INSTITUTE FOR ENERGY STUDIES
THE UNIVERSITY OF NORTH DAKOTA

# EVALUATION OF $CO_2$ CAPTURE FROM EXISTING COAL FIRED PLANTS BY HYBRID SORPTION USING SOLID SORBENTS (CACHYS™)

*Submitted to:*

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**North Dakota Industrial Commission**
**State Capitol**
**600 East Boulevard Avenue, Department 405**
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Proposal Amount: $350,000

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## ABSTRACT

The proposal is submitted to the North Dakota Industrial Commission to request cost share support of $350,000 for the overall program funded at $3,690,000. The project was selected by the US Department of Energy for funding. The objective of this project is to scale up and demonstrate a hybrid solid sorbent technology for $CO_2$ capture and separation from coal combustion-derived flue gas. The technology -- Capture from Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents (CACHYS™) is a novel solid sorbent technology based on the following ideas: reduction of energy for sorbent regeneration, utilization of novel process chemistry, contactor conditions that minimizes sorbent-$CO_2$ heat of reaction and promotes fast $CO_2$ capture, and low cost method of heat management. The other key component of the technology is the use of a low cost sorbent. Our team – University of North Dakota, Envergex LLC, Burns & McDonnell and Solex Thermal Sciences along with industrial support from Allete, BNI Coal, SaskPower and North Dakota Industrial – is uniquely qualified to develop the CACHYS technology. The project will enable migration of the concept to the next scale (pilot) and eventually to full-scale demonstration and commercialization. The project will develop key information for the CACHYS™ process - sorbent performance, energy for sorbent regeneration, physical properties of the sorbent, the integration of process components, sizing of equipment, and overall capital and operational cost of the integrated CACHYS™ system. An efficient, reliable and cost-effective process for $CO_2$ capture with solid sorbents will be developed. The duration of the project is three years beginning October 1, 2011 and ending September 30, 2014.

## PROJECT SUMMARY

The objective of this project is to scale up and demonstrate a hybrid solid sorbent technology for $CO_2$ capture and separation from coal combustion-derived flue gas. The technology -- Capture from Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents Capture (CACHYS$^{TM}$) is a novel solid sorbent technology based on the following ideas: reduction of energy for sorbent regeneration, utilization of novel process chemistry, contactor conditions that minimizes sorbent-$CO_2$ heat of reaction and promotes fast $CO_2$ capture, and low cost method of heat management. The other key component of the technology is the use of a low cost sorbent. Our team – University of North Dakota, Envergex LLC, Burns & McDonnell and Solex Thermal Sciences along with industrial support from Allete, BNI Coal, SaskPower and North Dakota Lignite Energy Council – is uniquely qualified to develop the CACHYS technology. The project will enable migration of the concept to the next scale (pilot) and eventually to full-scale demonstration and commercialization. In the project, the following tasks are proposed.

- **Task 1.0 - Project Management and Planning** - Coordination and planning of the project.
- **Task 2 - Initial Technology and Economic Feasibility Study** - Initial evaluation of the technical and economic feasibility of the CACHYS concept.
- **Task 3 - Determination of Hybrid Sorbent Performance Metrics** - Defining the envelope of optimum process conditions using hybrid sorbent for $CO_2$ capture.
- **Task 4 - Designing, Building and Testing of Hybrid Sorbent Performance** -Design, build and shake-down a bench-scale hybrid sorbent adsorption/desorption system.
- **Task 5 - Adsorber and Regenerator Testing and Updating of Process Design and Economics** Operation of bench-scale system to obtain technical feasibility and process scale-up information.

The project will develop key information for the CACHYS process - sorbent performance, energy for sorbent regeneration, physical properties of the sorbent, the integration of process components, sizing of equipment, and overall capital and operational cost of the integrated CACHYS system. An efficient, reliable and cost-effective process for $CO_2$ capture with solid sorbents will be developed.

## PROJECT DESCRIPTION

### Goals and Objectives

The objective of this project is to scale up and demonstrate a novel technology for $CO_2$ capture and separation from combustion-derived flue gas including coal combustion. The project involves the use of novel sorbents and methods of use of these sorbents to capture $CO_2$ to obtain superior performance as compared to solvent based systems. The project will develop key information on the effectiveness of the sorbent to capture $CO_2$ from flue gases, energy required to regenerate the sorbent, physical properties of the sorbent, the integration of process components, sizing of equipment, and overall capital and operational cost of the integrated CACHYS™ system. Development of a cost-effective $CO_2$ capture and separation technology will facilitate the continued use of North Dakota lignite for power generation while minimizing greenhouse gas emissions.

