**POWER GEN INTERNATIONAL**
**DEC 14 TO 16, 2010**
**ORLANDO, FLORIDA, USA**

**TRACK: Carbon Capture II, Environmental Issues I**

**TITLE:**

# DEVELOPMENT OF POST COMBUSTION CAPTURE TECHNOLOGY - DESIGN, CONSTRUCTION AND OPERATION OF A RESEARCH TEST FACILITY AND FIELD DEMONSTRATION UNITS AT SCOTTISH AND SOUTHERN ENERGY AND BASIN ELECTRIC POWER COOPERATIVE

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## ABSTRACT

To achieve the global target reduction in $CO_2$ emissions of some 80% by 2050, the capture and storage of carbon dioxide (CCS) from power plants will be necessary. CCS technologies will be required for retrofit to existing power plants, as well as for construction of new power plants.

Doosan Power Systems is developing a competitive post-combustion capture (PCC) technology for application on coal and natural gas fired power plants for commercialization by 2020. Doosan has licensed PCC process technology from HTC Purenergy Inc., headquartered in Regina, Saskatchewan, Canada, and has purchased a 15% equity stake in the Company.

Doosan Power Systems is currently retrofitting a PCC pilot to its 160 kWt Emissions Reduction Test Facility (ERTF), located at its R&D center in Renfrew, Scotland. This pilot, sized to capture approximately 1 metric tonne per day (tpd) of $CO_2$, will expand upon earlier testing conducted by HTC where they validated the long-term performance of their proprietary RS-2™ solvent and TKO™ advanced process flow scheme.

This presentation will discuss Doosan Power Systems PCC, development and commercialization program, with emphasis on the construction, operation and testing of the ERTF, as well as the design of a 100 metric tpd demonstration plant to be constructed at Scottish and Southern Energy's Ferrybridge Power Station. The presentation will also address the Front End Engineering Design (FEED) being developed to consider retrofitting the Basin Electric Antelope Valley Station with PCC technology to capture up to 1.0 million short tons per year of $CO_2$.

## INTRODUCTION

Carbon dioxide ($CO_2$) is one of the greenhouse gases whose increasing concentration within the atmosphere is believed to have direct impact on global climate change. The combustion of fossil fuels for the generation of electricity is a major contributor to the concentration of $CO_2$ in the atmosphere. Fossil fuel currently supplies over 85% of the world's energy needs, due to it being a reliable technology for energy production, low cost, high availability and energy density [1]. The Energy Information Administration (EIA) within the U.S. Department of Energy (DOE) estimates that the consumption of fossil fuels will increase by 27% over the next 20 years. A major international effort is therefore required to ensure cost effective energy generation to sustain global economic growth while reducing $CO_2$ emissions. The European Commission recommended the targets to cut EU greenhouse gas emissions by 20% from the 1990 level by 2020 with the ambition to go to a 30% cut if other non-EU states were prepared to collaborate. The UN climate summit reached an outline of a global agreement in Copenhagen in December 2009, the so-called Copenhagen accord "recognizes" the scientific case for keeping temperature rises to no more than 2°C (3.6°F). Technologies that control $CO_2$ emissions from fossil fuel combustion sources will play a key role in meeting this major challenge.

The worldwide drive to reduce $CO_2$ emissions combined with the continued role of fossil-fired power plants in meeting energy requirements means that carbon capture and storage (CCS) will be required. Legislation will require new plants to be carbon capture ready and, beyond a certain date, to be equipped with CCS. It is also likely that existing power plants will require CCS to be retrofitted once the technologies have been demonstrated to be economically viable on a commercial scale. Emission trading and $CO_2$ caps will also provide a strong economic incentive to install CCS on both existing and new plants.

Post-Combustion Capture (PCC) represents one of the most commercially ready technologies for application to fossil-fired power plants because of its well-established application to natural gas processing and to the refinery industry. However, the parasitic load is the main drawback of this technology, primarily resulting from: a) the decrease in steam turbine power output, due to the required steam extraction for solvent regeneration; and b) the auxiliary load for $CO_2$ compression. Chemical degradation of the solvent by flue gas impurities such as $O_2$, $SO_x$, $NO_x$ and particulates, as well as thermal degradation by the solvent regeneration process increase the costs for byproduct disposal and solvent replacement. Corrosion can have a direct impact on the plant's economics as it results in unplanned downtime, production losses and reduced equipment life. In order to commercialize PCC technology for large-scale power plants, the conventional process must be optimized to operate with very high reliability, but at a lower capital and operating cost.

## DOOSAN POWER SYSTEMS HISTORY

Doosan Power System's heritage provides a solid foundation for a unique and inspiring engineering and technology business, providing solutions to the energy industry. Originally established as Babcock and Wilcox Ltd in 1891, the company delivered the first fusion-welded steam drum in 1923, constructed the Drakelow supercritical plant (steam conditions 3,700 psi, 1110°F) in 1960, the company (then Mitsui Babcock Energy Ltd) developed the POSIFLOW™ vertical tube, low mass flux, once-through boiler.

The company was acquired in 2006 by Doosan Heavy Industries & Construction, becoming Doosan Babcock Energy Ltd. In late 2009, Doosan Heavy Industries & Construction acquired Škoda Power. This led to the creation of Doosan Power Systems, which acts as the umbrella for four business units: Doosan Babcock; Škoda Power; Doosan Power Systems Americas and Doosan Power Systems Europe.

## DOOSAN POWER SYSTEMS PCC DEVELOPMENT ROADMAP

With a vision to be an international leader in delivering advanced clean energy technologies, products and services, Doosan Power Systems designs, supplies and constructs advanced steam generation technology for the power industry and develops some of the cleanest, most efficient coal-fired power plants in the world. To this end, Doosan Power Systems is committed to delivering unique and advanced carbon capture solutions. Doosan currently provides customers with a variety of solutions that reduce $CO_2$ emissions through the commercial application of advanced, supercritical combustion technologies, efficiency enhancements to existing facilities and tailored solutions to co-fire biomass. Doosan Power Systems also offers solutions for air quality control.

To continue our commitment to delivering clean coal solutions to the market, Doosan Power Systems is developing carbon capture technologies. There are three main pathways to the capture of $CO_2$ from fossil-fuel power plants. While Doosan Heavy Industries offers integrated gasification combined cycle (IGCC) technology, Doosan Power Systems is focused on the development and commercialization of PCC technology and OxyCoal™ technology (Doosan Power Systems implementation of oxyfuel combustion technology to coal-fired power plants). Our objective is to provide Customers with:

- Advanced $CO_2$ capture technologies that are fully integrated and tailored to their needs;
- The most efficient solutions of $CO_2$ capture from fossil-fired power plants;
- Solutions that minimize the impact on their generation capability; and
- Solutions compatible with all options for $CO_2$ reuse or geological storage.

Doosan Power Systems views PCC technology, using advanced amine solvents, as one solution that can meet these objectives.

The key objectives behind Doosan Power System's strategy to develop a commercial business to provide PCC solutions for power generation can be summarized as follows:

- Take a licensed PCC process technology and develop and commercialize a product solution for commercial-scale power generation;
- Build a competitive PCC engineering center of excellence and infrastructure to execute FEEDs, execute pilots and progressively larger demonstration projects, leading to commercial project execution;
- Identify and focus research and development activities on next generation, process enhancements;
- Leverage internal technical expertise and/or develop strategic alliances to fully support the entire PCC value chain.

