot air rinse stream, improved the integrated economics of the VeloxoTherm™ CO_2 capture process and supersonic compression technology. System level analysis indicates if the control volume is drawn around the compression and hot air rinse stream, the CO_2 waste heat stream developed contains significant energy to heat the hot air rinse required by the VeloxoTherm™ TSA cycle to the desired temperature. This alleviates the need to integrate the hot air rinse stream with the coal flue gas preheating system, and avoids significant fuel costs that could be required if the hot air rinse stream were heated using a natural gas fired heater.

7.4.3.3 Separators

There are three separator vessels specified for the CO_2 capture and compression process designed for Case 12V. V-2107A, V-2107B and V-2501 are vertical knock-out drums used to collect condensed water from the two-phased CO_2 product stream after the first LP, second LP, and IP compression stage intercoolers, respectively – the condensed water is sent to the waste water treatment system.

7.4.4 Carbon Dioxide Removal Ancillaries

In addition to the RAMs, compression train, some ancillary unit operations such as fans, heat exchangers and separator vessels have also been specified.

7.4.4.1 VeloxoTherm™ Fans

High efficiency 2-stage axial fans were specified for use in the design of the VeloxoTherm™ process used in Case 12V. These included the BL-2101 Induced Draft Feed Gas Fan, the BL-2102 Induced Draft Feed Recycle Fan, the BL-2105 Induced Draft Cooling Air Fan, and the BL-2106 Induced Draft Hot Air Rinse Fan. Each of these fans serves a slightly different purpose in moving various low pressure gases into and out of the RAMs, R-2101.

BL-2101 Induced Draft Feed Gas Fan pulls suction on a section of the RAM on the side opposite the incoming flue gas to the RAM from a flue gas duct at the adjacent power plant. The flue gases are cool (around 60°C/140°F) after the WFGD and are a mixture of primarily nitrogen, carbon dioxide, water, and oxygen with small amounts of secondary gases and some particulates typical of flue gas from a coal-fired power plant. The head developed by BL-2102 is expected to be approximately 1.35 psi. The fan will be driven direct by a single speed medium voltage electric motor. Control of flow will be via an actuated louvered inlet damper.

BL-2102 Induced Draft Feed Recycle Fan pulls suction on a section of the RAM on the side opposite the incoming fresh feed to the RAM. The fan removes a portion of the gas that has passed through the adsorbent and recycles it back to the incoming fresh flue gas. The head developed by BL-2102 is expected to be approximately 1.45 psi. The fan will be driven direct by a single speed medium voltage electric motor. Control of flow will be via an actuated louvered inlet damper.

The BL-2105 Induced Draft Cooling Air Fan pulls suction on a section of the RAM that is open to atmosphere on the inlet to that section. It pulls outside air through the adsorbent bed for cooling/drying and then discharges the warmed air to the plant vent stack. The head developed by BL-2105 is expected to be approximately 1.45 psi. The fan will be driven by a single speed medium voltage motor. Control of flow will be via an actuated louvered inlet damper.

BL-2106 Induced Draft Hot Air Rinse Fan pulls suction on a section of the RAM on the side opposite the incoming heated fresh air to the RAM (hot rinse section). It discharges warm air to the plant vent stack. The head developed by BL-2106 is expected to be approximately 1.75 psi. The fan will be driven by a single speed medium voltage motor. Control of flow will be via an actuated louvered inlet damper.

7.4.4.2 Heat Exchangers

The group of heat exchangers covered in this description includes E-1102A, B and C (Hot Air Rinse Heaters), E-2107A and B (LP Stage Compression Intercoolers), E-2501 (IP Stage Compression Intercooler), and E-2502/E-2503 (HP Stage 1 and HP Stage 2 Compression Intercoolers).

The Hot Air Rinse Heaters (E-1102A, B and C) are plate and frame heat exchangers with a design duty of 46.8, 23.6 and 42.7 GJ/hr respectively. The Hot Air Rinse Heaters recover heat from the supersonic compression stage and are rated based on the waste heat integration study performed by Dresser-Rand during Phase 1.

Compression Stage Intercoolers, E-2107A/B, E-2501, E-2502, and E-2503 are horizontal shell and tube exchangers that use cooling water from the circulating water system and reject heat to the cooling water tower.

7.5 Performance Results

7.5.1 Summary

Exhibit 7-12: Case 12V Performance Summary

Performance Summary		
Total Gross Power, MW		**711.6**
CO2 Capture/Removal Auxiliaries, kW		48.5
CO2 Compression, kW		67.2
Balance of Plant, kW		35.4
Total Auxiliaries, MW		**151.1**
Net Power, MW		**560.5**
HHV Net Plant Efficiency (%)		30.7%
HHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	11,716	(11,114)
LHV Net Plant Efficiency (%)		31.9%
LHV Net Plant Heat Rate, kJ/kWh (Btu/kWh)	11,300	(10,719)
Condenser Duty, GJ/hr (MMBtu/hr)	1,583	(1,500)
As-Received Coal Feed, kg/hr (lb/hr)	242,217	(533,996)
Limestone Sorbent Feed, kg/hr (lb/hr)	24,036	(57,245)
HHV Thermal Input, kWth (Btu)	1,824,230	(1,730,445)
LHV Thermal Input, kWth (Btu)	1,759,505	(1,669,036)
Raw Water Withdrawal, m3/min (gpm)	16.0	(4,226)
Raw Water Consumption, m3/min (gpm)	6.2	(1,628)

Exhibit 7-13: Case 12V Auxiliary Loads & Power Summary

POWER SUMMARY (Gross Power at Generator Terminals, kWe)	
Steam Turbine Power	711,588
Total Gross Power	**711,588**
Auxiliary Load Summary	
Coal Handling and Conveying	497
Pulverizers	3,625

POWER SUMMARY (Gross Power at Generator Terminals, kWe)	
Sorbent Handling & Reagent Preparation	1,160
Ash Handling	691
Primary Air Fans	1,650
Forced Draft Fans	2,339
Induced Draft Fans	9,485
SCR	65
Baghouse	91
Wet FGD	3,873
VeloxoTherm™ Auxiliaries	48,481
CO_2 Compression	67,162
Miscellaneous Balance of Plant[1,2]	2,000
Steam Turbine Auxiliaries	400
Condensate Pumps	1,052
Circulating Water Pumps	3,805
Ground Water Pumps	380
Cooling Tower Fans	1,815
Transformer Losses	2,491
Total Auxiliaries	**151,062**
Net Power	**560,526**

1. Boiler Feed Pumps are Turbine driven
2. Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

7.5.2 Environmental Performance

As for Case 12 in the Reference Baseline Report, the air emissions calculated for Case 12V is presented in Exhibit 7-14.

Exhibit 7-14: Case 12V Air Emissions Table

	kg/GJ (lb/MMBtu)	Tonne/year (ton/year)	kg/MWh (lb/MWh)
SO_2	0.037 (0.086)	1809 (1995)	0.34 (0.75)
NOx	0.03 (0.07)	1473 (1624)	0.28 (0.61)
PM	0.006 (0.013)	274 (302)	0.05 (0.11)
Hg	4.9E-7 (1.14 lb/TBtu)	0.024 (.026)	4.5E-6 (1E-5)
CO_2	8.76 (20.35)	428,557 (472,403)	80.8 (178.2)

A carbon balance has also been calculated for Case 12V based on the process simulation work completed in Aspen+ and demonstrated in Exhibit 7-15. Carbon is introduced to the overall system in the coal feedstock and limestone feed, as well as via primary and secondary air to the PC boiler, infiltration air, hot air rinse and cooling air in to the VeloxoTherm™ process (via CO_2) and oxidation air to the FGD system. This carbon is balanced by the CO_2 product stream, as well as the stack gas (including the vented streams from the RAMs) and FGD product.

Exhibit 7-15: Case 12V Carbon Balance

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Coal	154,413	Stack Gas	16,261
Air (CO_2)	2,351	FGD Product	2,230
FGD Reagent	2,884	CO_2 Product	141,157
TOTAL	159,648	TOTAL	159,648

The sulfur balance for Case 12V considers the sulfur composition of the design coal, as well as the sulfur removed in the FGD and the sulfur vented to the stack in the hot air rinse stream from the VeloxoTherm™ capture process. The VeloxoTherm™ capture process is resilient to SOx and it is regenerated from the adsorbent beds during the TSA cycle, so the stack composition of SO_2 is higher than in the reference Capture Case, but meets the air emissions performance targets and does not produce any degradation products.

Exhibit 7-16: Case 12V Sulfur Balance

Sulfur In		Sulfur Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Coal	6,080 (13,404)	FGD Product	5,958 (13,136)
		Stack Gas (After CO2 Capture Process)	122 (268)
TOTAL	**6,080 (13,404)**	**TOTAL**	**6,080 (13,404)**

Exhibit 7-17: Case 12V Water Balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
VeloxoTherm CO_2 Capture	0	0	0	0	0
FGD Makeup	3.8 (992)	0	3.8 (992)	0	3.8 (992)
BFW Makeup	9.8 (2,596)	0	9.8 (2,596)	0	9.8 (2,596)
Cooling Tower	583.3 (154,092)	577.1 (152,464)	6.16 (15.96)	0	6.16 (15.96)
Total	596.9 (157,680)	577.1 (152,464)	19.76 (5,215)	0	19.76 (5,215)

The overall water use balance for Case 12V is provided in Exhibit 7-17. For the purposes of this table, Total water demand for the Cooling Tower is interpreted as the total circulating flow rate, with raw water withdrawal and consumption being equal and accounting for evaporative, drift and blowdown losses. Because the VeloxoTherm™ process contacts the regeneration steam extracted from the LP turbine with the adsorbent and process gases, a boiler feedwater makeup stream is required. For water-constrained sites a direct contact cooler could be specified to recover most of the water from the regeneration steam from the hot air rinse to stack stream (this water would relatively clean and suitable for direct return to the existing full-flow condensate polishing system).

7.6 Economic Evaluation

7.6.1 Capital Cost Estimation

The capital costs have been estimated for Case 12V in keeping with the methodology presented in the Reference Baseline Study, as well as the June 2011 cost update to that study. This involves estimating and reporting the capital costs at four (4) different levels:

- **Bare Erected Cost (BEC):** Process Equipment Costs, supporting facilities, materials and labor
- **Total Plant Cost (TPC):** BEC + engineering/construction management/home office and contractor premiums (the cost estimate is based on an engineering, procurement and construction management – or EPCM - approach), and process and project contingencies
- **Total Overnight Costs (TOC):** TPC + preproduction costs, inventory capital, financing costs and other owners costs
- **Total As Spent Cost (TASC):** TOC + escalation during capital expenditure period and interest during construction

This TEA has also been prepared according to an AACEi Class IV level of estimate and project definition. The definition of a Class IV estimate is provided in Exhibit 7-18.

Exhibit 7-18: AACEi Cost Estimate Classification (AACEi, 2011)

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges (*)
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	**L**: -20% to -50% **H**:+30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	**L**: -15% to -30% **H**:+20% to +50%
Class 3	10% to 40%	Budget Authorization or control	Semi-detailed unit costs with assembly level line items.	**L**: -10% to -20% **H**:+10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	**L**: -5% to -15% **H**:+5% to +20%
Class 1	65% to 100%	Check Estimate or bid/tender	Detailed unit cost with detailed take-off	**L**: -3% to -10% **H**:+3% to +15%

The details of the cost estimation methodology can be found in the Reference Baseline Report, with additional detail and information being available in the following QGESS documents:

- Cost Estimation Methodology for NETL Assessments of Power Plant Performance. DOE/NETL-2011/1455
- Capital Cost Scaling Methodology. DOE/NETL-341/013113
- Performing a Techno-economic Analysis for Power Generation Plants. DOE/NETL-2015/1726

The capital costs for the majority of the power plant, not including novel equipment or new technologies were estimated using the DOE/NETL guidelines for capital scaling methodologies from the Reference Capture Case, while novel equipment was estimated using a bottoms-up approach from vendor quotes, parametric models and the AACEi distributive factors method for labor and materials.

7.6.1.1 Power Plant

The DOE and NETL have provided a QGESS document for scaling cost estimates that are published in the DOE/NETL's systems studies and Baseline Studies, entitled "Capital Cost Scaling Methodology" (Jan 2013). Inventys has adopted this approach for estimating the equipment, material, labor and Bare Erected Cost (BEC) for the unit operations associated with power plant (see BFD and scope provided above). The reference Capture Case (Case 12 from the Reference Baseline Report) was used to scale capital costs for each element of the Chart of Accounts (COA) of the power plant, as Case 12 is closest in scale to Case 12V.