### Work Plan

***Task 1 - Project Management and Planning***

The purpose of this task is coordination and planning of the Project with DOE-NETL, Project co-sponsors, and Participants. We will address the following items throughout the project duration:

1. Monitoring and control of project scope
2. Monitoring and control of project cost
3. Monitoring and control of project schedule

4. Monitoring and control of project risk
5. Updating the project plan periodically to reflect changes in scope/budget/schedule/risks
6. Using the project plan to report budget and schedule variances

UND and other project participants as required will provide quarterly technical reports, topical reports, participate in meetings, and make presentation at contractor's conferences as required by DOE and other project sponsors.

***Task 2 - Preliminary Technology and Economic Assessment***

The overall goal of this task is to conduct a preliminary technology and economic feasibility study of $CO_2$ and compression system based upon the proposed CACHYS™ concept. The proposed CACHYS™ concept is anticipated to be comprised of a fluidized bed reactor for adsorption and a moving bed heat exchanger for the regeneration setup. Process flow diagrams for the CACHYS process will be developed and major heat and material balances will be generated using ASPEN Plus simulation software. Burns & McDonnell will utilize and refine process flow diagrams and heat and material balance streams provided by UND and Envergex to reflect the additional details and adjustments required to accurately represent a full scale $CO_2$ capture and compression system. The outputs of the refined study by Burns & McDonnell will be:

- General process flow diagram identifying all major process equipment for the combined $CO_2$ capture and compression system.
- Material and energy balances around the combined $CO_2$ capture and compression system and around all major pieces of equipment (heating/cooling duties and power requirements).
- An updated and reviewed stream tables complete with process flow diagrams.
- Equipment definition list with associated vendor and/or in-house fabrication quotations.
- Estimation of plant performance based on a developed auxiliary load list obtained from equipment quotations or through an in-house database. The plant performance impact summary will be estimated using the steam extraction from a turbine as defined by this FOA.

- A conceptual site plan detailing the arrangement of the $CO_2$ capture and compression system in a conceptual existing facility.
- Development of feasibility level capital cost estimates for an existing facility retrofitted with a $CO_2$ capture and compression system. This capital cost estimate will indicate the all-in costs for the facility including infrastructure from the site fence line, interconnection to existing facilities, equipment costs, construction costs, construction indirects, and owner's costs.
- A definition of consumable quantities and costs inclusive of waste streams to estimate the operating and maintenance costs (both fixed and variable).
- Estimate of the $/ton of $CO_2$ removed using the economic criteria provided by DOE.
- A quantification and definition of the air and water emissions and solid wastes produced by the carbon capture and compression system including offsite disposal options.
- A definition of toxicological effects of substances used in the process and associated regulatory requirements.
- An evaluation on the ability to reduce or mitigate the production of potentially hazardous materials.
- Identification of precautions for safe handling of sorbent materials and associated waste streams.
- The above information will be used to determine process and cost advantages of the proposed technology as well as the key success drivers and risk factors. This will provide items to focus and address for the remainder of the project.

***Task 3 - Initial Sorbent Formulation and Testing***

The overall objective of this task will be to evaluate effective and cost-competitive hybrid sorbent formulations for $CO_2$ capture. Hybrid sorbents identified in previous studies (DOE-STTR conducted by Envergex LLC and UND) will be selected, formulated and developed under the direction of Envergex. UND personnel will prepare and test the sorbents. Both Envergex and UND have knowledge and extensive experience in the sorbent preparation and functionality.

Chemicals and materials required for the producing the sorbents for testing will be purchased by UND. The sorbents will be prepared by varying the amounts of active component, promoter, and support.

A TGA/DTA system will be used to determine the weight gain/loss as a function of a temperature and as a result of reaction or phase changes associated with the capture and release of $CO_2$ from the sorbent. The proposed testing requires testing under a broader range of pressures. A pressurized TGA/DSC analyzer will be purchased and installed at UND. A gas composition that approximately simulates flue gas (~15% $CO_2$) will be used by blending high purity gases. A water vapor generation system is added in order to simulate moisture content in flue gas. A schematic of the experimental setup is shown in Figure 1.