**Figure 1** illustrates the PCC process that Doosan Power Systems is developing for application to commercial-scale, fossil-fueled power plants. The process takes the flue gases from a conventional power plant and passes them through a scrubbing process where the $CO_2$ is absorbed into the solvent and removed from the flue gas stream. This $CO_2$ rich solvent is then pumped into a regeneration column where it is heated and the solvent releases the absorbed $CO_2$. The $CO_2$ is then vented into a compressor where it is dried and compressed, ready for transportation, reutilization for Enhanced Oil Recovery (EOR) or other options in development, or permanent storage in depleted oil and gas wells or deep saline aquifers.

## DOOSAN POWER SYSTEMS – HTC PURENERGY ALLIANCE

In 2008, Doosan Power Systems executed a license agreement with HTC Purenergy to offer their process technology in commercial-scale, post-combustion projects worldwide. Doosan Power Systems also acquired a 15% share in the company.

HTC Purenergy is headquartered in Regina, Saskatchewan, at Innovation Place, one of Canada's newest university integrated research parks. Situated next to the International Test Center for $CO_2$ Capture at the University of Regina, HTC is strategically positioned amongst leading-edge petroleum and environmental sciences facilities, including the new International Performance Assessment Centre for $CO_2$ Geological Storage (IPAC- $CO_2$). HTC participates in collaborative research with the University of Regina which has pioneered Carbon Capture and Storage technology development since 1992. The University now boasts the most comprehensive carbon capture research and development facilities in the world; the University's Greenhouse Gas Technology Center is home to the International Test Center for $CO_2$ Capture (ITC). The ITC is dedicated to fundamental and bench-scale research with in-house facilities that include a fully-operational $CO_2$ capture pilot plant. The pilot plant is used to test and evaluate the performance of the latest $CO_2$ absorbing solvents, column internals, and the latest in heat integration process designs that minimize energy usage in the $CO_2$ capture process.

HTC working in partnership with the University of Regina has developed significant technical expertise in advanced solvents and process flow schemes. HTC has developed the Thermal Kinetics Optimization™ (TKO) process [2]. The TKO$^{TM}$ process presents a suite of robust and scalable process systems which are brought together to load and unload $CO_2$ solvent flows with reduced energy penalties and operational overhead. It is designed to substantially reduce the energy requirements of post combustion capture of $CO_2$ from coal and natural gas fired power plants through improved heat recovery, thermal balancing and optimized process flow.

The amine based Regina Solvents (RS™) are proprietary designer solvents that can be formulated to provide cost effective optimized separation of $CO_2$ from any flue gas stream. The solvents are formulated with unique ingredients having specific properties that contribute to the desired characteristics of the solvent to suit a specific task. The solvents can be customized depending on the content of the flue gas to ensure increased absorption and loading characteristics, improved stripping and stability while reducing corrosion. The main potential advantage of the system is that when used with RS™ solvents, power plant steam consumption can be reduced.

The resulting solvent and process technology has been developed and validated using extended bench-scale and field pilot testing, combined with actual operating data from several commercial-scale plants capturing hundreds of tons of $CO_2$ per day. Through these activities, HTC and the UoR have developed a thorough understanding of: the physical and chemical properties (kinetics, diffusivity, etc.), process operating conditions and the proper application of numeric modeling tools, necessary to model the process and size equipment to scale-up the process for commercial size demonstration projects.

In order to capitalize on the expertise within HTC and the UoR, industry links and experience within the two companies, an extensive technology transfer took place. Doosan seconded around 30 engineers and specialists to HTC Purenergy for a period of six months to fully transfer the process technology and tools. Doosan Power Systems, HTC and the University of Regina continue to actively collaborate on various projects and research and development activities, resulting in additional technology transfer between the different groups.

The modeling/design/simulation processes being applied by Doosan Power Systems, have the ability to scale and model, absorption columns and packing profiles and solvent absorption ensures maximum efficiencies are achieved while reducing the energy penalties in solvent regeneration. The customized process control/ instrumentation and data acquisition systems for all components of the $CO_2$ capture process ensure the continuous optimization of the overall working capacity for the capture process achieving the most cost effective solution in single and multiple site operations.

## FEATURES OF THE DOOSAN PCC PROCESS TECHNOLOGY

Doosan Power System's application of 1st generation, advanced PCC technology offers the following advantages to the Customer:

- High efficiency $CO_2$ capture incorporating proprietary technology that includes: an advanced, process flow scheme and tailored solvent formulation that reduce energy consumption relative to both conventional amine solvents, as well as other advanced solvents in development;
- A business model that provides the Client the ability to procure the solvent components from commodity and intermediate chemical suppliers;
- The result is a competitive PCC solution that reduces the overall through life operating costs.

The remainder of this paper focuses on the current projects that support Doosan Power Systems' PCC development strategy.

## BOUNDARY DAM DEMONSTRATION

Boundary Dam Power Station is a coal fired station owned by SaskPower, located near Estevan, Saskatchewan, Canada. The station consists of six units with a combined generating capacity of $813MW_{e.}$ The Boundary Dam solvent scrubbing demonstration plant was first built in 1987, and became a dedicated carbon capture test facility in 2000. Since then, extensive long-term operating experience has been obtained for a range of solvents, process and packing configurations. The solvent scrubbing plant operates on a slipstream of flue gas resulting in approximately 4 metric tonnes of $CO_2$ captured per day.

In early 2009, HTC and the UoR performed an extended test run at the Boundary Dam, utilizing the HTC Purenergy proprietary RS™ solvent and the Thermal Kinetics Optimization™ advanced process flow scheme. This test was performed in support of a specific project that required a capture rate of 85%. The testing was conducted for over 1,400 hours.

**Figure 2** summarizes the critical test results over a one-month period.

As noted in **Figure 2**, the pilot operated at the desired absorption efficiency of 85%; with the average steam consumption measured at around 1.1lb of steam consumed for each lb of $CO_2$ captured. During this test the solvent degradation rate was observed to be low.

## EMISSIONS REDUCTION TEST FACILITY

The Emissions Reduction Test Facility (ERTF), located at Doosan Power System's Research and Development Centre in Renfrew, Scotland, was originally designed for the investigation of primary in-furnace $NO_x$ control technologies. It has since been modified to allow investigation of Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) post-combustion $NO_x$ reduction processes.

A schematic diagram of the ERTF and the main equipment associated with it is shown in **Figure 3**. Note the facility is capable of oxyfuel operation as well as conventional combustion. The furnace is 16.0 ft long and 20 inches in diameter, arranged vertically. The burner (a residence-time scaled-down version of a 42 $MW_t$ commercial low-$NO_x$ axial swirl burner) is located at the top of the furnace and fires vertically downwards. The furnace is lined with castable refractory (96% alumina), backed by insulating board to control the thermal environment. A water jacket removes heat to a forced draught air-cooled heat exchanger.

The facility can operate at 160$kW_t$ on either natural gas or coal or can fire at higher rates by using a combination of both fuels. Pulverized coal is supplied pre-ground with a typical size distribution of 80% less than 75 micron. The coal is manually loaded into a hopper and is fed at a controlled rate by a loss-in-weight feeder.