The general methodology for scaling cost estimates from NETL's reference systems studies involves using the following equation for each of the equipment, materials and labor categories.

$$SC = RC * \left(\frac{SP}{RP}\right)^{Exp}$$

Where:

- Exp – Exponent from corresponding account and technology/category from the "Capital Cost Scaling Methodology" report
- RC – Reference cost for cost category from Reference Capture Case (Case 12 of Reference Baseline Report)
- RP – Value of reference parameter (i.e. coal feed rate) from Reference Capture Case
- SC – Scaled Cost
- SP – Value of reference parameter for new scale (i.e. coal feed rate)

For each account, the estimates for engineering, construction management, home office expenses and fees/premiums (Eng'g CM HO & Fee) are calculated based on the corresponding % of BEC for the Reference Capture Case as a % of BEC, generally 8-10%. Process Contingences are applied on a % basis and project contingencies are applied as a % of (BEC + Eng'g CM HO & FEE + Process Contingency).

7.6.1.2 CO_2 Capture System and Compression

For the novel equipment associated with VeloxoTherm™ and used in the Case 12V TEA presented herein, a mixture of cost estimation techniques was used to arrive at purchased equipment costs, including:

a) **Direct vendor quotes:** The RAM is the only piece of non-standard equipment included in the scope of the VeloxoTherm™ process, and it is based on existing rotary air preheaters which have been produced at the same scale as considered in Case 12V. Inventys acquired a budgetary quote for the full scale RAM from Arvos for the purposes of this TEA. Case 12V also considers the Dresser-Rand supersonic CO_2 compression technology (DATUM-S) due to unique heat integration benefits, Dresser-Rand provided a budgetary quote for the supersonic compression train, including conceptual cost guidance for the LP stages required to accommodate the Case 12V product vacuum.

b) **Recent Vendor Quotes:** High efficiency axial fans have been used for the blowers sized for the VeloxoTherm™ process, these are produced by a large utility-industry OEM and a recent vendor quote, along with capital scaling over a small size range was used.

c) **Standard Parametric Models and Study Estimates:** Heat exchangers and separators were costed using the updated database available in the Aspen Process Economics Analyzer, along with capital scaling. Recent vendor conference presentations on CO_2 compression and dehydration technology were used for estimating scaled TEG installed equipment costs.

Inventys has considered this data, and adopted the practice of the AACEi for developing a Techno-Economic Analysis as presented in AACEi 16R-90. Inventys has used the 16R-90 distributive factors approach to estimate materials and labor costs as factors of equipment costs when developing the BEC cost estimate for the novel portion of the Case 12V cost estimate. These factors for bulk materials and labor are provided in Exhibit 7-19 and were applied to equipment costs to arrive at a BEC cost for each sub-account of the CO_2 capture and compression system which uses novel equipment.

Exhibit 7-19: AACEi Distributive Factors used for Case 12V novel equipment capital costs (BEC)

AACEi Table B-3: Distributive Factors for Bulk Materials			
Gas Process <400°F, <150 psig			
Bulk Category	**Materials [a]**	**Labor [b]**	**Comments**
Foundations	6%	133%	
Structural Steel	5%	50%	
Buildings	~~3%~~	~~100%~~	Included in Reference Capture Case accounts, no incremental buildings for VeloxoTherm™ required
Insulation	1%	150%	
Instruments	6%	40%	
Electrical	~~8%~~	~~75%~~	Electrical costs are a separate account in the Reference Capture Case and are scaled on total auxiliary load, including VeloxoTherm™
Piping	45%	50%	
Painting	50%	300%	
Miscellaneous	~~3%~~	~~80%~~	Included in Reference Capture Case accounts

*Material Costs = [a] * Equipment Costs*
*Labor Costs – [b] * Material Costs*

Although the DOE's Reference Baseline Report does not include estimates for indirect labor costs, the capital cost for the VeloxoTherm™ CO_2 capture process and novel supersonic compression train does include a conservative estimate of indirect labor costs. The indirect costs considered for Case 12V includes the following:

- Indirect Field Labor (supervision, field and staff engineering, support personnel, overhead, etc..)
- Construction Support (temporary buildings, roads and construction utilities)
- Construction supplies, large equipment, small tools and consumables
- Labor benefits and fringes

Consistent with the guidelines provided in Table B-6 and Figure 1-Appendix B of AACEi 16R-90 these indirect costs have been applied as percentage of direct labor costs for equipment setting, installation and construction. The operating labor estimates provided in the June-2011 cost update to the Reference Baseline report were used to arrive at a base year average crew direct wage rate of \$39.70/hr and a labor burden rate of 30% for fringes and benefits.

In addition to the above labor and materials for plant bulks and associated labor, setting equipment in place requires additional labor and material costs. AACEi 16R-90 provides factors to determine labor cost to set equipment onto prepared foundations/supports which includes costs for rigging, alignment and making equipment ready for operation. However, AACEi 16R-90 specifies that these factors are not appropriate for large equipment as seen in both the Large Scale Pilot (CO_2NCEPT ~25MWe slipstream proposed for Phase 2) and the Full Scale Commercial equipment for Case 12V. In preparing the Project Baseline for Phase 2, however, man-hours and labor costs, as well as materials and subcontracts were estimated for all equipment installation for an AACEi Class III budgetary control cost estimate. This allowed the direct calculation of labor and material costs for setting equipment specific to the VeloxoTherm™ process, which is presented in Exhibit 7-20 and compared to the equipment setting costs assumed for Case 12V.

Exhibit 7-20: Case 12V vs Large Scale Pilot (CO_2NCEPT) Equipment Setting Costs for VeloxoTherm™

Equipment Setting Costs			
Ratio of labor and materials to purchased equipment cost for setting equipment			
Purchased Equipment	**CO_2NCEPT Large Scale Pilot** Class 3 Estimate	**Case 12V Assumption**	**Comments**
RAM	5.2%	10.0%	Case 12V estimate based on conversations with rotary air preheater manufacturer (ARVOS)
Blower/Fan	3.3%	5.0%	
Compressor	4.0%	5.0%	
Heat Exchanger	2.0%	5.0%	
Cooling Tower	1.6%	5.0%	
Vessels	1.2%	5.0%	
Pumps	5.4%	5.0%	

As per the cost estimation methodology, Eng'g CM HO & Fee, process and project contingencies for the novel equipment categories were applied as percentages. A process contingency of 20% was applied both to the VeloxoTherm™ technology and the supersonic compression train in Case 12V.

7.6.1.3 Total Overnight Cost

Total Plant Cost is estimated for each account in the Baseline Studies COA for Case 12V, and built up to a total TPC. This TPC is then built up to Total Overnight Cost (TOC) using the DOE methodology and assumptions. TOC being the sum of:

a) Preproduction Costs which are the sum of:

- 6 months all labor
- 1 month maintenance materials
- 1 month non-fuel consumables
- 1 month waste disposal
- 25% of 1 month's fuel cost at 100% Capacity Factor
- 2% of Total Plant Cost

b) Inventory Capital are the sum of:
    - 60 day supply of fuel and consumables at 100% capacity factor
    - 0.5% of TPC for spare parts
c) Initial Cost of Catalyst and Chemicals
d) Land at $900,000
e) 15% of TPC for Other Owners Costs (Management Reserve)
f) Financing Costs at 2.7% of TPC

Total As Spent Cost (TASC) is calculated using the TASC multiplier of 1.14 based on a high risk investor-owned utility, with a 5 year construction period and a 30 year plant operational life.

Exhibit 7-21: Case 12V Capital Cost Estimate Detail

	Case:	12V - Supercritical PC w/ VeloxoTherm™CO2 Capture							Estimate Type:	Class IV/V Study	
	Plant Size (MWe, net):	560.526							Cost Base:	Jun 2011	
Acct.		Equipment	Material	Labor		Bare Erected	Eng'g CM	Contingencies		Total Plant Cost	
No.	Item/Description	Cost	Cost	Direct	Indirect	Cost	H.O. & Fee	Process	Project	$/1,000	$/kW
1. COAL & SORBENT HANDLING											
1.1	Coal Receive & Unload	$4,819	$0	$2,171	$0	$6,990	$606	$0	$1,139	$8,735	$16
1.2	Coal Stackout & Reclaim	$6,228	$0	$1,392	$0	$7,621	$645	$0	$1,240	$9,506	$17
1.3	Coal Conveyors	$5,790	$0	$1,377	$0	$7,167	$608	$0	$1,166	$8,941	$16
1.4	Other Coal Handling	$1,515	$0	$318	$0	$1,833	$155	$0	$298	$2,286	$4
1.5	Sorbent Receive & Unload	$194	$0	$58	$0	$252	$22	$0	$41	$315	$1
1.6	Sorbent Stackout & Reclaim	$3,129	$0	$565	$0	$3,695	$311	$0	$600	$4,606	$8
1.7	Sorbent Conveyors	$1,116	$243	$270	$0	$1,629	$136	$0	$265	$2,030	$4
1.8	Other Sorbent Handling	$675	$159	$349	$0	$1,183	$101	$0	$192	$1,476	$3
1.9	Coal & Sorbent Hnd.Foundations	$0	$5,580	$7,356	$0	$12,936	$1,213	$0	$2,122	$16,271	$29
	SUBTOTAL 1:	**$23,467**	**$5,981**	**$13,857**	**$0**	**$43,305**	**$3,798**	**$0**	**$7,342**	**$54,167**	**$97**
2. COAL & SORBENT PREP & FEED											
2.1	Coal Crushing & Drying	$2,789	$0	$536	$0	$3,325	$281	$0	$541	$4,147	
2.2	Coal Conveyor to Storage	$7,143	$0	$1,538	$0	$8,681	$734	$0	$1,412	$10,828	$19
2.3	Coal Injection System	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2.4	Misc.Coal Prep & Feed	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2.5	Sorbent Prep Equipment	$5,330	$231	$1,092	$0	$6,652	$560	$0	$1,082	$8,295	$15
2.6	Sorbent Storage & Feed	$642	$0	$243	$0	$884	$76	$0	$145	$1,105	$2
2.7	Sorbent Injection System	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2.8	Booster Air Supply System	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2.9	Coal & Sorbent Feed Foundation	$0	$658	$578	$0	$1,236	$115	$0	$202	$1,553	$3
	SUBTOTAL 2:	**$15,904**	**$889**	**$3,986**	**$0**	**$20,779**	**$1,766**	**$0**	**$3,382**	**$25,928**	**$46**
3. FEEDWATER & MISC. BOP SYSTEMS											
3.1	Feedwater System	$26,374	$0	$8,504	$0	$34,878	$2,980	$0	$5,679	$43,537	$78
3.2	Water Makeup & Pretreating	$4,602	$0	$1,456	$0	$6,058	$553	$0	$1,322	$7,933	$14
3.3	Other Feedwater Subsystems	$8,297	$0	$3,406	$0	$11,703	$1,006	$0	$1,906	$14,616	$26
3.4	Service Water Systems	$921	$0	$482	$0	$1,403	$126	$0	$306	$1,836	$3
3.5	Other Boiler Plant Systems	$10,391	$0	$9,824	$0	$20,214	$1,839	$0	$3,308	$25,362	$45
3.6	FO Supply Sys & Nat Gas	$349	$0	$407	$0	$756	$68	$0	$123	$947	$2
3.7	Waste Treatment Equipment	$5,368	$0	$3,108	$0	$8,475	$816	$0	$1,858	$11,149	$20
3.8	Misc. Equip.(cranes,AirComp.,Comm.)	$3,414	$0	$1,057	$0	$4,471	$425	$0	$979	$5,874	$10
	SUBTOTAL 3:	**$59,716**	**$0**	**$28,243**	**$0**	**$87,959**	**$7,814**	**$0**	**$15,481**	**$111,254**	**$198**