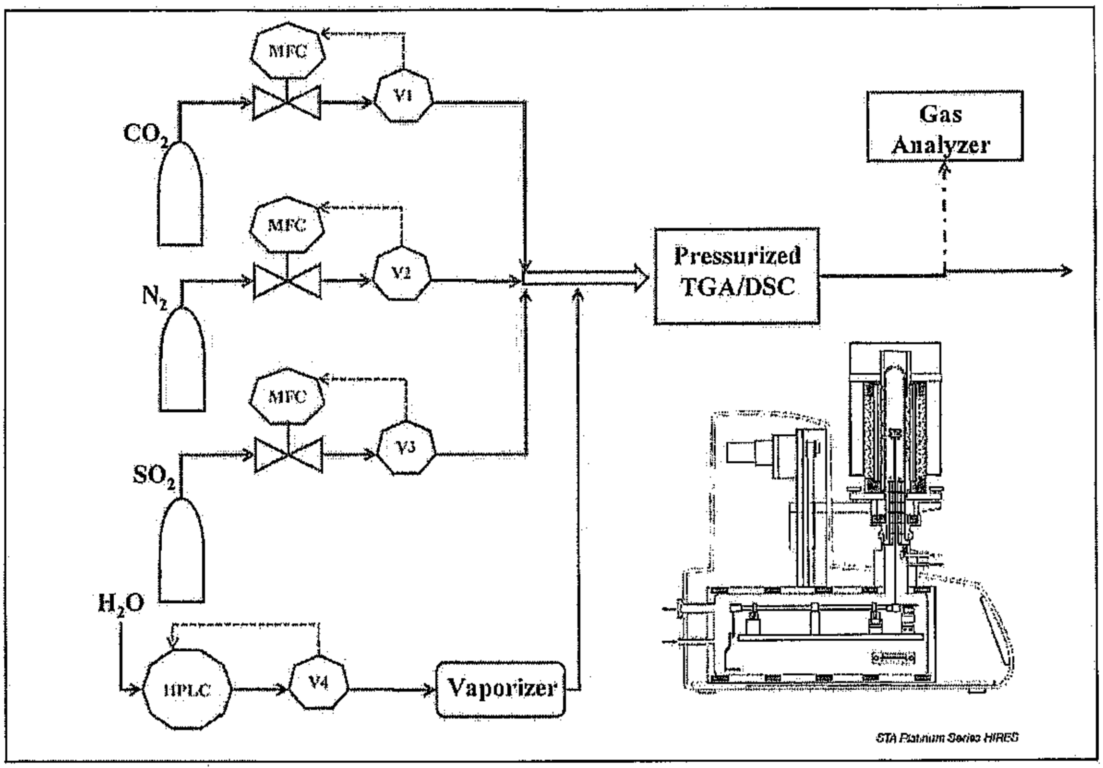



**Figure 1. Thermo-gravimetric Analyzer-Differential Scanning Calorimeter (Pressurized).**

The equilibrium loading of the prepared hybrid sorbents (g mol $CO_2$ adsorbed/kg sorbent) during adsorption and desorption will be obtained using the pressurized TGA/DSC analyzer. Factors to be varied in the tests include:

a. **Adsorption and desorption temperature:** The adsorption temperature will be varied between 50°C - 90°C and the desorption temperature varied between 120°C -200°C. Since the adsorption reaction is highly exothermic, a lower temperature of operation is thermodynamically favorable for high conversions. By varying the adsorption temperature, the sorption capacity of the sorbent as a function of temperature will be determined. Also, varying the desorption temperature will allow for the identification of the optimum effective temperature at which maximum desorption of $CO_2$ from the sorbent occurs.

b. **Adsorption and desorption pressure and sweep gas composition:** A range of adsorption and desorption pressures will be evaluated. The sweep gas composition will be varied to accommodate varying amounts of $CO_2$, $N_2$ and water vapor. During desorption varying mixtures of $CO_2$ and steam will be used. This information will provide sorbent capacities as a function of sweep gas composition. Also, the sweep gas composition will be varied to include acid gases such as $SO_2$. The effect of $SO_2$ contaminant concentration on the sorbent capacity will be determined by noting the weight.

c. **Initial sorbent composition** – quantity of additives, and sorbent compositions, as the sorbent is subjected to multi-cycle adsorption and desorption experiments.

The heat of adsorption and desorption (kJ/mol $CO_2$) steps as well as the heat capacity data (kJ/kg K) for the individual sorbents will be obtained as a function of temperature, pressure and sweep gas composition. This data will be obtained through weight gain/loss and heat flow data.

Data from the TGA/DSC testing will identify the envelope for operation of the adsorber and the regenerator, sorbent composition, temperature, pressure and sweep gas composition.