Primary air is supplied by a blower and is pre-heated electrically to give a delivery temperature of around 140 to 160°F at the burner. Secondary air is supplied by a forced draught fan and is heated electrically to around 450°F. The secondary air can be split into two separately metered streams - main combustion air to the burner and overfire air to the furnace. Overfire air injection ports are located at 14 levels with 3 ports at each elevation. These allow the injection of combustion air to the furnace downstream of the burner so that global air staging can be investigated. A total of 28 sampling ports are located along the length of the furnace which may also be used for reburn fuel injection if required.

Control of the ERTF is broadly manual but data logging is automated, by means of a Eurotherm 2500 data logging series modules system using proprietary software iTools, direct to a PC. Analysis of the data (averaging and consistency checking) is carried out "just off line" during the set-up period for the following test. Spurious data are quickly identified allowing repeat tests to be undertaken as appropriate.

Gas analysis sample points are located at the furnace exit, SCR outlet, and transport duct. Gas analysis is performed utilizing a total of 6 Xentra 4900 Continuous Emissions Analyzers supplied by Servomex. These units are protected by moisture capture systems; all measurements are thus presented on a dry basis. Under typical operation the concentrations of $NO_x$, $O_2$, CO, $SO_2$ and $CO_2$ are analyzed at the furnace exit; $NO_x$ and $O_2$ concentrations are analyzed at the SCR outlet or ESP outlet.

The test facility was significantly upgraded in 2008 for oxyfuel operation as part of the first phase of the collaborative OxyCoal-UK program.

### ERTF Upgrade for Solvent Scrubbing

The upgrade of the ERTF for solvent scrubbing includes the equipment required for capture of the $CO_2$ from the flue gas as well as a Flue Gas Desulfurization (FGD) skid, located downstream of the ESP, to control the $SO_2$ content and the temperature of the gas reaching the absorber column.

A booster fan has been specified to overcome the additional pressure loss introduced by the new equipment associated with the solvent scrubbing upgrade. The booster fan is located downstream of the existing ESP, upstream of the new

### Flue Gas Desulfurization

A custom-made, caustic (sodium hydroxide) scrubbing system, as shown at the right of the schematic **Figure 4**, is employed to provide very high removal efficiency of $SO_2$ from the flue gas and is also designed to provide control over the flue gas temperature from the FGD scrubber exit and into the solvent scrubbing system. Although limestone slurry FGD systems are more common on commercial power plants, the caustic system offers more flexible and reliable operation at the pilot scale. To assess potential operational impacts from wet limestone systems on full scale plant, dosing of fine limestone/gypsum particulate into the FGD exit gas will be considered later in the test program.

The FGD scrubber system is designed to operate with two distinct gas-liquid interaction steps: in the inlet leg of the scrubber vessel, the caustic solution is sprayed into the vessel at two elevations with nozzles oriented both co- and counter-current, here the dominant mechanism is direct cooling of the flue gas; in the downstream counter-current, packed section, the same solution is used, with spray nozzles at a single elevation; but the significantly enhanced mass transfer through the Koch Glitsch 1 inch Flexiring® PVDF random packing means that the bulk of the desulfurization occurs here.

The FGD scrubber is a custom-made PFA-lined Glass-Reinforced Plastic (GRP) body supplied by BEC Plastics, the nozzles used are manufactured by BETE. The $SO_2$ content of the flue gas is measured at both inlet and outlet of the scrubber vessel. The caustic solution sprayed into the vessel is collected from the vessel sump and re-circulated by peripheral pump, with periodic purge and make-up of the inventory to maintain the appropriate operating pH.

### Solvent Scrubbing

The solvent scrubbing system is depicted on the left hand side of **Figure 4**. The flue gas from the FGD exit passes through the counter-current solvent absorber vessel. The vessel contains stainless steel, structured packing and is fitted with a series of ports suitable for temperature and pressure measurement and gas-phase sampling. The column features a number of solvent inlet locations to offer a range of operating configurations. The scrubbed flue gas exits the absorber vessel before entering the water wash vessel. The water wash also contains stainless steel, structured packing and counter-current contact between the flue gas and circulating water entrains any remaining trace of solvent, the flue gas then leaves the water wash before being recombined with the stripped $CO_2$ stream and ducted to atmosphere. The remaining equipment items shown include the solvent handling, heat recovery and solvent regeneration operations.

The solvent exiting the absorber vessel (rich solvent) is pumped through a lean-rich exchanger (in one configuration of the system) where its temperature is increased due to heat transfer from the lean solvent exiting the stripper vessel, before being introduced into the stripper vessel. The stripper vessel is fitted with a series of temperature and pressure measurement points along its length.

The heat required to liberate the absorbed $CO_2$ from the solvent in the stripper is supplied by steam from a Fulton EP100 100kW electric steam generator.

Stainless steel gasketed plate-and-frame heat exchangers are used throughout the upgraded plant for heat transfer operations as they offer small-footprint equipment sizes, low temperature approach as well as their potential for expansion/modification and ease of disassembly/maintenance. One of the key design features of the facility is the ability to demonstrate the Thermal Kinetics Optimization™ (TKO) process developed by HTC Purenergy to substantially reduce the energy requirements for capture of $CO_2$ from flue gas. The TKO system maximizes the internal re-use of energy within the solvent handling and regeneration unit operations, reducing the requirement for the application of external heat.

Pumping duties in the solvent and water circuits are met by a range of variable-speed-drive diaphragm pumps which offer the ability to deliver comparatively low flow rates at variable delivery pressures without mechanical seals, thereby reducing the risk of personnel exposure to the pumped solvent.

The capture system is designed to minimize environmental impact: all liquid wastes generated by the process are retained for disposal by waste management specialists; and process vessels and equipment are located in bunds for spill control. To help ensure the safety of test facility personnel, permanent $CO_2$ detection alarms have been sited around the test facility structure, in addition to personal $CO_2$ detection alarms worn by personnel working on site. The full process is depicted in schematic form in **Figure 5**.

**ERTF Test Program and Results**

The ERTF was commissioned in June 2010 and initial testing commenced in July 2010. Initial tests focused on accruing operational experience and developing “baseline” results for the facility. Aqueous monoethanolamine (MEA) (30% w/w) has been used as the solvent to allow meaningful comparison with available data from existing solvent scrubbing pilot installations. El Cerrejon, a Colombian bituminous coal, has been used for the initial test phase as it has been used successfully in the past on both the ERTF and the larger Clean Combustion Test Facility.

**Figure 6** shows the $CO_2$ concentrations in the flue gas at FGD outlet and the off gas at the outlet of the water wash. The $CO_2$ concentration at FGD exit is 14.49 %v/v and at the water wash outlet 1.40 %v/v resulting in a capture rate of ~91% which meets the design requirement [3].

Baseline testing of the ERTF solvent scrubbing process was in progress at the time this paper was written. Once the baseline tests are concluded, future testing will seek to further validate the performance of the HTC Purenergy RS2™ formulated solvent. Test data from the ERTF will be compared against earlier test data collected by HTC and the UoR at the Boundary Dam and ITC pilot plants.

Thereafter, testing will seek to validate the operational impacts of such process variables as: absorber inlet flue gas temperature; absorber inlet solvent temperature; lean solvent loading; solvent circulation rate; stripper bottom pressure; reboiler steam pressure and others upon the performance of the system. Later testing will focus on further process parameter changes as well as changes to the equipment configuration – including testing of alternative packing materials and testing of alternative solvent formulations. In support of commercial activities, the ERTF will also be used to perform targeted testing; e.g., capture of $CO_2$ from flue gas derived from coals specific to a power station.