	Case:	12V - Supercritical PC w/ VeloxoTherm™CO2 Capture						Estimate Type:	Class IV/V Study		
	Plant Size (MWe, net):	560.526						Cost Base:	Jun 2011		
Acct.		Equipment	Material	Labor		Bare Erected	Eng'g CM	Contingencies		Total Plant Cost	
No.	Item/Description	Cost	Cost	Direct	Indirect	Cost	H.O. & Fee	Process	Project	$/1,000	$/kW
4. PC BOILER											
4.1	PC Boiler & Accessories	$222,034	$0	$126,514	$0	$348,548	$33,545	$0	$38,210	$420,303	$750
4.2	SCR (w/4.1)					$0	$0	$0	$0	$0	$0
4.3	Open					$0	$0	$0	$0	$0	$0
4.4	Boiler BoP (w/ ID Fans)					$0	$0	$0	$0	$0	$0
4.5	Primary Air System	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
4.6	Secondary Air System	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
4.8	Major Component Rigging	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
4.9	Boiler Foundations	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
	SUBTOTAL 4:	**$222,034**	**$0**	**$126,514**	**$0**	**$348,548**	**$33,545**	**$0**	**$38,210**	**$420,303**	**$750**
5. FLUE GAS CLEANUP											
5.1	Absorber Vessels & Accessories	$79,970	$0	$17,098	$0	$97,068	$9,011	$0	$10,608	$116,687	$208
5.2	Other FGD	$4,173	$0	$4,697	$0	$8,870	$840	$0	$971	$10,681	$19
5.3	Bag House & Accessories	$23,215	$0	$14,631	$0	$37,846	$3,557	$0	$4,140	$45,544	$81
5.4	Other Particulate Removal Materials	$1,571	$0	$1,669	$0	$3,240	$307	$0	$355	$3,902	$7
5.5	Gypsum Dewatering System	$6,508	$0	$1,098	$0	$7,606	$705	$0	$831	$9,142	$16
5.6	Mercury Removal System	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5.9	Open	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
	SUBTOTAL 5:	**$115,436**	**$0**	**$39,194**	**$0**	**$154,629**	**$14,420**	**$0**	**$16,905**	**$185,954**	**$332**
5B. CO2 REMOVAL & COMPRESSION											
5B.1	CO2 Removal System	$39,754	$13,403	$10,640	$9,249	$73,046	$6,803	$14,609	$18,892	$113,350	$202
5B.2	CO2 Compression & Drying	$59,218	$35,827	$26,784	$21,497	$143,326	$13,379	$28,665	$37,074	$222,445	$397
	SUBTOTAL 5B:	**$98,972**	**$49,230**	**$37,425**	**$30,746**	**$216,372**	**$20,183**	**$43,274**	**$55,966**	**$335,795**	**$599**
6. COMBUSTION TURBINE/ACCESSORIES											
6.1	Combustion Turbine Generator	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
6.2	Open	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
6.3	Compressed Air Piping	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
6.9	Combustion Turbine Foundations	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
	SUBTOTAL 6:	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
7. HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
7.2	HRSG Accessories	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
7.3	Ductwork	$10,983	$0	$6,933	$0	$17,916	$1,513	$0	$2,915	$22,344	$40
7.4	Stack	$10,942	$0	$6,359	$0	$17,301	$1,624	$0	$1,892	$20,818	$37
7.9	Duct & Stack Foundations	$0	$1,097	$1,302	$0	$2,400	$224	$0	$525	$3,149	$6
	SUBTOTAL 7:	**$21,925**	**$1,097**	**$14,594**	**$0**	**$37,616**	**$3,362**	**$0**	**$5,332**	**$46,310**	**$83**

	Case:	12V - Supercritical PC w/ VeloxoTherm™CO2 Capture							Estimate Type:	Class IV/ V Study	
	Plant Size (MWe, net):	560.526							Cost Base:	Jun 2011	
Acct.		Equipment	Material	Labor		Bare Erected	Eng'g CM	Contingencies		Total Plant Cost	
No.	Item/ Description	Cost	Cost	Direct	Indirect	Cost	H.O. & Fee	Process	Project	$/ 1,000	$/ kW
8. STEAM TURBINE GENERATOR											
8.1	Steam TG & Accessories	$76,878	$0	$9,463	$0	$86,341	$7,580	$0	$9,392	$103,312	$184
8.2	Turbine Plant Auxiliaries	$483	$0	$1,029	$0	$1,512	$145	$0	$166	$1,823	$3
8.3	Condenser & Auxiliaries	$6,705	$0	$2,454	$0	$9,159	$855	$0	$1,002	$11,016	$20
8.4	Steam Piping	$27,406	$0	$12,177	$0	$39,583	$3,034	$0	$6,392	$49,009	$87
8.9	TG Foundations	$0	$1,443	$2,382	$0	$3,825	$360	$0	$837	$5,022	$9
	SUBTOTAL 8:	**$111,472**	**$1,443**	**$27,505**	**$0**	**$140,419**	**$11,973**	**$0**	**$17,788**	**$170,181**	**$304**
9. COOLING WATER SYSTEM											
9.1	Cooling Towers	$8,535	$0	$2,639	$0	$11,174	$1,041	$0	$1,222	$13,437	$24
9.2	Circulating Water Pumps	$1,606	$0	$128	$0	$1,733	$148	$0	$188	$2,069	$4
9.3	Circ.Water System Auxiliaries	$512	$0	$68	$0	$580	$53	$0	$63	$696	$1
9.4	Circ.Water Piping	$0	$4,314	$3,907	$0	$8,221	$728	$0	$1,342	$10,291	$18
9.5	Make-up Water System	$458	$0	$589	$0	$1,046	$96	$0	$172	$1,314	$2
9.6	Component Cooling Water Sys	$417	$0	$320	$0	$738	$67	$0	$121	$926	$2
9.9	Circ.Water System Foundations & Structures	$0	$2,400	$3,985	$0	$6,384	$602	$0	$1,397	$8,383	$15
	SUBTOTAL 9:	**$11,527**	**$6,714**	**$11,635**	**$0**	**$29,876**	**$2,735**	**$0**	**$4,505**	**$37,116**	**$66**
10. ASH/ SPENT SORBENT HANDLING SYS											
10.1	Ash Coolers	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10.2	Cyclone Ash Letdown	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10.3	HGCU Ash Letdown	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10.4	High Temperature Ash Piping	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10.5	Other Ash Recovery Equipment	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10.6	Ash Storage Silos	$824	$0	$2,521	$0	$3,345	$321	$0	$367	$4,033	$7
10.7	Ash Transport & Feed Equipment	$5,473	$0	$5,425	$0	$10,898	$1,004	$0	$1,190	$13,092	$23
10.8	Misc. Ash Handling Equipment	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10.9	Ash/ Spent Sorbent Foundation	$0	$186	$228	$0	$414	$39	$0	$91	$544	$1
	SUBTOTAL 10:	**$6,297**	**$186**	**$8,175**	**$0**	**$14,657**	**$1,364**	**$0**	**$1,647**	**$17,669**	**$32**
11. ACCESSORY ELECTRIC PLANT											
11.1	Generator Equipment	$2,183	$0	$349	$0	$2,532	$227	$0	$207	$2,965	$5
11.2	Station Service Equipment	$6,594	$0	$2,211	$0	$8,804	$819	$0	$722	$10,345	$18
11.3	Switchgear & Motor Control	$7,569	$0	$1,315	$0	$8,884	$822	$0	$970	$10,676	$19
11.4	Conduit & Cable Tray	$0	$5,190	$16,768	$0	$21,959	$2,050	$0	$3,601	$27,609	$49
11.5	Wire & Cable	$0	$9,882	$17,665	$0	$27,548	$2,212	$0	$4,463	$34,223	$61
11.6	Protective Equipment	$306	$0	$1,063	$0	$1,369	$131	$0	$150	$1,650	$3
11.7	Standby Equipment	$1,647	$0	$38	$0	$1,685	$155	$0	$184	$2,023	$4
11.8	Main Power Transformers	$15,723	$0	$226	$0	$15,949	$1,209	$0	$1,716	$18,874	$34
11.9	Electrical Foundations	$0	$413	$1,050	$0	$1,463	$138	$0	$321	$1,922	$3
	SUBTOTAL 11:	**$34,021**	**$15,485**	**$40,686**	**$0**	**$90,192**	**$7,762**	**$0**	**$12,334**	**$110,287**	**$197**

Case:		12V - Supercritical PC w/ VeloxoTherm™CO2 Capture						Estimate Type:	Class IV/V Study		
Plant Size (MWe, net):		560.526						Cost Base:	Jun 2011		
Acct. No.	Item/Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/kW
12. INSTRUMENTATION & CONTROL											
12.1	PC Control Equipment	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
12.2	Combustion Turbine Control	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
12.3	Steam Turbine Control	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
12.4	Other Major Component Control	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
12.5	Signal Processing Equipment	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
12.6	Control Boards,Panels & Racks	$628	$0	$384	$0	$1,013	$95	$51	$173	$1,332	$2
12.7	Distributed Control System Equipment	$6,346	$0	$1,132	$0	$7,478	$691	$374	$854	$9,397	$17
12.8	Instrument Wiring & Tubing	$3,826	$0	$6,963	$0	$10,790	$875	$539	$1,830	$14,033	$25
12.9	Other I & C Equipment	$1,793	$0	$4,152	$0	$5,944	$568	$297	$681	$7,491	$13
	SUBTOTAL 12:	**$12,594**	**$0**	**$12,631**	**$0**	**$25,225**	**$2,228**	**$1,261**	**$3,539**	**$32,253**	**$58**
13. IMPROVEMENTS TO SITE											
13.1	Site Preparation	$0	$61	$1,291	$0	$1,351	$131	$0	$297	$1,779	$3
13.2	Site Improvements	$0	$2,014	$2,661	$0	$4,675	$464	$0	$1,028	$6,167	$11
13.3	Site Facilities	$3,610	$0	$3,788	$0	$7,398	$736	$0	$1,627	$9,761	$17
	SUBTOTAL 13:	**$3,610**	**$2,075**	**$7,740**	**$0**	**$13,425**	**$1,331**	**$0**	**$2,951**	**$17,707**	**$32**
14. BUILDINGS & STRUCTURES											
14.1	Boiler Building	$0	$10,440	$9,175	$0	$19,615	$1,726	$0	$3,201	$24,542	$44
14.2	Turbine Building	$0	$15,031	$13,998	$0	$29,029	$2,561	$0	$4,739	$36,329	$65
14.3	Administration Building	$0	$758	$800	$0	$1,558	$139	$0	$255	$1,951	$3
14.4	Circulation Water Pumphouse	$0	$117	$93	$0	$209	$18	$0	$34	$262	$0
14.5	Water Treatment Buildings	$0	$604	$551	$0	$1,156	$102	$0	$189	$1,446	$3
14.6	Machine Shop	$0	$506	$340	$0	$846	$74	$0	$137	$1,057	$2
14.7	Warehouse	$0	$343	$344	$0	$687	$61	$0	$112	$860	$2
14.8	Other Buildings & Structures	$0	$280	$239	$0	$519	$45	$0	$85	$649	$1
14.9	Waste Treating Building & Str.	$0	$515	$1,559	$0	$2,074	$193	$0	$340	$2,607	$5
	SUBTOTAL 14:	**$0**	**$28,594**	**$27,100**	**$0**	**$55,694**	**$4,919**	**$0**	**$9,091**	**$69,703**	**$124**

	Case:	12V - Supercritical PC w/ VeloxoTherm™CO2 Capture							Estimate Type:	Class IV/ V Study	
	Plant Size (MWe, net):	560.526							Cost Base:	Jun 2011	
Acct.		Equipment	Material	Labor		Bare Erected	Eng'g CM	Contingencies		Total Plant Cost	
No.	Item/ Description	Cost	Cost	Direct	Indirect	Cost	H.O. & Fee	Process	Project	$/1,000	$/kW
TOTAL COST		$736,974	$111,695	$399,283	$30,746	$1,278,698	$117,199	$44,535	$194,472	$1,634,626	$2,916
OWNERS COSTS											
Preproduction Costs											
	6 Months All Labor									$11,240	$20
	1 Month Maintenance Materials									$1,559	$3
	1 Month Non-fuel Consumables									$2,824	$5
	1 Month Waste Disposal									$475	$1
	25% of 1 Month's Fuel Cost at 100% CF									$3,347	$6
	2% of TPC									$32,693	$58
	Subtotal									**$52,138**	**$93**
Inventory Capital											
	60 day supply of fuel and consumables at 100% CF									$31,962	$57
	0.5% of TPC (spare parts)									$8,173	$15
	Subtotal									**$40,135**	**$72**
	Initial Cost of Catalyst and Chemicals									**$15**	**$0**
	Land									**$900**	**$2**
	Other Owner's Costs									**$245,194**	**$437**
	Financing Costs									**$44,135**	**$79**
TOTAL OVERNIGHT COSTS (TOC)										$2,017,142	$3,599
	TASC Multiplier								(IOU, high-risk, 35 year)	1.140	
TOTAL AS SPENT COST (TASC)										$2,299,541	$4,102

7.6.2 Initial and Annual Operating and Maintenance Costs

The initial fills and annual fixed and variable operating and maintenance expenses were estimated for Case 12V in keeping with the methodology and results presented for Case 12 in the Reference Baseline Report on a Jun-2011 cost basis. Specific annual operating costs which were treated differently for Case 12V consist of:

- BFW makeup water costs – in addition to the standard water supply costs from the stated municipal and groundwater sources on a \$/1000 gallon basis, an additional \$1.00/m^3 (\$3.79/1000 gallons) expense was added to the portion of raw water withdrawal that is required to make up for the VeloxoTherm™ steam extraction. This nominal value is to allow for any incremental treatment that may be required for the BFW makeup, and is in line with previous experience for utility assumptions related to large over-the-fence volumes of demin water
- MEA Solvent and NaOH – these costs are removed from Case 12V as the capture process is based on a solid structured adsorbent that is not replaced.