**CCPILOT100+**

This project will see Doosan Power Systems $CO_2$ capture technology installed at Ferrybridge power station in Yorkshire, United Kingdom. Ferrybridge is a 2,000MWe coal-fired station owned and operated by Scottish and Southern Energy plc (SSE). The $32 million project focuses upon the construction and demonstration of Europe's largest post-combustion $CO_2$ capture plant – a 5MWe slipstream equivalent to 100 metric tonnes per day of $CO_2$ captured. Vattenfall of Sweden are also partnering with Doosan Power Systems to develop this world class facility along with three UK universities, all leaders in the training of researchers in this sector. The project is co-funded by the Technology Strategy Board, the Department for Energy and Climate Change (DECC) and the Northern Way partnership [3][4].

**Figures 7 and 8** provide a view of the SSE Ferrybridge power plant and the design of the CCPILOT100+. Following a one year construction and commissioning phase, the project is scheduled to begin start-up and testing in the spring of 2011. The project is budgeted to continue testing for a two year period. During the testing phase, the demonstration plant will be typically operated in line with the power station. This extended testing will provide valuable insight into the validation of long-term phenomena, including: rates of corrosion and degradation mechanisms; transient operations and their impact on PCC performance and process control; solvent degradation and replacement; byproduct waste streams and handling requirements.

In addition to the industrial research and development focus, university researchers will participate in the project to gain operational experience, carry out complementary research and help to build the UK's skills capacity in this sector.

## BASIN ELECTRIC

In December 2009, Doosan Power Systems was selected to undertake a FEED study for a major carbon capture project with US utility Basin Electric Power Cooperative. The project is led by Doosan Power Systems in partnership with HTC Purenergy.

Basin Electric Power Cooperative is investigating opportunities to develop a $CO_2$ Capture Plant at its Antelope Valley Station (AVS), located at Beulah, North Dakota. AVS is a lignite-fired mine-mouth facility with two 450MWe sub-critical boilers. As shown in **Figure 9**, the AVS facility (located in the background and painted blue) is located adjacent to the Dakota Gasification Company (DGC). DGC is also a lignite coal mine mouth facility and, through a gasification process, converts this low rank fuel into a pipeline quality, synthetic natural gas. Over the years, DGC has implemented a number of novel, process enhancements that have made beneficial reuse of byproducts generated from the gasification process. This includes the production of $CO_2$. DGC has a sales contract to sell approximately 3.0 MTPY of $CO_2$ for use in Enhanced Oil Recovery. The $CO_2$ is transported through a 205 mile pipeline that runs from DGC to the Weyburn Oil Fields in Saskatchewan, Canada where the $CO_2$ is injected.

The Front End Engineering Design (FEED) Study for AVS has been based upon the application of the Doosan/HTC PCC process technology that will separate $CO_2$ from a slip stream of the flue gases produced by Unit No. 1. The PCC facility includes: flue gas pre-treatment; $CO_2$ absorption; solvent regeneration; and $CO_2$ compression and dehydration. The PCC plant was designed with a total nominal capacity of 3,000 short tons per day, or 1.0 million short tons per year.

The FEED Study was developed as a collaborative effort, with the Project Team comprised of members from Doosan Power Systems, HTC Purenergy, Basin Electric, Dakota Gasification Company and Burns and McDonnell (Basin Electric's Owners Engineer). The Project Team developed the project scope of supply, evaluated and identified the optimal terminal points for the different utilities (steam, air, water, etc.). To this extent, the contribution of the engineers from Basin Electric and Dakota Gasification Company was invaluable as, over the years, they have gained extensive experience in the operation and maintenance of $CO_2$ compressors, purification systems, and transportation. This collaboration also enabled the Doosan/HTC team the opportunity to work to ensure that the concerns of the AVS plant were addressed, including; reliability, operability, maintainability and efficient integration into the existing AVS and DGC infrastructure.

A key part of the initial phase of the FEED was to determine the detailed scope of supply for the PCC plant and Balance of Plant; in order to freeze the PCC process design. To accomplish this milestone, the project team first had to evaluate a number of design options. For example, one of the initial considerations regarded the location of the $CO_2$ compression and purification equipment. The Project Team evaluated two options. The first option was to locate this equipment adjacent to the PCC plant at the AVS station. The second option was to construct a low pressure pipeline from the PCC plant to the existing compression station at DGC. The Project Team looked at various considerations, including capital cost, potential to recover reject heat, and the benefits to AVS and DGC in having the new $CO_2$ compressor located adjacent to the existing compressors. After some analysis and consideration, the Project Team decided to pursue the second option. Similarly, there was many other design options evaluated, thus leading to a final process design. **Figure 10** illustrates the final design layout of the PCC Process Plant. The footprint of the PCC Process Plant is approximately 55,000 $ft^2$.

**Figure 11** illustrates the proposed location of the PCC Process Plant relative to AVS and DGC. **Figure 11** also indicates how the captured $CO_2$ from the PCC Process Plant will be transported to a new $CO_2$ compressor and dehydration system that is proposed to be located adjacent to the existing $CO_2$ compressor station at DGC where it is compressed, dehydrated, and fed into the existing carbon dioxide pipeline system. This design provides Basin Electric the flexibility to sell the captured $CO_2$ for enhanced oil recovery or sequester the $CO_2$ into nearby wells, utilizing the existing infrastructure.

**Figure 11** also indicates the proposed location for the PCC Cooling Tower which exhausts the heat captured by the PCC Process.

The FEED Study commenced in February 2010 and is on schedule to be completed before the end of 2010. The Project Team is currently developing the FEED Deliverables which include:

1. A proposed EPC Scope of Work; based upon the final design of the PCC Process Plant and Balance of Plant;
2. A ±15% EPC CAPEX and OPEX Estimate for the proposed EPC Scope of Work;
3. A Level 2 EPC Project Schedule for the proposed EPC Scope of Work.

When, completed, the FEED Deliverables will provide Basin Electric with a comprehensive assessment that will enable them to decide whether to proceed with the EPC phase of the project.

## CONCLUSION

The extensive testing and validation activities that have been previously completed by HTC Purenergy, with support from the University of Regina at the Boundary Dam facility and International Test Center and combined with various studies performed on commercial Carbon Capture plants have provided an initial validation of the PCC process technology being offered by Doosan Power Systems. However, the testing being carried out at the ERTF is of significant importance; not only because it provides a further level of validation of the process technology, but it also validates Doosan Power System’s design methods. The testing and validation programs conducted at Boundary Dam, the ERTF and later at the CCPilot100+ will be used to thoroughly validate the scalability of HTC technology under a variety of real world operating conditions. Key parameters validated during these programs, include: a) the actual rate of solvent degradation under industrial conditions; b) solvent make up requirements; c) steam consumption; and d) other auxiliary power requirements.

Further, the commissioning and testing programs undertaken at the Boundary Dam, ERTF and Ferrybridge plants will provide invaluable knowledge which will be incorporated for the full commercial deployment of PCC technology for power plant.

The FEED Study for Basin Electric has provided Doosan the opportunity to rigorously apply the technology to a commercial-scale plant. If Basin Electric elect to proceed with the EPC project, this will enable Doosan Power Systems to complete the requirements of it's roadmap through the commercial-scale application and demonstration of Doosan's PCC technology to the marketplace.

The ongoing research and development and cumulative experience of pilot plant operation will ensure that the deployment of commercial scale PCC plant can be achieved with rigorous operating guarantees, robust procedures and competitive performance, delivering an effective means to reduce greenhouse gas emissions from power generation.

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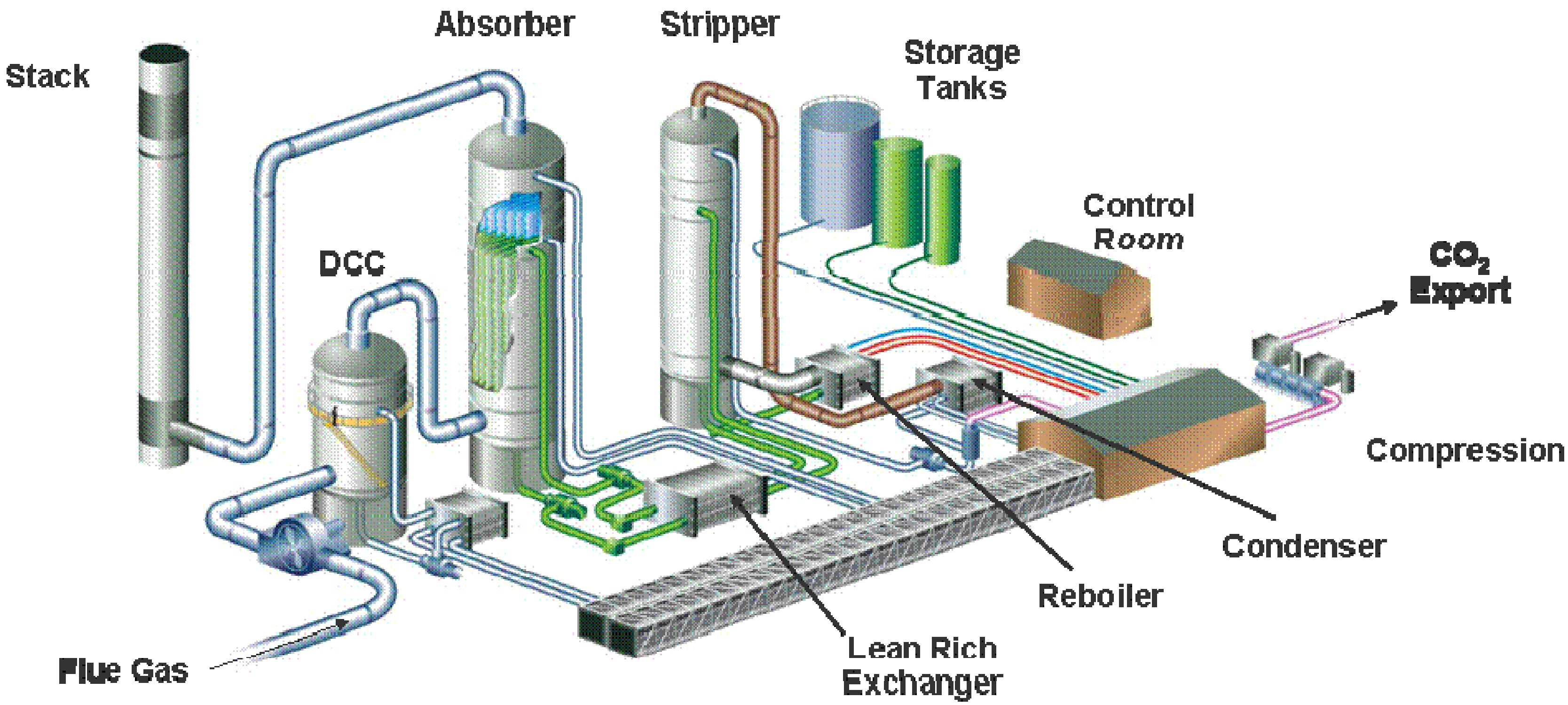
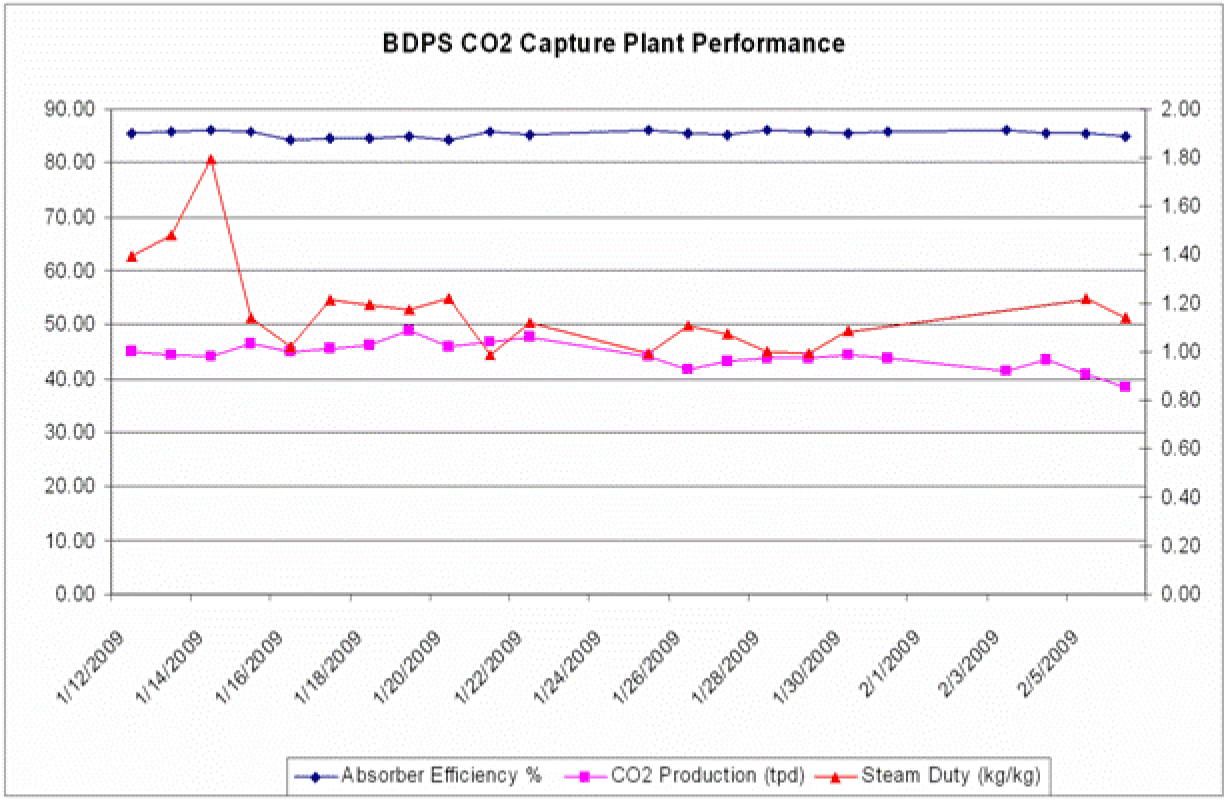