Case:	**12V - Supercritical PC w/ VeloxoTherm™CO2 Capture**				**Cost Base:**	**Jun 2011**
Plant Size (MW,net):	**560.526**	**Heat Rate-net (Btu/kWh):**		**11,114**	**Capacity Factor (%):**	**85**
Operating & Maintenance Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		39.70	**$/hour**	Skilled Operator:		2.0
Operating Labor Burden:		30.00	**% of base**	Operator:		11.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		1.0
				Lab Tech's, etc.:		2.0
				Total:		**16.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kW-net)**
Annual Operating Labor:					$7,384,208	$13.17
Maintenance Labor:					$10,599,890	$18.91
Administrative & Support Labor:					$4,496,024	$8.02
Property Taxes and Insurance:					$32,556,514	$58.08
Total:					**$55,036,637**	**$98.19**
Variable Operating Costs						
					($)	**($/MWh-net)**
Maintenance Material:					$15,899,834	$3.81
Consumables						
	Consumption					
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	6,086	$1.67	$0	$7,556,912	$1.81
Makeup and Waste Water Treatment Chemicals (lbs):	0	29,457	$0.27	$0	$2,447,836	$0.59
Limestone (ton)	0	636	$33.48	$0	$6,604,948	$1.58
Carbon (Mercury Removal) lb	0	0	$1.63	$0	$0	$0.00
MEA Solvent (ton)	0	0	$3,481.91	$0	$0	$0.00
NaOH (tons)	0	0	$671.16	$0	$0	$0.00
H_2SO_4 (tons)	69	7	$214.78	$14,820	$435,673	$0.10
Corrosion Inhibitor	0	0	$0.00	$0	$0	$0.00
Activated Carbon (ton)	0	1,643	$1.63	$0	$828,342	$0.20
Ammonia (19% NH_3, ton)	0	96	$330.00	$0	$9,815,430	$2.35
VeloxoTherm™Chemicals [A]						$0.00
Subtotal:				**$14,820**	**$27,689,141**	**$6.63**
Other						
Supplemental Fuel (Mbtu)	0	0	$6.13	$0	$0	$0.00
SCR Catalyst (m3)	0	0	$8,938.80	$0	$1,117,329	$0.27
Emissions Penalties	0	0	$0.00	$0	$0	$0.00
Subtotal:				**$0**	**$1,117,329**	**$0.27**
Fly Ash (ton)	0	497	$25.11	$0	$3,872,531	$0.93
Bottom Ash (ton)	0	124	$25.11	$0	$968,133	$0.23
Subtotal:				**$0**	**$4,840,664**	**$1.16**
By-Products						
Gypsum (ton)	0	1,002	$0.00	$0	$0	$0.00
Subtotal:				**$0**	**$0**	**$0.00**
Variable Operating Costs Total:				**$0**	**$49,546,968**	**$11.86**
Fuel Cost						
Illinois Number 6 (ton)::	0	6,417	$68.60	$0	$136,574,450	$32.70
Total:					**$241,158,055**	**$57.74**

7.7 Lifecycle Costs and Economic Analysis

The results of the Case 12V capital cost estimate and annual fixed and variable operating cost estimates provided above are used to calculate the primary economic figures of merit which are the first year COE and the cost of CO_2 captured (via comparison to the COE for Case 11 – the No Capture Case).

7.7.1 Cost of Electricity

The first year of operations nominal COE is calculated via the following formula:

$$COE = \frac{CCF * TOC + OC_{fix} + CF * OC_{VAR}}{CF * MWh}$$

The economic assumptions made for this analysis include.

- CCF – Capital Charge Factor of 0.124, in line with a High Risk Investor Owned Utility (IOU) that has a 5.5% nominal cost of debt, 12% nominal cost of equity, 45% debt in the capital structure, with a 5 year construction period and a 3% capital cost inflation rate during construction
- TOC – Total Overnight Cost as calculated above.
- OC_{fix} – Fixed annual operating costs as calculated above
- OC_{VAR} – Annual variable operating costs, including fuel costs, on a 100% capacity factor basis, as calculated above
- CF – Capacity Factor of 85%
- MWh – Annual megawatt-hours of net electricity produced to the grid on a 100% availability basis

Exhibit 7-22 provides the results of the COE calculation for Case 12V, this COE represents the nominal dollar COE in the first year of power plant operation that will yield the targeted return for a generator with a High-Risk IOU capital structure.

Exhibit 7-22: Case 12V Cost of Electricity

First Year COE (Nominal)		
CCF	*factor*	0.124
Capacity Factor	*%*	85%
TOC	*$USMM*	$2,017
OC_{fix}	*$USMM*	$55
OC_{VAR} (100%CF)	*$USMM*	$219
MWh (100% CF)	*Million MWh*	4.91
COE	***$/MWh***	**$117.63**

7.7.2 Cost of Capture

The cost of CO_2 captured is calculated by the difference in cost of electricity for the novel Capture Case, Case 12V, and the reference No Capture Case, Case 11 from the Reference Baseline Report. The power plant designed in Case 12V has a net power exported of ~560 MWe, as opposed to 550 MWe for Case 11, however as the COE is the cost object for the cost of capture calculation this allows the analysis to remain valid. The cost of CO_2 captured is calculated as follows:

$$Cost\ of CO_2\ Captured = \frac{(COE_{Case\ 12V} - COE_{Case\ 11})}{CO_2 captured/MWh_{Case\ 12V}}$$

Exhibit 7-23: Case 12V Cost of CO_2 Captured

Cost of CO2 Captured		
Case 11 COE (Jun-11)	*\$/MWh*	\$80.95
Case 12V COE (Jun-11)	*\$/MWh*	\$117.63
CO_2 Captured	*MT/d*	12,418
MWh (100% CF)	*MWh/d*	13,453
Cost of CO_2 Captured	***\$/MT***	**\$39.73**

8 Environmental, Health & Safety Risk Assessment

The EH&S risk assessment completed during Phase 1 was specifically developed to assess the environmental friendliness and safety of the materials, emissions, and effluents of the Inventys' VeloxoTherm^{TM} process. While performing this assessment, the process was found to be relatively benign from a safety, health and environmental sense. This is because the unique feature of this process when compared to other baseline post-combustion carbon capture technologies is the activated carbon laminate adsorbent media, which is an already well-understood and versatile method of filtering that has been broadly deployed in numerous purification and gas treatment applications throughout industry. Inventys has merely patented a process to structure the activated carbon into a specific fabric media and uniquely integrated this media with the necessary mechanical equipment and sequential process steps to specifically treat large volume, ambient pressure, flue-gas steams with high in O_2. As you will find in this section, all other equipment, emissions, effluents, and waste streams necessary to operate the process are commonly deployed and already being utilized at similar industrial sites. Finally, the process works at relatively low temperatures and pressures (near ambient) which reduces safety risks to the plant and personnel.

With that said, this section further details all the potential EH&S risks identified with the construction and operation of the proposed plant, and at this time, there are no known barriers to the commercialization of this technology from an EH&S standpoint.

The Inventys process does not create, modify, transform, or introduce any hazardous constituents into any of the emissions or effluents. All constituents listed in the waste streams are a result from the upstream combustion of coal. Coal combustion by products and the handling of streams with coal combustion by productions are well-understood and managed through existing environmental regulations and processes already deployed at the host site. Accordingly, the project plans to utilize existing waste treatment facilities to process water based upon the characterization worked carried out during Phase 1. Additionally, since the basis of the Inventys trial is to recycle all flue gas streams back into the existing stack and remix with the host unit flue gas, it is not anticipated that an air permit or permit modification would be necessary. These assumptions would need to be validated in Phase 2.

Through the work completed in Phase 1, the only new EH&S risk this process introduces into the immediate project area is the increased concentration of CO_2 prior to being routed back to the stack and remixed with the flue gas. Although CO_2 is naturally occurring, non-flammable, and chemically non-reactive, it is heavier than air and if emitted slowly it can flow down slope and could accumulate at low elevations if not dispersed quick enough (primarily determined by ambient weather conditions and topography). At high concentration, CO_2 becomes a toxic gas (irritation of the eyes, nose and throat occurs) and can be an asphyxiate gas (due to the lack of oxygen). The NRG team is aware and experienced with this risk from their work on the Petra Nova project and were planning to evaluate this risk further during Phase 2 to take the appropriate countermeasures (CO_2 monitoring, evacuation protocols, PPE/oxygen masks, etc.).

8.1 EH&S processes and procedures for Construction and Operation

NRG holds the health & safety of their employees, business partners' personnel, the stakeholders of their projects and facilities, and the public at large to be their highest priority - "Safety and Preservation of the Environment over Production."

NRG management believes that all injuries are avoidable and that anyone associated with their projects and facilities should leave work in the same condition that they arrived or better. Zero injuries at is always the goal, and NRG insists that all project partners embrace that same goal and conduct their business to the highest extent possible to deliver on that goal.

NRG, as a good corporate citizen, believes it is their responsibility to protect the well-being of the environment through the design and delivery of our projects, and NRG's operations and projects are committed to complying with all applicable Environmental, Safety & Health legislation, regulations, policies and procedures. Given more than one approach, NRG will select the more stringent. NRG will continuously review, monitor, refine, and improve all policies and procedures, to be an industry leader in EH&S performance and execution.

The Project partners Inventys, NRG and Lauren E&C planned to develop project specific policies and procedures that are in accordance with NRG's overarching philosophy of ensuring a safe work place in accordance with good environmental stewardship. The Construction and operations associated with the proposed project would occur within the footprint of the existing plant and contribute only minor environmental impacts as further described below.

8.1.1 EH&S during Construction

The Project Team planned to work together during Phase 2 to develop site specific EH&S policies and procedures to govern the construction work on the site. Lauren's standard E&C procedures would've been utilized as a basis to develop these site specific procedures and only further improved with NRG's stringent guidelines for Contractors. Site specific aspects of the plan would've been implemented, such as indigenous wildlife and critters, heat illness prevention measures, hurricane preparedness, etc.

Lauren E&C's project specific EH&S plan would've been developed to align project stakeholders and participants while ensuring compliance with NRG's guidelines as well as state and federal regulations. Each section of the plan would've referenced applicable policy standards and corresponding federal statute, summarizing the scope, execution, roles and responsibilities of the policy. Upon its completion, the site specific EH&S Plan would've become the governing document, outlining project EH&S expectations and objectives during the execution of the project.

In addition to the EH&S execution plant, the team was designing and engineering all systems to include adequate isolation, shutdown, and containment philosophies for the safe operation, maintenance, and reliability of the equipment for the life of its intended use. NRG planned to complete a hazard analysis early in the Phase 2 design process to review the conceptual design prior to the development of detailed engineering and design.

Otherwise, the construction-related environmental impacts were anticipated to be typical of those associated with a medium-sized industrial construction projects and would primarily be related to air emissions, construction traffic, fugitive dust emissions from site disturbance, and storm water runoff from construction areas. Accordingly, there would likely be the permanent loss of some previously disturbed, but currently undeveloped, property within the existing plant site to erect the newly proposed facilities. For example, construction of the BOP facilities would involve minor excavation in previously disturbed soils to install the footings and foundation for the equipment reference above and any required utility connections (e.g., water, waste, and electrical).

Construction of the proposed project would also generate typical construction wastes. The predominant waste streams would include soils and debris from site clearing, used lube oils, surplus materials, and empty containers. Surplus, scrap, and waste materials and used lube oils would be recycled or reused to the extent practicable. Solid wastes (i.e., garbage and rubbish) would be collected for disposal in a licensed, off-site disposal facility.

All necessary permits would be obtained to comply with regulatory requirements during construction.

8.1.2 EH&S during Operations

NRG is committed to conducting its operations in a manner that focuses on continual improvement and meets or beats all applicable environmental and safety laws and regulations, through;

- Utilization of industry best practices with regard to safety of its employees and operation of equipment;
- Diligent efforts and the use of cleaner technologies, designed to quantify and reduce the climate change and environmental impacts of its operations, as the project exemplifies;
- Compliance with applicable laws and regulations regarding safety and environmental protection as the responsibility of each officer and employee;
- Identifying and responding to regulatory trends that have the potential to significantly impact existing and planned facilities, and;
- Promotion of continuous improvement of policies and procedures including stewardship and biodiversity at all NRG locations.

NRG Operations reviews and communicates its environmental health and safety goals and performance on a monthly basis to maintain focus on these important metrics.

Operations would've been governed by the NRG corporate EH&S policies and procedures that govern our entire fleet of operating facilities. These procedures meet or exceed industry standards and are continuously reviewed and modified to conform with lessons learned over time and best practices as they continue to develop. NRG embraces state and federal regulatory agency involvement in our EH&S programs as is exemplified by NRG's strive to have plants obtain the OSHA Voluntary Protection Program (VPP) status and by its efforts to maintain an excellent working relationship with state and local environmental agencies.

Operational Emissions & Effluents associated with the new demonstration equipment would've included:

- Waste water from the Direct Contact Cooler (DCC) and the Cooling Tower Blowdown.
- Natural gas-fired Aux. boiler emissions (if deployed).
- Treated Flue Gas and separated CO_2 streams (returned to existing stack).
- Process Consumables (described below).

8.1.2.1 Process Consumables

This new process would not utilize or consume any chemicals that are not presently already used on the site. Chemicals similar to those already used at the Plant would be needed for circulating (cooling) water chemical treatment, steam conditioning, and make-up water treatment.

No exotic compounds or materials are used or consumed in this process. The process will consume various items over the life of its operation including lubricants, water treatment chemicals, filters, seals, and possibly the adsorbent media depending on the life of the project and observed performance.