**Figure 1** Post-Combustion Capture (PCC) Process Description

**Figure 2** Test Results from Boundary Dam Pilot Plant Operating with RS-2 Solvent



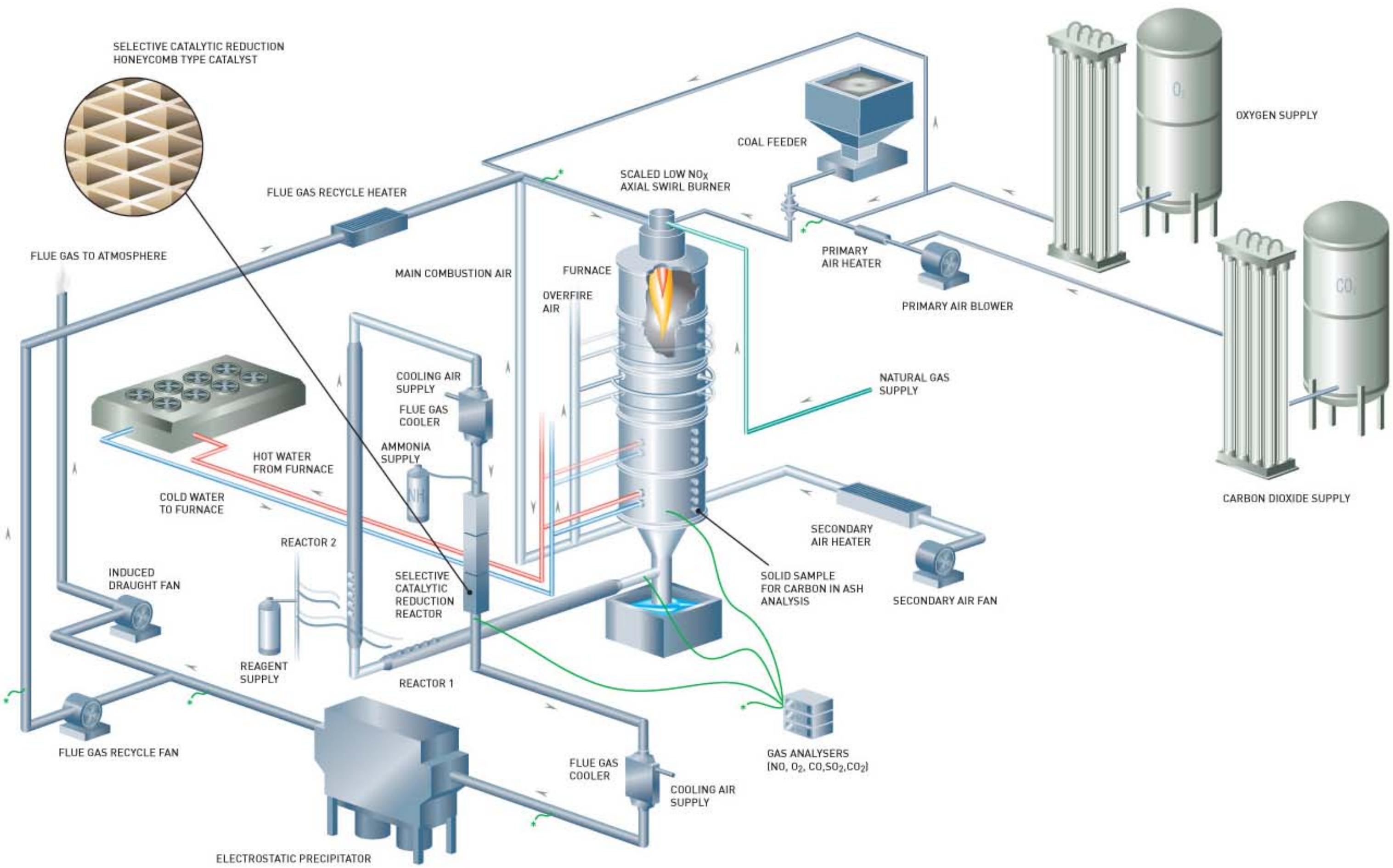



**Figure 3** ERTF Schematic – with oxyfuel capability

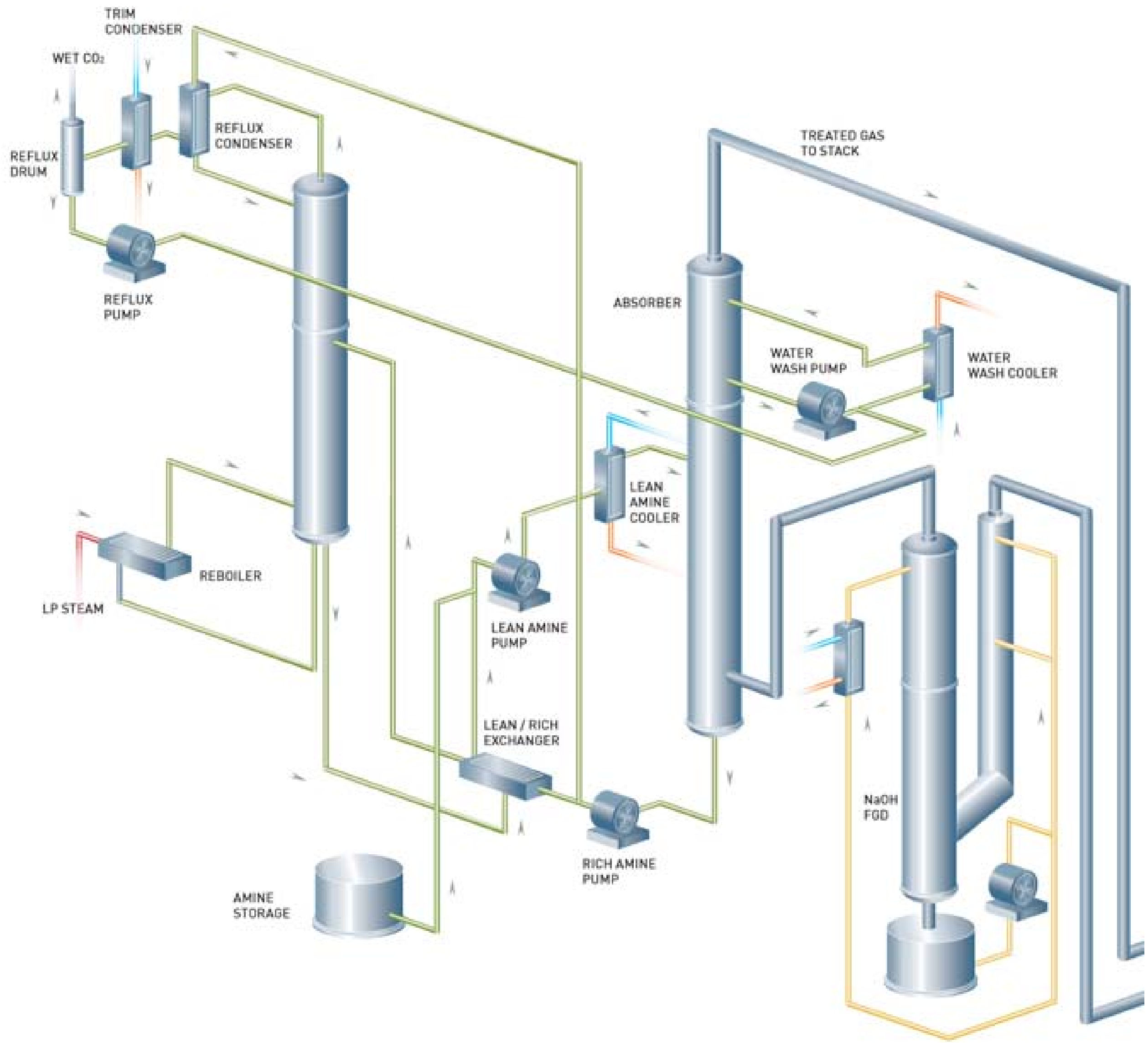



**Figure 4** Solvent scrubbing and FGD upgrade

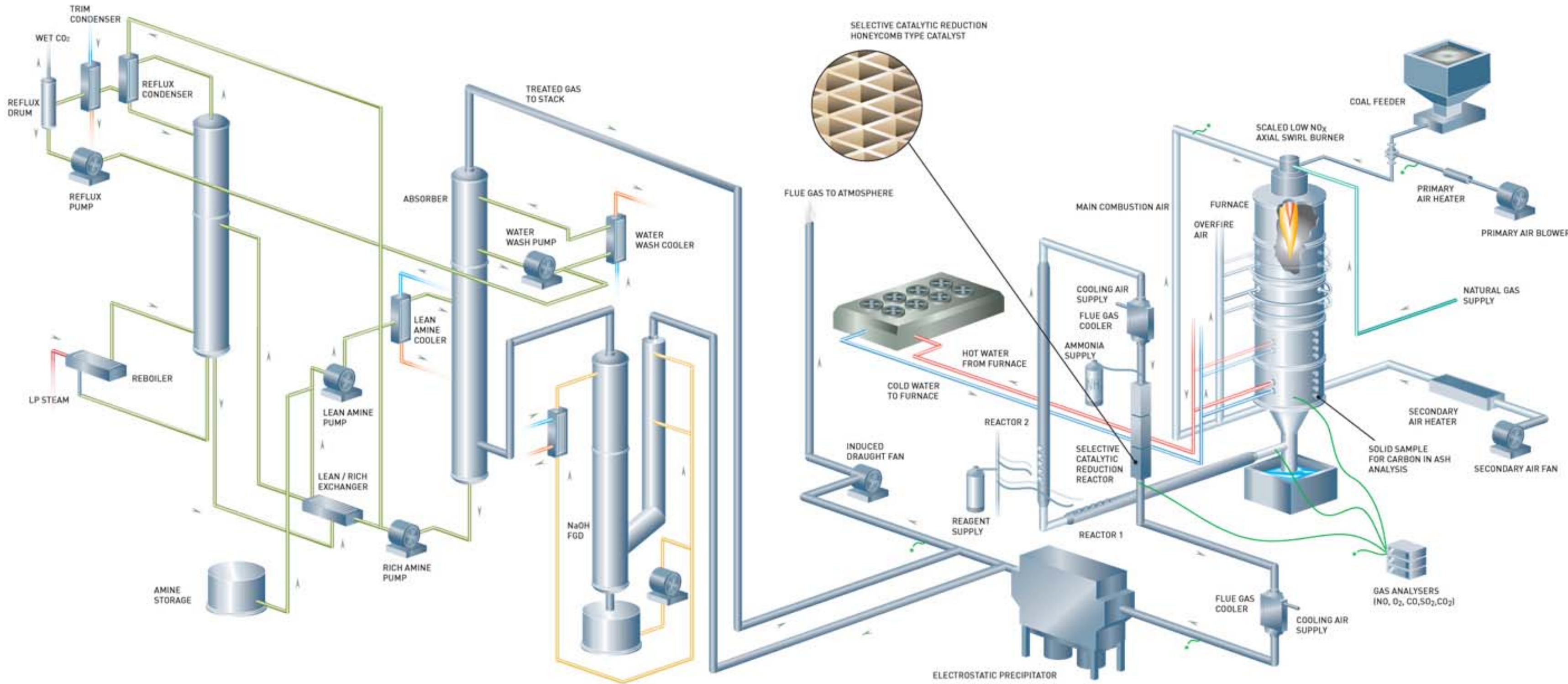