The adsorption media is a non-toxic carbon laminate structures. If replacement is required, this material may be disposed of by recycling, landfilling or burning in a furnace. Otherwise, facility O&M personnel are experienced in the proper handling of all other chemicals and materials outside of the absorbent media and already have proper procedures in place. There are no volatile, flammable or explosive materials in the consumable list.

8.1.3 Compliance with U.S. EH&S laws and associated standards

As you will see in the Phase 1 results section below, the Project would've been operated by the existing W.A. Parish Operations team that is responsible for monitoring, reporting and compliance with all safety and environmental permits, regulations and NRG's standard procedures. The W.A. Parish personnel have a strong track record in compliance with operating facilities. The W.A. Parish Team recognizes the benefits of good environmental and safety stewardship and its impact on all of the Project stakeholders. As with the current Plant the team understands that all decisions made must take into account potential environmental and safety impacts. Among those things to be considered are personnel safety, air emissions, proper operation of equipment, water use, energy efficiency, hazardous materials and waste minimization.

To ensure compliance with NRG's corporate policies and procedures, regular audits and assessments are performed to test compliance. Furthermore NRG maintains subject matter experts within its corporate structure both nationally and regionally to provide ongoing support to individual facilities and to clearly communicate changes in regulations and policies and potential impacts to existing plans and procedures.

9 Large Scale Pilot Program: CO_2NCEPT

The primary purpose of the Phase 1 program was to determine the feasibility of a 10 to 25 MWe large scale pilot project applying the VeloxoTherm™ post-combustion capture technology to a flue gas slip stream from one of NRG's a coal fired generation units along the Gulf Coast – a project entitled CO_2NCEPT (**C**onfirmation **O**f **N**ovel **C**ost-effective **E**merging **P**ost-combustion **T**echnology). During the Phase 1 performance period, a conceptual front end engineering and design FEED study was completed for the large scale pilot, and a project management plan, EH&S risk assessment and project baseline were developed.

9.1 CO_2NCEPT Project Description

NRG, as the largest independent power producer (IPP) in the US with a fleet of conventional fossil fuel plants across the country, recognizes the challenge of combating climate change while maintaining a reliable, low-cost electric supply in the U.S. Deploying clean energy technologies on the scale necessary to meet the nation's energy imperative will depend in part on achieving incremental advancements in existing technologies, but predominantly on the development and commercial deployment of next-generation, advanced energy technologies. In the near term, no single technology can address the challenge of making energy reliable, affordable, clean, and secure, so coal-fired generation is likely to remain an integral part of the balanced energy mix for the next few decades. Advanced coal technologies, including the development and integration of carbon capture, and storage (CCS) systems, is a compelling opportunity that can help meet energy needs, reach climate policy goals, revive established industries, create new ones, stimulate the economy, provide jobs, and enhance national energy security.

Project CO_2NCEPT was based on Inventys's VeloxoTherm™ process as previously described above to prove that this technology can be reliably deployed on coal flue gas and that the cost of capture, both from an upfront capital requirement as well as from an operating standpoint, is lower using this technology when compared to existing baseline technologies. Secondary benefits were to determine and demonstrate that it has a reduced the footprint in comparison to competing baseline technologies, and to the extent that this technology can be deployed on coal units without high efficiency scrubbers, would've demonstrated another advantage over current baseline technologies.

NRG (host), Inventys (technology provider), and Lauren Engineers and Constructors (Constructors) planned to construct a 500-tonne per day, (tpd) Post-Combustion CO_2 Capture Plant, designed to capture CO_2 from a slipstream of flue gas from one of NRG's coal-fired power plants located on the gulf coast. Central to the design is the VeloxoTherm™ CO_2 capture process which has been described in previous sections of this report.

Through the work completed during Phase 1 as summarized herein, the proposed capture system was intended to be constructed on NRG's 4,880-acre WA Parish Plant in rural Fort Bend County near the small town of Thompsons, Texas. This plant site includes four gas-fired utility boilers and four coal/gas-fired utility boilers (Units 1 through 8), which produce steam for the generation of electricity. The plant also includes a gas turbine, which supplies electricity in emergency situations. Other equipment at the plant includes coal, limestone, and material loading, unloading, and handling equipment, tanks, cooling towers, pollution control equipment, degreasers, engines, and oil-water separators. Smithers Lake, which is located on the north side of the plant, is a 2,430-acre man-made water body used for plant cooling water.

9.2 Front End Engineering & Design Study

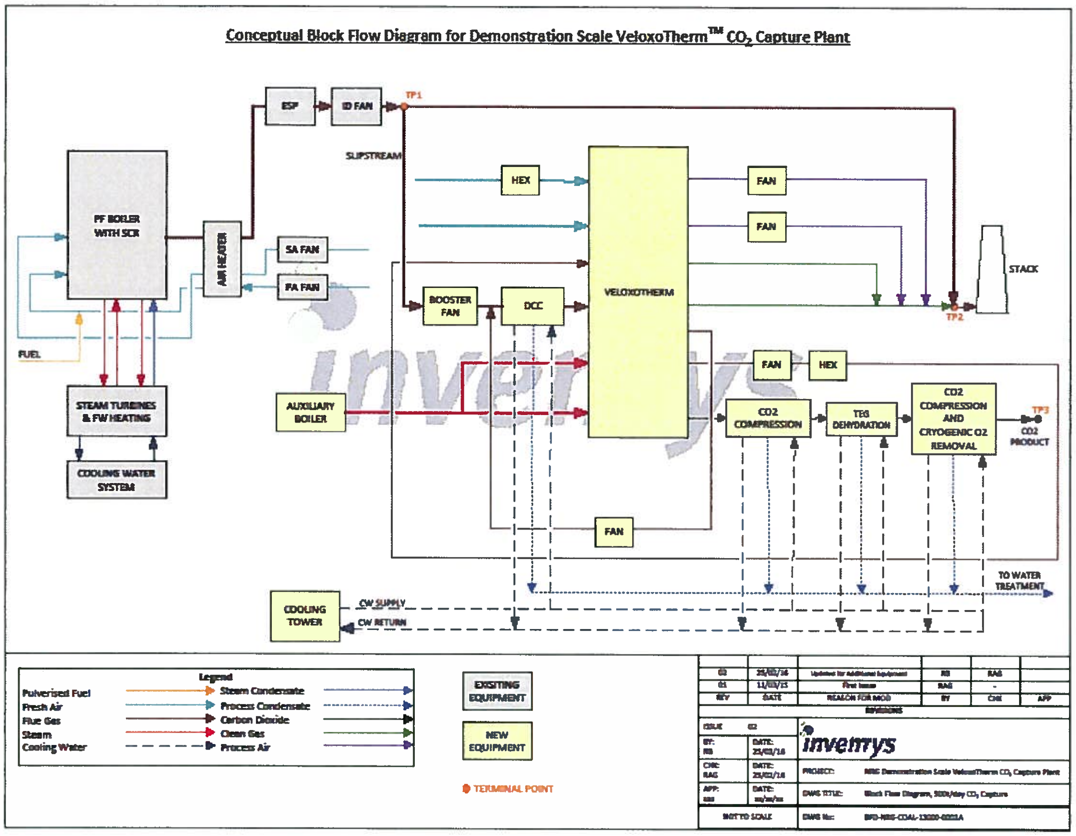
Phase 1 intentions were to develop the project scope in the preparation of a more comprehensive and defined Phase 2 application. Phase 2 application documents were due on 03/31/2016 which allowed six months to conduct the Phase 1 study work and prepare the resulting application documentation. Accordingly, further definition and refinements to the project were anticipated to be administered during Phase 2.

The project kicked off Phase 1 during upon award effective 10/01/2015 and the team began establishing the scope of work, division of responsibility, how the project was going to be structured and executed, determine the location of the demonstration, size the project, conduct preliminary design efforts and identify any key issues that need to be addressed before a project is undertaken. With the contractual arrangements in place, the team quickly determined that they would begin work toward developing a 25 MWe scale slipstream to capture up-to 500 tpd of CO_2, unless space and/or budget constraints became a deterrent. NRG had also determined that W.A. Parish facility in Fort Bend County, TX (about 27 miles SW of Houston) would be the selected host site.

Further evaluation of the host site was then required to determine which host unit to pull the flue gas slipstream from. Existing site constraints, possibility of future work, and other considerations were made by NRG and ultimately converged on Unit 5 as being the most suitable host unit until for preparing this body of work. This is because there is a comparatively large court yard between the SCR structure and Stack where the old precipitator resided (prior to tying in the baghouse behind that Stack) that the team felt they could locate RAM within. This would've made for easier slipstream take-off and return tie-in of the treated flue gas back to the existing stack breaching duct. With these key elements defined, Inventys and Lauren began their engineering efforts under the guidance of the design basis document provided by NRG.

The team then spent the balance of Phase 1 focused on developing/optimizing the site arrangement/orientation, Process Flow Diagrams (PFDs), preliminary (P&IDs), Mass Balances, equipment sizing and lists, commodity requirements, execution approach, project estimates, and Phase 2 application documents. A block flow diagram illustrating the fundamental retrofit approach is illustrated in the exhibit below.

Exhibit 9-1: CO_2 Capture Plant Block Flow Diagram



The proposed Large Scale Pilot CO_2 capture plant described by Exhibit 9-1 first involves the receipt of a slipstream of coal-fired flue gas from the WAP host power generation unit (i.e. Unit 5), which is then passed through a forced draft booster fan and introduced to a DCC. The DCC cools the flue gas to an appropriate temperature prior to introducing it into the RAM which is criticalfor the TSA cycle. This pre-conditioning step also provides co-benefit reduction of SOx and particulate matter in the flue gas feed. The cooled flue gas is then introduced to the RAM where it undergoes the CO_2 adsorption step of the VeloxoTherm™ TSA cycle optimized for coal-fired flue gas applications. The regeneration of the adsorbent and recovery of the CO_2 product is then promoted by the direct injection of low pressure steam, which can be sourced from an auxiliary natural gas fired boiler or from available process waste heat at the WAP host site. The product CO_2 stream is then cooled and water is recovered, leaving a 95% pure CO_2 stream, which could be compressed and dried if determined that there is sufficient business justification and end-use of the CO_2. The major battery limit tie-in points, as well as existing equipment and unit operations vs. new equipment contemplated by the CO_2NCEPT project are also highlighted in Exhibit 9-1. A more specific description of the VeloxoTherm™ process and RAM equipment is provided in Section 5 of this report.

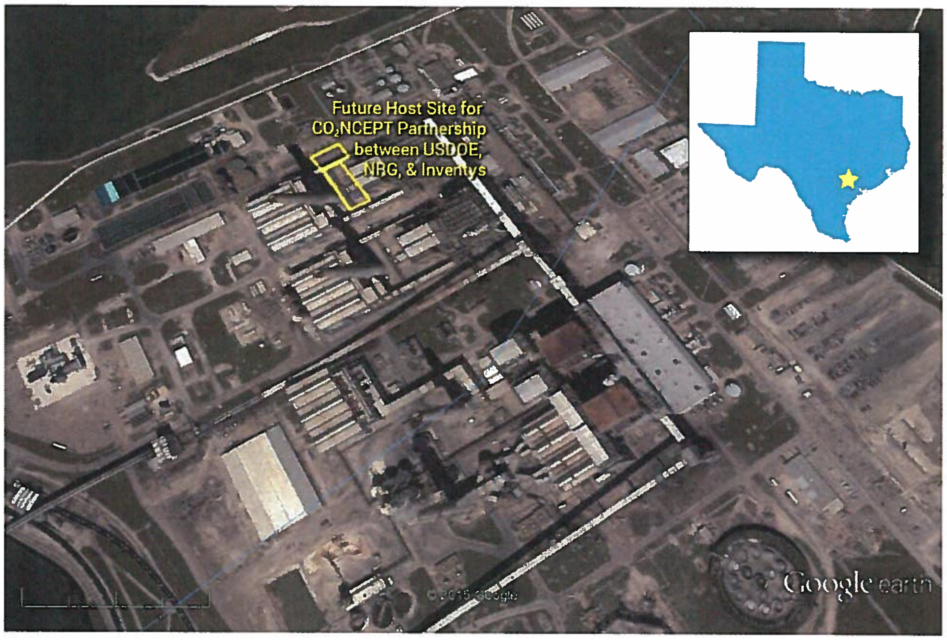
A series of meetings and site visits were administered throughout Phase 1 to coordinate the preparation of the facility design, estimate, and Phase 2 application materials. The following sections further detail the results of these efforts.

9.2.1 CO₂NCEPT Project General Arrangement

The general arrangement for the Post-Combustion CO_2 Capture Plant was created using information from existing drawings of the facility as well as from preliminary, vendor and manufacturer supplied equipment proposal information.

The proposed CO_2 capture facility would have a footprint of approximately 175 feet by 200 feet (0.8 acres) within the existing WA Parish Plant, as shown in the exhibit below Exhibit 9-2. Including the CO_2 capture facility, auxiliary equipment, and other project areas (staging, management, and laydown), a total of approximately 2 acres within the existing plant boundaries would be used during construction.

Exhibit 9-2: NRG's WA Parish Power Plant

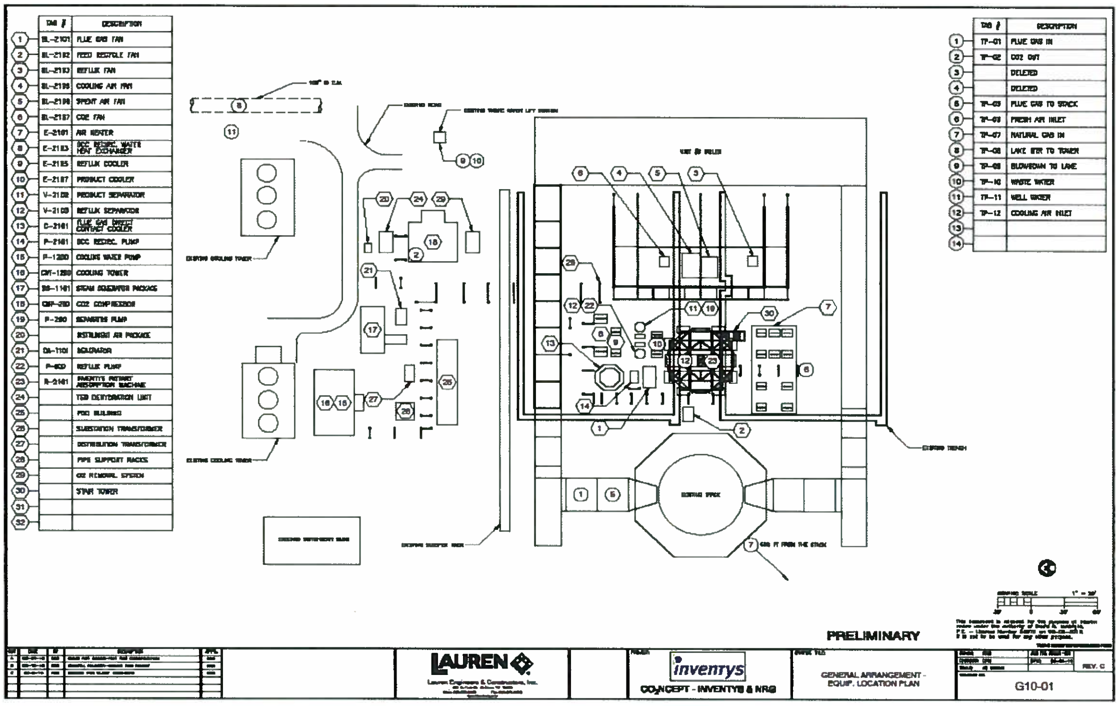


The new VeloxoTherm™ device was planned to be placed directly east of the existing stack/chimney and west of the existing SCR structure where the precipitator was formerly located. Included within the courtyard area is an existing control building for the former precipitator. Also located within the courtyard area is an existing pipe rack that runs in a North-South direction between the existing large, overhead gas ductwork. Both the existing control building and the existing pipe rack were planned to be removed/demolished.

The area to the north of the courtyard area contains existing auxiliary cooling tower structures. Within this area, the project would have added a new cooling tower for the Inventys process. Additionally, this area would contain the following new project equipment: Steam Generator package (if utilized), power distribution center (PDC) Building and transformers, Tri-Ethylene Glycol (TEG) Hydration Unit (if CO_2 conditioning was contemplated), and the CO_2 Product Compressor (if deployed). This area will be connected to the courtyard area utilizing a new pipe rack that runs in a North-South direction, through the large, overhead gas ductwork structure, and aligns with the western edge of the existing SCR structure as showing in the Exhibit below.

The area directly under the SCR steel structure would be utilized to place several of the blower-type pieces of equipment. The area directly South of the new VeloxoTherm™ device will be used to place several of the heat exchanger pieces of equipment. The area directly North of the new VeloxoTherm™ Device will be used to place separators, pumps, heat exchangers and coolers.

Exhibit 9-3: CO_2 Capture Plant General Arrangement



9.2.2 Carbon Capture System (CCS) Island

The carbon capture system (CCS) Island consists of the unit operations directly required to implement the VeloxoTherm™ process, including the RAM, and associated heat exchangers, fans, pumps, vessels, and contact cooler.

9.2.2.1 Rotary Adsorption Machine

RAM Design

The RAM is a rotating device that houses the proprietary structured adsorbent for the VeloxoTherm™ process. The design of the RAM for the 500 tpd project incorporates many standard features of the Ljungström® Air Preheater combined with specially developed features unique to the RAM application.

RAM Sizing Basis

RAM equipment sizing was based on a Productivity Factor of the structured adsorbent, bed length, and a safety margin applied to account for inefficiency of rotary valve and losses in packing density of adsorbent structure within the rotor.

9.2.2.2 Centrifugal Fans

There are six independent centrifugal fans used in the design. These include the Flue Gas Fan, the Feed Recycle Fan, the Reflux Fan, the Cooling Air Fan, the Spent Air Fan, and the CO_2 Product Fan. Each of these fans serves a slightly different purpose in moving various low pressure gases into and out of the RAM. Section 7.4.4.1 of this report describes some of these fans and their functions further.

9.2.2.3 Centrifugal Pumps

The group of centrifugal pumps would include the DCC Recirculation Pump, the Product Separator Pump, the Reflux Separator Pump, and the Cooling Water Pump. Each of these pumps would be furnished as either API-610 Pumps (more ruggedly built and better in hot services) or ASME-B73.1 Pumps (less ruggedly built but cheaper in price but is acceptable for cooler services).

9.2.2.4 Direct-Contact Cooler (DCC)

The Direct-Contact Cooler (DCC) was designed to be low pressure vertical vessel measuring approximately 14' diameter by 40' seam to seam. The vessel will contain structured packing where a recirculating stream of cool water flowing downward will contact an upflow of fresh flue gas and recycle flue gas. The purpose of the contact is to cool the hot flue gases and to wash out of the gases minor amounts of particulates and water soluble impurities prior to the gases entering the RAM.

9.2.2.5 Heat Exchangers

A group of heat-exchangers are needed to maintain temperatures throughout the process. These exchangers include the Air Heater Exchanger, the DCC Recirculation Cooler, the Reflux Cooler, and the CO_2 Product Cooler. Different types of heat exchangers were offered by the vendors for these services. These include shell and tube, plate and frame, and block type heat exchangers. With further refinement of the required process details for these services, it is felt that the designs and pricing for these exchangers would be improved in Phase 2.

9.2.3 Balance of Plant

The BOP is defined as the unit operations and equipment that provides all the utilities and interconnections to enable the CCS or RAM unit to run. These are site specific and would likely be the scope of a new plant build depending on the approach and preexisting site facilities. BOP equipment for the CO_2NCEPT project includes a cooling tower, steam source, electrical equipment and control systems further described in subsequent sections.

9.2.3.1 Cooling Tower

A cooling tower is required in this process to cool various gas streams down to the required temperatures for the carbon capture process. For the purpose of the FEED study, we investigated using both field-erected and modular tower designs to determine the best fit in terms of cost and reliability for the equipment. The best fit based on the current process conditions appears to be a two-cell, counterflow, field-erected tower placed on a new concrete tower basin in the near vicinity of two existing towers currently at the site.

9.2.3.2 Steam Generator

The CO_2 capture process requires steam input at certain points in the process which makes a standalone steam generation system (Auxiliary Boiler) the most straightforward choice to also provide heat as required in the process. The team evaluated what this would entail during Phase 1 and determined that the steam generation system for this process would need to include a steam generator with stack, deaerator, boiler feed pump and steam blowdown vessel. With this arrangement and cost better understood, the Project Team planned to explore alternative methods to obtain low grade steam in lieu of the auxiliary boiler, including integration with the WA Parish Host Unit 5 to see if it can be done more cost-effectively. Although this will need to be assessed both from a regulatory and technical front, it should reduce the capital costs if concluded feasible. These considerations were planned to be explored further during Phase 2.

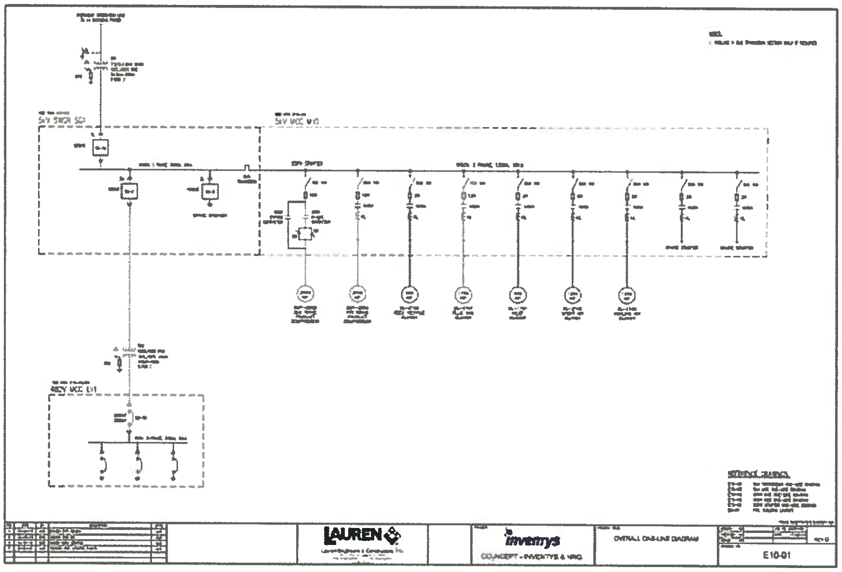
9.2.4 Electrical Engineering and Design

9.2.4.1 Overview of Power Distribution

The incoming electrical power was planned to be an extension of an existing 35 kV overhead line on a wooden-pole structure that will be brought close to the main substation transformer. There are two transformers in the project. The main transformer will provide 4160V power to the 5kV switchgear which is located in the PDC Building. The distribution transformer would step the 4160V down to 480V to power associated equipment. Both transformers are anticipated to utilize mineral oil as the cooling medium. The option of using Ester Fluid (less flammable) in lieu of mineral oil is an option to consider. The system grounding will be High-Resistance Grounding (HRG) for both transformers. The transformers will be located on the north side of the PDC building as show in the general arrangement above.

Electrical one-lines were produced to show all power distribution from the 35 kV supply down to all 4160V loads and all 480V loads, an example of an overall one-line diagram is shown in Exhibit 9-4.

Exhibit 9-4: Overall Electrical One-Line Diagram – CO_2NCEPT



9.2.4.2 Electrical Building & Control Systems

The electrical building was planned to be a prefabricated building with a steel channel base and steel interlocking panels. The building would be elevated approximately 4 feet to allow for cable tray and cable entry through the floor of the building. Cable will also enter through the walls of the building where required. The building will contain an electrical room to contain all electrical equipment and a controls room to contain all Distributed Control System (DCS) cabinets, marshalling cabinets, and operator stations.

The project control system would've provided control for the CO_2 capture system. The DCS would monitor and control all the equipment functions to operate the CO_2 capture system. Much of the process controls are for monitoring and conditioning the process streams as they enter and exit the RAM. A Human Machine Interface (HMI) is provided to interface with the DCS and provide information to plant personnel and afford personnel control of the system.

Motor Control Schematics will be produced for every 4160V motor and every 480V motor. Motor control will be handled by the DCS. Hard-wire signaling will be used for interface between the DCS and the medium-voltage Motor Control Centers (MCCs) and low-voltage MCCs. Every starter will be equipped with two auxiliary relays for that will receive signals from the DCS for Start/Stop control. Every motor will have a Hand-off-Auto (HOA) switch in the field for manual testing and for allowing automatic operation through the DCS.