**Figure 5** ERTF with solvent scrubbing and FGD upgrade

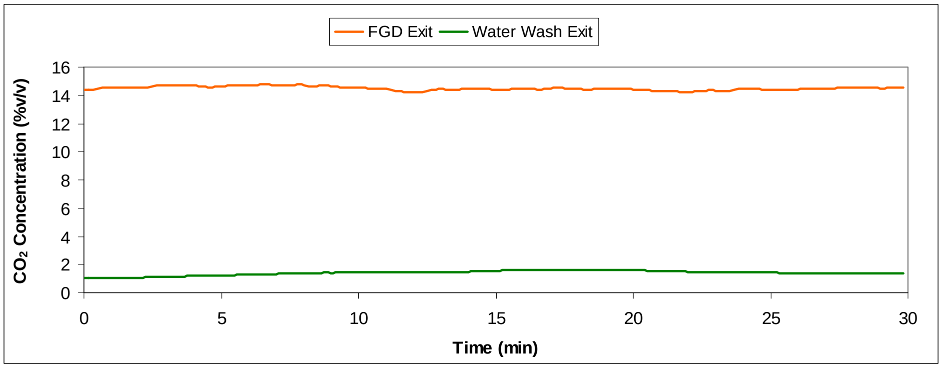



**Figure 6** Gas Analysis for $CO_2$ at FGD Exit (Absorber Inlet) and Water Wash Exit.

**Figure 7** Ferrybridge power station

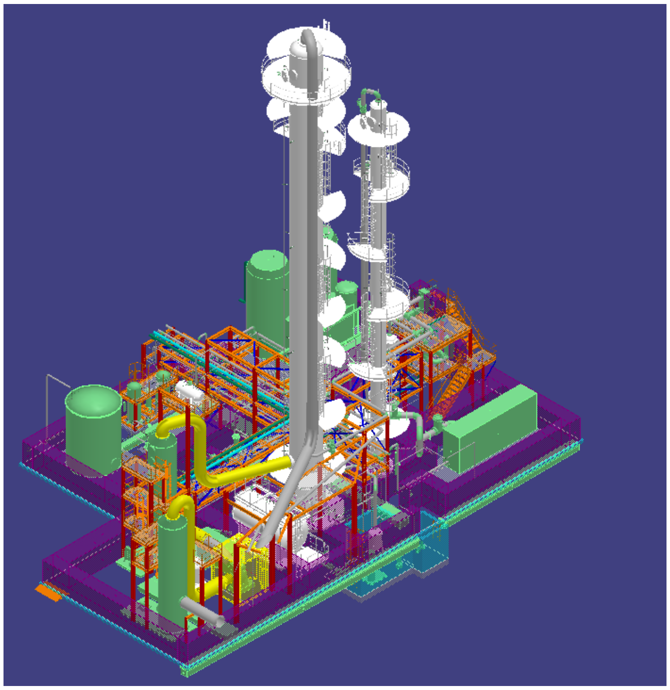


**Figure 8** Proposed design of the CCPILOT100+

**Figure 9** Basin Electric's Antelope Valley Station (in background) and Dakota Gasification Company's Facility (in foreground)