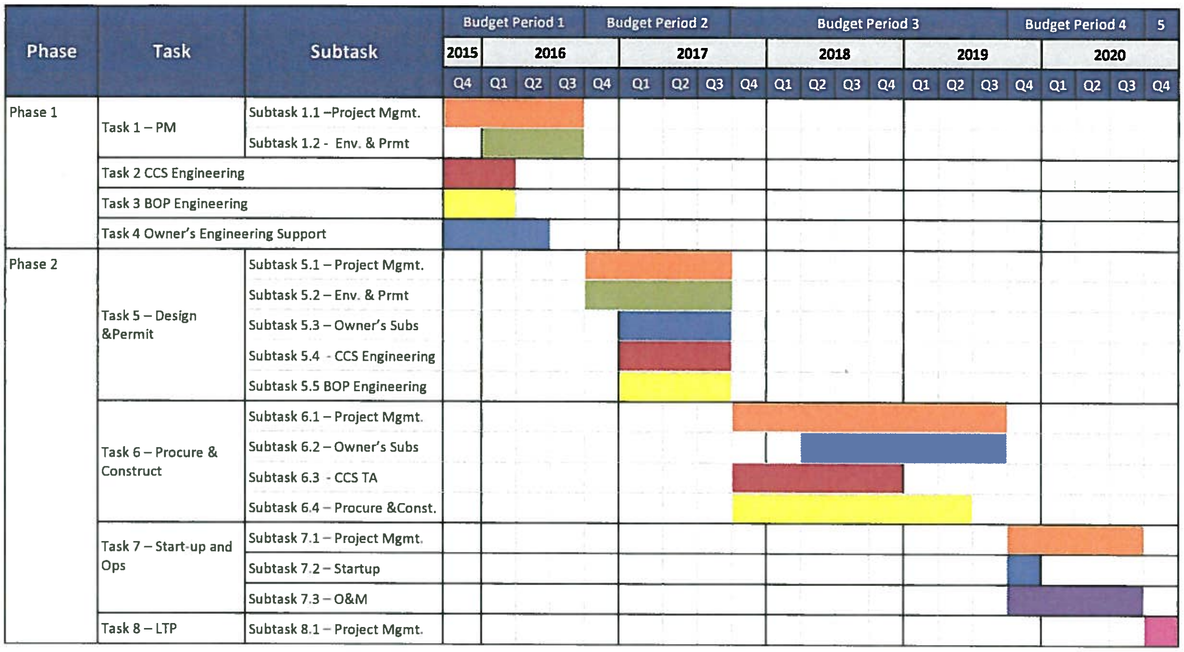
9.2.5 Phase 1 Results

The purpose of the pre-FEED was to develop the Project sufficiently enough to further define the approach, scope, schedule, and financials well enough in order to move the project into the next stage of project delivery for all stakeholders. The results of the Phase 1 pre-FEED study included a proposed schedule, AACEi Class III (+/-20%) budgetary cost estimate, as well as the Design Basis Memorandum (DBM) and associated PFDs, P&IDs, drawings, schematics, etc. Additional adjustments to scope were planned to be assessed during the detailed design and engineering tasks of Phase 2 in order to see if there are attractive trade-offs could be while still aligning with the overarching objectives of the DOE and the project participants and stakeholders.

9.2.5.1 Overall Schedule

The team prepared what the Phase 2 plan would look like during Phase 1 following the FOA guidance which indicates that the entire project cannot be longer than 60 months. With Phase 1 utilizing 12 months, there would be 48 months left to complete Phase 2. Below is the high level breakout of what Phase 2 was planned to look like with some details provided in subsequent sections.

Exhibit 9-5: Overall Phase 2 Schedule and Budget Periods



9.2.5.1.1 Engineering, Procurement, & Construction

The team was prepared to advance the design to the next level of definition, firm up the cost estimates, refine the scope, and baseline the schedule for phased decision making into the next budget period sequence if selected for Phase 2. This budget period was envisioned to take 9 to 12 months to complete including the endorsement of stakeholder approval to proceed.

Once the final development package was solidified and approved by all stakeholders, long lead equipment procurement and construction activities would follow. Procurement would consist of making an award, expediting vendor engineered drawings, management of vendor documents, development of ITP's (Inspection Test Plans), expediting fabrication, vendor shop inspections, witness testing, shipping logistics, and receiving at the project site. Construction would consist of site preparation activities that starting with getting the construction team set up at site, grading of the site, and erection of administrative facilities. Following site preparation, other phases of construction would commence including the installation of piles and foundations (civil), assembly of structural steel and building enclosures, and installation of mechanical and electrical systems.

Based on the information gathered during Phase 1, the team believed that the procurement and construction aspects of the project could be completed in 24 months both in its actual execution, but also because the period is limited to 24 months by the FOA guidelines.

9.2.5.1.2 Commissioning, Start-up, & Operation

Once mechanically complete whereby a clean, tight, operable, safe and complete system has been flushed, pre-tested, run-in, checked-out and turned-over to the commissioning and startup team, the commissioning activities would begin. Commissioning would continue with a systematic process for achieving, verifying, and documenting that the performance of each system and its various components meet the design intent and the functional and operational needs of the owners, users, and occupants.

Once a system is commissioned, the start-up plan will detail how the systems start interacting together and how they will be sequenced on-line to produce CO_2. After a successful start-up, a performance test-run will be conducted to confirm performance for the various process units and to satisfy proof-of performance criteria. Commissioning and Start-up is envisioned to take 3 to 6 months once mechanically complete.

9.2.5.1.2.1 Sustained Operations

The CO_2NCEPT facility would have been jointly operated by NRG and Inventys during the operational period. NRG would have provided skilled operators and maintenance personnel to support the daily O&M activities associated with operation of the unit. Inventys would have provided management and technical oversight of the operations group and with a focus on resolving any technical issues encountered along with optimization of unit operations. Inventys personnel will also be responsible for reporting the ongoing performance of the unit and coordination with WA Parish management personnel. The combined team of NRG's experienced O&M personnel and Inventys technical and management expertise would have leveraged each company's strengths to form a highly effective Operations Team whose goals are well aligned to maximize performance of the project during the operational period. The Operations period would have commenced after start-up and performance testing and would've run 6 – 9 months depending on the duration start-up schedule.

If sponsors and stakeholders do not have a long-term plan (LTP) in place to continue with the operation of the CCS facility, a decommissioning plan would've been developed by the team for the decommissioning and disposal or relocation of the plant. The plan would outline which one or more of the following steps would be mobilized depending on the future plan at that time: remediation, decommissioning, dismantling or demolition, and restoration of the CCS facility site. As part of the decommissioning plan, the team would determine the most appropriate way to recover asset value which may include relocation, resale, or scrap value of the system components or combination thereof.

9.2.5.2 Phase 2 Cost Estimate

The objective of the Phase 1 Study was to produce a capital cost estimate of the core Large Scale Demonstration Plant in preparation of a more refined Phase 2 application. Inventys and Lauren prepared the required engineering deliverables for the project, including process flow diagrams, process and instrumentation diagrams, electrical one line diagrams, facility general arrangements, and other documents as necessary. Once these deliverables were complete, material take-offs for all bulk commodities, including piping, cable, structural steel, and concrete were prepared. The quantities developed were then issued to their respective estimating teams. Equipment bid specs were developed and request for quotes (RFQs) were issued to qualified vendors on major equipment packages. Vendor responses/submissions and sophisticated in-house costing data were used by the estimating teams to develop a bottoms-up capital cost estimate for the project, including estimates for engineering, procurement, construction, and commissioning work. The team also performed several integration and optimization studies as required to support the project and make equipment selections.

The estimate was based on the assumption the work will be done on a competitive bid basis and the contractor will have a reasonable amount of time to complete the work. The field construction work was estimated using standard unit work hours with a productivity adjustment to reflect site hours and location. Material and equipment pricing was based on a combination of vendor pricing, historical project databases and factored equipment lists. The complete bottoms-up estimate approach for the facility includes labor costs, material and equipment pricing, indirect costs, productivity rates, escalation, contingency, construction management and all other below the line costs. In addition to these, NRG established owner's costs to account for owner's project management costs, facility-wide construction management services, utility interconnections, startup and commissioning support, insurance, permitting fees, capital spares, contingency, and escalation assumptions. More estimation refinement work was planned for in Phase 2 and the final cost of the project will be impacted by contracting approach, labor availability and rates, equipment and material pricing, implementation schedule and other dynamic market conditions leading up to notice to proceed.

The original estimate prepared in Phase 1 included the entire standalone system as described above, which included a separate package boiler, CO_2 offtake configuration (compressor/dehydration), and other conservative estimates and contingencies to bookend what the upper limit of a 25MWe system could look like based on those assumptions. This "all-in" estimate was higher than what the stakeholders were willing to commit for Phase 2 so some optimization and de-scoping efforts were considered.

The first exercise was to determine if the overall system size should be reduced or if it should be kept it as-is (25MWe) with a reduction of scope. Since the primary objective is to demonstrate a breakthrough in post combustion capture technology at sufficient scale, which "sufficient-scale" was concluded to be a 25MWe system, the team elected to keep the system size and remove parts of the scope (and associated costs) to get within the funding limits of the sponsors.

The first item evaluated was the CO_2 compression and product polishing facilities. CO_2 compression, drying and product polishing (oxygen control) is only required if there's a suitable end-user for the product CO_2 which was still under discussion by the project participants and other stakeholders at the time of completing Phase 1. It is the team's belief that any offtake arrangement should be supported by the off-taker itself and didn't need to be included as part of this particular scope at this time. Accordingly, the cost of compression and product conditioning was removed entirely from the Phase 2 estimate. Without an off-taker to fund the equipment required for transport, the demonstration would be designed to be a "catch and release" facility whereby it would capture the CO_2 and then route back up through the existing host unit stack for exhaust.

This reduction alone didn't get the project within the funding window the sponsors had envisioned, so the next step was to pursue steam integration opportunities with the host unit and eliminate the standalone package boiler. Although this still needed to be fully evaluated both from a regulatory and technical front during subsequent development work, the team believes that this would help incrementally reduce the capital costs and reflected that as part of the Phase 2 application.

Finally and although the compressor was removed from the scope as noted above, power costs to run the plant are not insignificant and the team believes there could be a lower cost solution. If power could be purchased from the power plant and not from the 35kV line then a wholesale agreement could be worked out instead of paying retail from the power line. All of this would need to be verified in subsequent phases of development, but preliminary discussions with internal experts led the team to believe that this could be possible.

The team believes that this combined scope reduction solution (compression, integration, wholesale power) would get us down within the sponsor funding targets established. As stated above, more work is needed to verify these opportunities during Phase 2, but the basis of the Phase 1 estimate presumes that the above-mentioned was feasible.

A summary of the proposed cost baseline is provided below by budget period, with funding profiles and additional information available in the Phase 2 application materials.

Exhibit 9-6: Phase 2 Proposed Budget (Cost Baseline)

	Phase 1	Phase 2				Total
CATEGORY	Feasibility	Design	Procurement & Construction	Commissioning & Operation	LTP	Total Costs
INVENTYS	$1.00	$1.15	$2.15	$6.70	$ -	**$11.00**
NRG	$0.25	$1.45	$10.15	$1.15	$ -	**$13.00**
LAUREN E&C	$ -	$5.70	$42.80	$ -	$ -	**$48.50**
Total Project Costs	$1.25	$8.30	$55.10	$7.85	$-	$72.50
DOE Share	$1.00	$6.64	$44.08	$6.28	$-	$58.00
Owner's Share	$0.25	$1.66	$11.02	$1.57	$-	$14.50

10 Adsorbent Performance Update

The raw material used by Inventys in the development of its structured adsorbent beds is comprised of a hydrophobic version of an activated carbon-based sorbent that has been recently developed by one of Inventys' suppliers. During Phase 1, two primary strategies were identified for increasing the likelihood that the VeloxoTherm™ process using this sorbent within a TSA cycle optimized for coal flue gas would be capable of meeting key performance targets. Section 5.2 describes these strategies and they are included in the Phase 1 Gap Analysis, however they consisted of:

a) Increasing the bulk density of the adsorbent beds ("Bed Densification"), which increases the CO_2 capacity of a given volume of adsorbent – having a positive impact on the effective steam ratio and productivity of the process (see Section 5.2.2); and

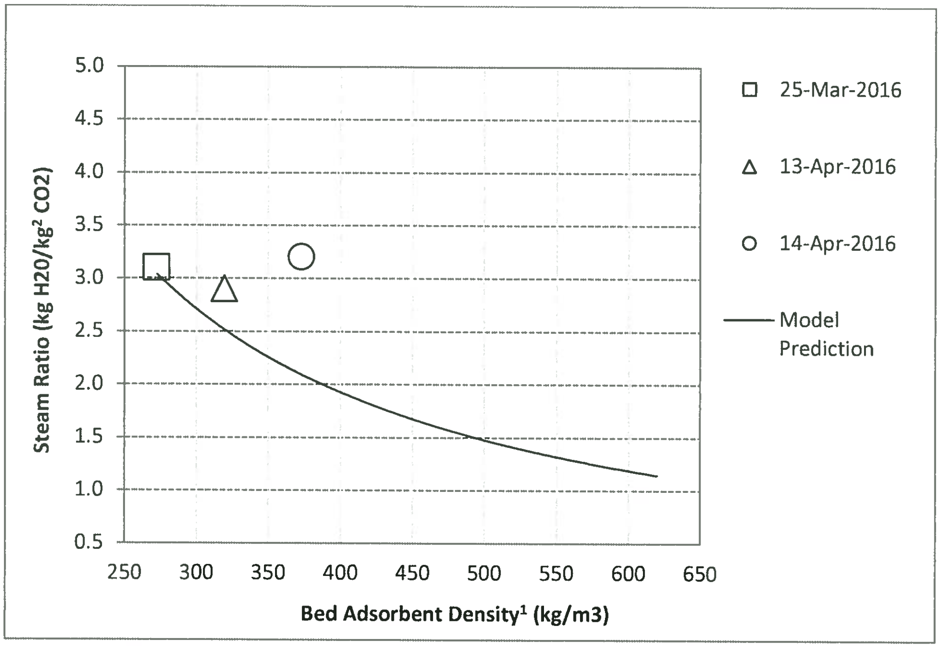
b) The introduction of a vacuum regeneration strategy, allowing extraction steam to be utilized for regeneration with a lower relative parasitic load and assisting in the desorption of CO_2 during the regeneration step.

As at the time of the Phase 2 application deadline, testing programs were still underway on higher density adsorbent beds with a vacuum-assisted cycle being implemented on the VTS apparatus so model predicted performance was used in developing the design basis for the Large Scale Pilot and for the Phase 1 TEA. Subsequent to the application deadline, but still during the Phase 1 performance period, Inventys completed additional testing that indicated there were significant risks of the selected sorbent not meeting performance targets estimated for the Phase 1 TEA. This testing program demonstrated unfavorable capillary pore condensation of water in the adsorbent - a physical mechanism that was an original motivation for the selection of a hydrophobic activated carbon-based sorbent.

As at March 24, 2016 the selected adsorbent had been tested with a bed adsorbent density of ~275 kg/m^3, with a regeneration step vacuum (relative to a standard atmosphere) of ~1.6 psig. This compares with Phase 1 targets of a bed adsorbent density of 570 kg/m^3 and a regeneration step vacuum of ~10 psig. The Phase 1 Gap Analysis summarized in Section 6 of this report includes the densification of the adsorbent beds and the testing and verification of the performance associated with target vacuum levels during regeneration. Experimental testing completed during April, 2016 provided early results on these technical performance gaps and the densification and vacuum-assisted gap closure strategies.

Exhibit 10-1 illustrates the early performance impacts, measured via steam ratio, demonstrated by increasing the bed adsorbent density.

Exhibit 10-1: Adsorbent Phase 1 Testing Program – Bed Densification vs Steam Ratio

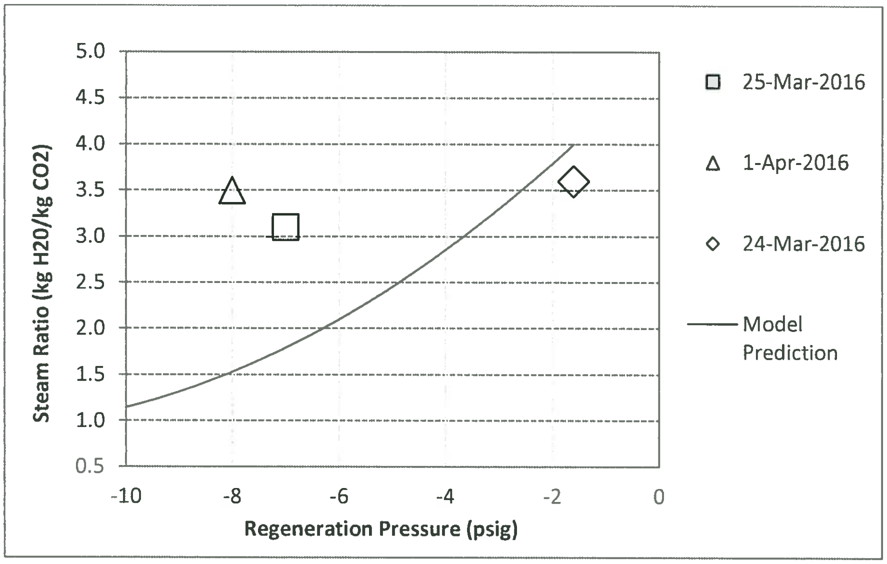


1. Bed adsorbent density is calculated using active material only, bed bulk density includes small amounts of additional material which will result in a higher figure.
2. Steam ratio performance data measured with a regeneration step vacuum of ~7psig, vs a 10psig target used in the Phase 1 TEA.

Achieving high adsorbent bed densities required significant effort due to the complexities involved in the manufacturing process of the structured adsorbent, and early results did originally show improved performance (see 13 Apr, 2016 data point in Exhibit 10-1). As the adsorbent bed density increased to ~375 kg/m3 however (closing ~34% of the gap between previous and target density), non-linear behavior of water became evident with respect to the onset of capillary pore condensation. It was determined that while higher density adsorbent increased the productivity and recovery of the adsorbent bed, it was also now causing an increase to the bed pressure drop. Higher pressure drop hinders the regeneration of the adsorbent bed during conditioning step. Therefore water locks in the pores and promoting capillary condensation of water.

The testing highlighted in Exhibit 10-1 presents experimental data with a regeneration step vacuum (defined relative to a standard atmosphere) of ~7psig, compared with a target vacuum of 10psig used to estimate performance targets used in the Phase 1 TEA. Limitations of the current VTS testing apparatus precluded testing of the full targeted vacuum level, however early indications from increasing the regeneration step vacuum from ~1.6psig to ~7psig again indicated the non-linear behavior of water in the adsorbent material was exhibiting capillary pore condensation; this is highlighted in Exhibit 10-2. It was hypothesized that as the temperature of the steam was reduced (a natural consequence of the reduced absolute pressure of the steam implied by a vacuum regeneration strategy), the temperature of the adsorbent bed decreased more than initially expected and the colder material promoted the onset of capillary pore condensation.

Exhibit 10-2: Adsorbent Phase 1 Testing Program – Regeneration Vacuum vs Steam Ratio



10.1 Implications of Absorbent Performance on Phase 1 TEA Performance Targets

The performance of the VeloxoTherm™ TSA cycle is described and measured through key figures of merit that have first-order effects on the economics of the capture plant, its impact on the host power generation unit, and other key technical feasibility, plant footprint, operability and maintenance considerations. These key performance metrics are explained in Section 5.2.2, but consist of product purity, CO_2 recovery, adsorbent bed productivity, steam ratio, and pressure drop through the adsorbent beds. It is important to note that these performance metrics are measured outputs from a dynamic TSA cyclic adsorption process and are not independent from each other. The sensitivity of each performance metric is affected by all the others, resulting in natural trade-offs between product purity and recovery, or steam ratio and productivity as examples.

It was discovered during the Phase 1 performance period, that increasing bed adsorbent density and increasing the amount of vacuum applied to the regeneration step of the TSA cycle, which were necessary to meet the merits of this award, began to have unpredictable impacts on the onset of capillary pore condensation of water in the adsorbent material. For this reason, it was determined that the performance targets used in the development of the Phase 1 TEA were at a high risk of not being achievable with the selected hydrophobic version of an activated carbon-based raw sorbent material. Exhibit 10-2 highlights the most critical Phase 1 TEA performance targets evaluated to be at risk given the updated testing results outlined in Section 10 above.

Exhibit 10-3: Phase 1 TEA performance targets at risk

Performance Metric	Phase 1 TEA Target	Updated estimation & risk assessment
Product Purity (%)	95%	Product purity was kept at the 95% target, with updated testing results showing that achieving this would likely require reduced CO_2 recovery, productivity and increased steam ratio
CO_2 Recovery (%)	90%	Updated testing of higher density beds under vacuum regeneration showed this target to be at risk
Productivity (TPD/m^3)	5	Updated testing of higher density beds under vacuum regeneration showed this target at risk
Steam Ratio (weight basis)	1.14	The onset of capillary pore condensation appeared to create a high risk that this would be unachievable with the selected adsorbent
Bed adsorbent density (kg/m^3)	570	Full target bed density was not achieved during Phase 1 testing, however unexpected adverse impacts of increased bed density became apparent at a bed adsorbent density of ~375 kg/m^3
Regeneration Vacuum (psig)	10	A vacuum of ~7psig (relative to a standard atmosphere) was achieved, providing important indications that increasing the vacuum to 10 psig would not have the estimated performance benefits
Product Oxygen Content (ppmv)	<100	Early indications that the product oxygen specification for EOR as defined by the DOE's QGESS documentation could be met became increasingly at risk during Phase experimental testing with the vacuum regeneration strategy applied. Product concentrations of O_2

The implications of the increased risk of not meeting performance targets with the selected hydrophobic activated carbon-based sorbent of the VeloxoTherm™ process as presented in the Phase 1 TEA include:

- **CO_2 Recovery & Productivity:** lower productivity and recovery implies that more individual rotary adsorption machines would be required for the 550 MW installation and the production of CO_2 for a given flue gas volume would be reduced.
- **Steam Ratio:** an increased steam ratio increases the parasitic load associated with the capture plant, and at a certain level could exceed the amount of steam available for extraction and use as for the regeneration of the adsorbent material.
- **Conditioning Flows & Fan Energies:** increased requirement for hot air rinse, cooling air, reflux and feed recycle flow rates or power requirements result in increased capital costs for fans and increased auxiliary loads for the capture system. The availability of waste heat for the hot air rinse stream could also be at risk, indicating the potential requirement for increased fuel to provide process heating utilities.
- **Direct Contact Cooler:** Modeling of experimental data obtained for higher density adsorbent beds with a vacuum-assisted regeneration strategy indicated that the a direct contact cooler before the RAM and after the WFGD could be required due to a lower adsorption temperature requirement than initially targeted, and to manage moisture levels for the feed step of the TSA cycle.

- **Product Oxygen Specification:** while testing indicated oxygen levels in the range to meet the EOR CO_2 product specification of <100ppmv of O_2, this could now require the use of low-temperature or even cryogenic oxygen separation unit operations to be incorporated into the product compression train.
- **Pressure drop:** a higher than expected pressure drop through the adsorbent beds as the adsorbent bed density is increased would result in an increase in the rating and auxiliary loads associated with the fans and blowers used to implement the TSA cycle.

10.2 Determination & Next Steps

Inventys' selection of raw sorbent material for development into its structured adsorbent design for post-combustion capture from coal-fired flue gases considered a number of trade-offs and factors, including, among others:

- CO_2/N_2 selectivity
- Equilibrium loading of CO_2
- Water equilibrium loading and behavior
- Thermodynamic properties (i.e. solid heat capacity, heats of adsorption, isotherm behavior)
- Kinetics
- Cost, commercial availability, and stability

Given the trade-offs between these properties, Inventys initially selected an activated carbon-based sorbent material which had been developed to be hydrophobic so as to minimize the risks and extent of capillary pore condensation of water during the TSA cycle. However, technology gap closure strategies were based on increased the bed adsorbent density and using vacuum regeneration in the TSA cycle in order to meet estimated Phase 1 TEA performance targets. As described above, it was determined through testing in Inventys' VTS cycle testing apparatus that these strategies (increased bed adsorbent density and implementing the vacuum regeneration strategy) although with the effort of improving the technology to meet the TEA performance targets, had created other unforeseen challenges (capillary pore condensation) that renders these strategies ineffective. Accordingly the TEA performance targets cannot currently be achieved with the activated carbon material.

While the possibility exists to further improve the performance of activated carbon, given the deviation in test results from expectations, and the high quality and hydrophobic nature of the latest generation of activated carbon selected, it was determined that more optimal recently developed adsorbents should be developed into Inventys' structured adsorbent design for coal-fired flue gas applications.

The selection of additional raw sorbent materials for inclusion into the structured adsorbent bed design does, however have certain implications for proposed work for the Phase 2 execution stage under the Solicitation, including:

- A reduction in the Technology Readiness Level (TRL) of the adsorbent beds – accelerated exposure and cyclic testing required in order to demonstrate required performance stability, durability and contaminant resilience of new structured adsorbent formulations
- A delay in the project schedule and execution timeline due to the requirement for sorbent screening, selection & testing prior to any design freeze required to enter the detailed engineering phase of the execution stage of the program

11 Conclusions & Recommendations

The results and conclusions of the study collected here significantly helped NRG and Inventys assess and determine the technical, commercial, and economical feasibility of retrofitting the Inventys VeloxoTherm^{TM} post-combustion technology to the WA Parish facility. The numerous design alternatives explored during these studies, including various flue gas/unit take-off locations, site arrangement/layout considerations, energy (steam and power) alternatives, equipment and material selections, waste handling and treatment considerations, among others, aided in the refinement of the scope and approach presented herein. These design considerations and recommendations combined with the development of the overall technical specifications, design basis, material balances, equipment lists, utility requirements, process flow diagrams, P&IDs, and other preliminary engineering deliverables provided a reasonable foundation to obtain equipment bids and generate the conceptual capital cost estimate.

Although this body of work increases confidence around the feasibility and capital cost of the carbon capture system itself, it was concluded that additional work still needs to be completed in various areas of the program before this program can move into Phase 2. The modeling work that accompanied the conceptual design efforts during Phase 1 provided indications that the techno-economic targets established by the DOE FOA were at risk with the current sorbent material, and as a result, NRG and Inventys have determined that the appropriate step would be to withdraw the application until additional work around adsorbent selection can predict the expected step-change in economics and TRL this FOA implies.

Inventys has determined to broaden their assessment into the universe of promising adsorbents in various stages of development to determine which, if any, could be utilized (and would be the most effective) with their patented structured adsorbent and TSA rapid cycle technology platform and to establish relationships with those development teams. Through the work completed during Phase 1, the VelexoTherm^{TM} process has proven it's potential to be deployed with the right adsorbent media. NRG will continue to consider and cautiously approach new technologies under this phased approach to ensure that they are technically feasible, commercially sound, economically viable, and financially responsible investment decisions with a well-understood risk profile before entering into subsequent phases of project development that can typically require significant additional resources.

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