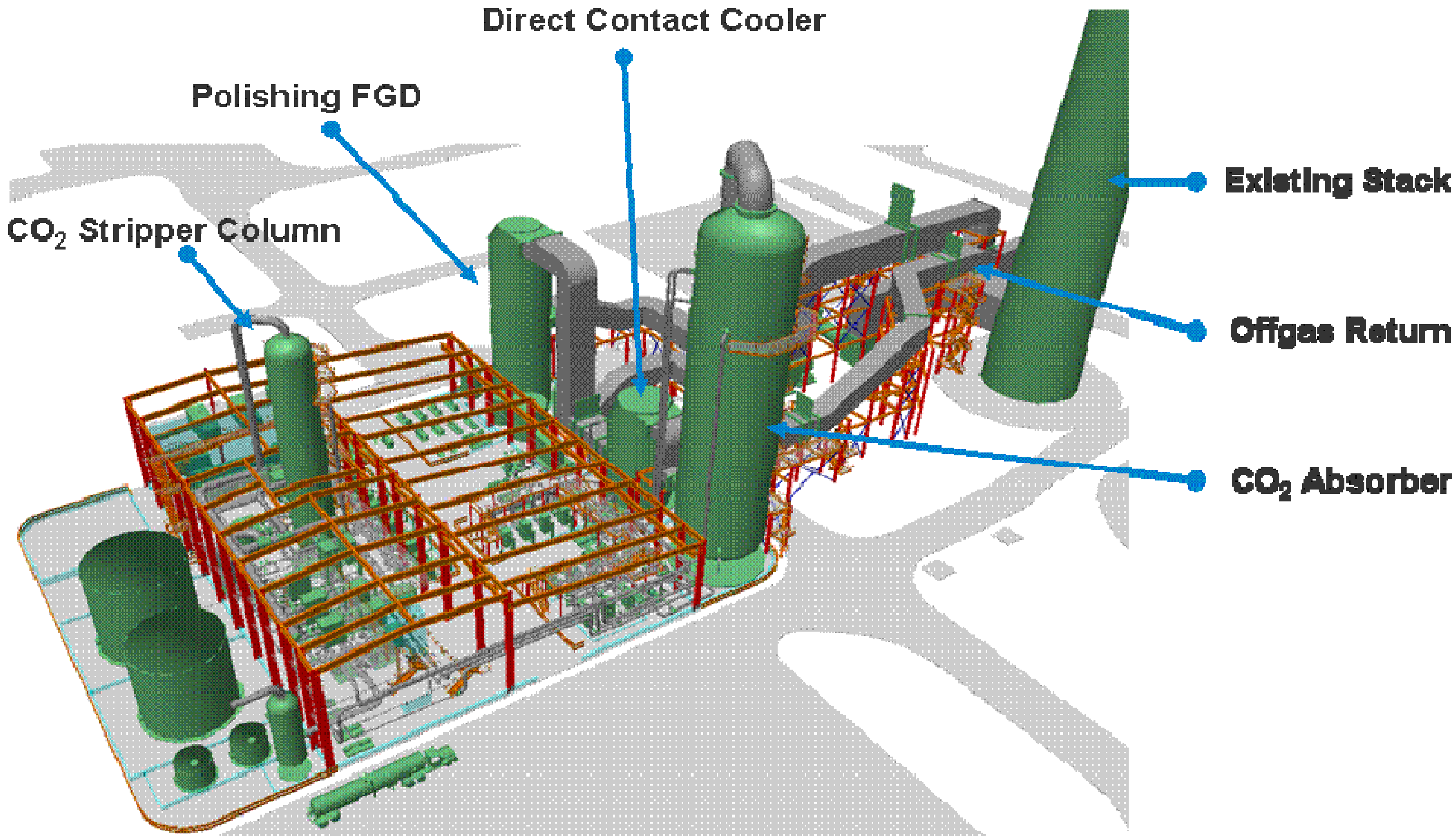



**Figure 10** Proposed PCC Process Plant Layout at Basin Electric's Antelope Valley Station

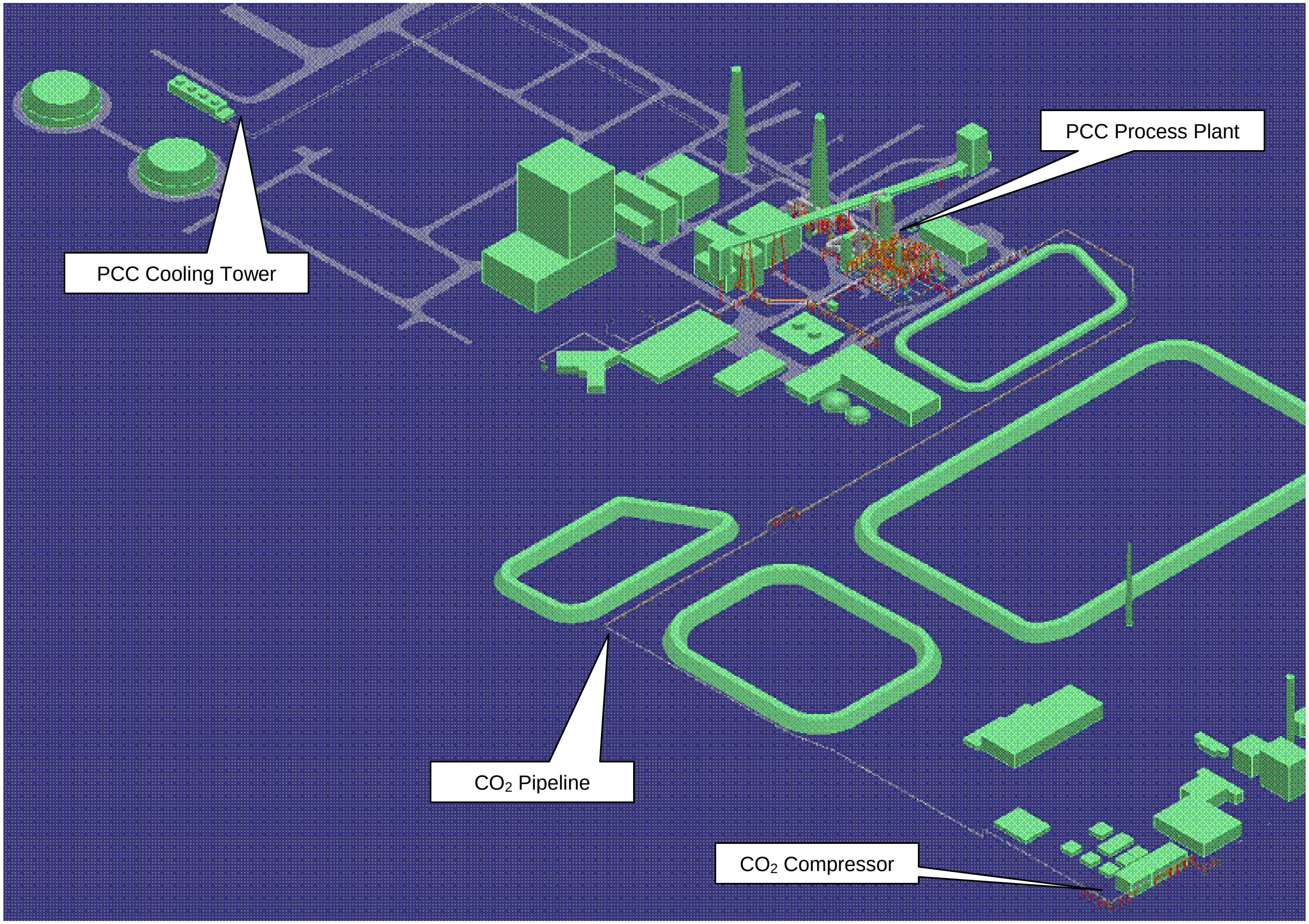



**Figure 11** 3D Model illustrating the proposed locations of: a) the PCC plant adjacent to AVS Unit No. 1; b) the $CO_2$ Pipeline running from the PCC Process Plant to the existing DGC $CO_2$ Compressor Station: c) the location of the PCC Cooling Tower