The kinetics of adsorption will be estimated using a different set-up, a sand bed reactor. The kinetics of carbonation will be characterized by measuring the degree of conversion of the sorbent material within a known period of time. The kinetics of adsorption will be studied by varying sorbent particle size, gas composition, adsorption temperature and adsorption $CO_2$ partial pressure. The reactor will initially be filled with sand and then heated to the test temperature. The superficial velocity of the fluidization gas will be held constant at the bed temperature. Experimental data will be collected by charging a fresh amount of sorbent to the sand bed and subjecting it to a continuous flow of $CO_2$ laden gas. At known time intervals, samples of elutriated fines will be collected. The length of the test will be determined when the outlet $CO_2$ concentration will become steady and equal the inlet gas concentration. Wet chemistry analysis of the collected fines will allow us to determine the reaction rate.

The physical properties of the sorbent will be determined for the relevant practical operating temperatures and pressures used in the sorbent heating and cooling steps. The data will be obtained for each of the hybrid sorbents prepared. Some of the sorbent testing will require samples to be shipped to a particle testing laboratory that is equipped with instruments that can conduct testing. An example of this laboratory is Micromeritics Analytical Services. The specific sorbent properties and tests include:

a. The heat capacity of the hybrid sorbents will be estimated using the UND TGA/DSC analyzer.

b. The true density of the sorbents will be measured using helium pycnometry. A sample of each of the hybrid sorbents will be taken and sent out to an analytical laboratory.

c. The bulk density of the sorbents can be estimated using standard method ASTM D 5004. This is done by noting the volume occupied by known mass of sorbents. The bulk density will both be estimated in-house and a sample shipped out to an analytical laboratory.

d. The average particle diameter will be estimated by taking a portion of the prepared sorbent material and either passing it through a series of sieves to estimate the particle size distribution or using a laser diffraction system to analyze the samples. It is imperative to note that during bench-scale testing, samples of the sorbent will be collected during each cycle and will be subjected to the same tests.

e. The crush strength of the hybrid sorbent materials will be measured using ASTM Test Method D 7084-04. This test method is used to measure the crush strength of catalysts in a bed. Sorbent samples will be collected during the multiple runs and subjected to this test. Samples of sorbent material will be sent out to an analytical laboratory.

f. The particle void fraction of the hybrid sorbents will be estimated using the measurements of the bulk and particle density.

g. The packing density will be estimated using bulk sorbent and active sorbent area measurements using the (Brunauer, Emmet, and Teller) BET theory. The measuring of the BET surface area will be done at an analytical laboratory and the packing density will then be estimated from these values.

h. A relative measure of the attrition index will be to compare the particle size distribution of a 'fresh' sorbent sample with sorbents collected at each cycle. This will provide an indication of the sorbent's attrition rate. Other tests that can be conducted to estimate the attrition index will be to estimate the attrition resistance using a modified three-hole air-jet attrition tester, which is based on the standard method, ASTM D 5757-95.

Previous proof of concept and technical feasibility testing as part of the DOE-STTR program was conducted with a laboratory fixed bed gas –solid reactor designed and constructed at UND. The fixed bed reactor was used to determine the solid loading capacity, sorbent breakthrough curves, and optimal regeneration process configuration and operation. It is proposed that the same fixed bed reactor system will be modified to include an upflow arrangement. The fixed bed reactor will be used to gather further design data on the adsorption and desorption kinetics, $CO_2$ capacity, heats of adsorption and desorption, cyclic operation, multi-cycle testing and performance determination as a function of number of cycles.

***Task 4 - Bench-Scale System Design, Fabrication and Shakedown Testing***

The overall goal of this task will be to design, build and conduct shakedown tests of the bench-scale adsorption and desorption system based on the CACHYS process. The system design will be based on parameters generated from initial sorbent testing using the TGA/DSC, sorbent physical properties and modified fixed bed testing results. A process schematic comprising a flue gas conditioning system and adsorption system is shown in Figure 2.

A flue gas stream of (~10-20 acfm) and at a temperature of 300-400 °F will be extracted from the duct system of the subbituminous coal-fired stoker boilers at the UND steam plant. The flue gas will be contacted with a trona powder injection system and allowed for sufficient reaction time to reduce the $SO_2$ levels to approximately 45 ppmv or below. The resulting flue gas will then be routed through a small bag-house followed by a preconditioning unit that will both cool/heat to levels needed for adsorption. The flue gas will be routed to a circulating fluidized bed that has tie-ins to sorbent feeding systems, flue gas outlet systems, and a cyclone system to separate the flue gas from the sorbent. The fluidized bed system will be designed and fabricated by UND. Preliminary dimensions of the absorber with gas and solid flow rates are shown below.

These will be updated based on results of Task 2 and 3. The absorber unit will be instrumented to obtain the necessary measurements for determining sorbent performance.

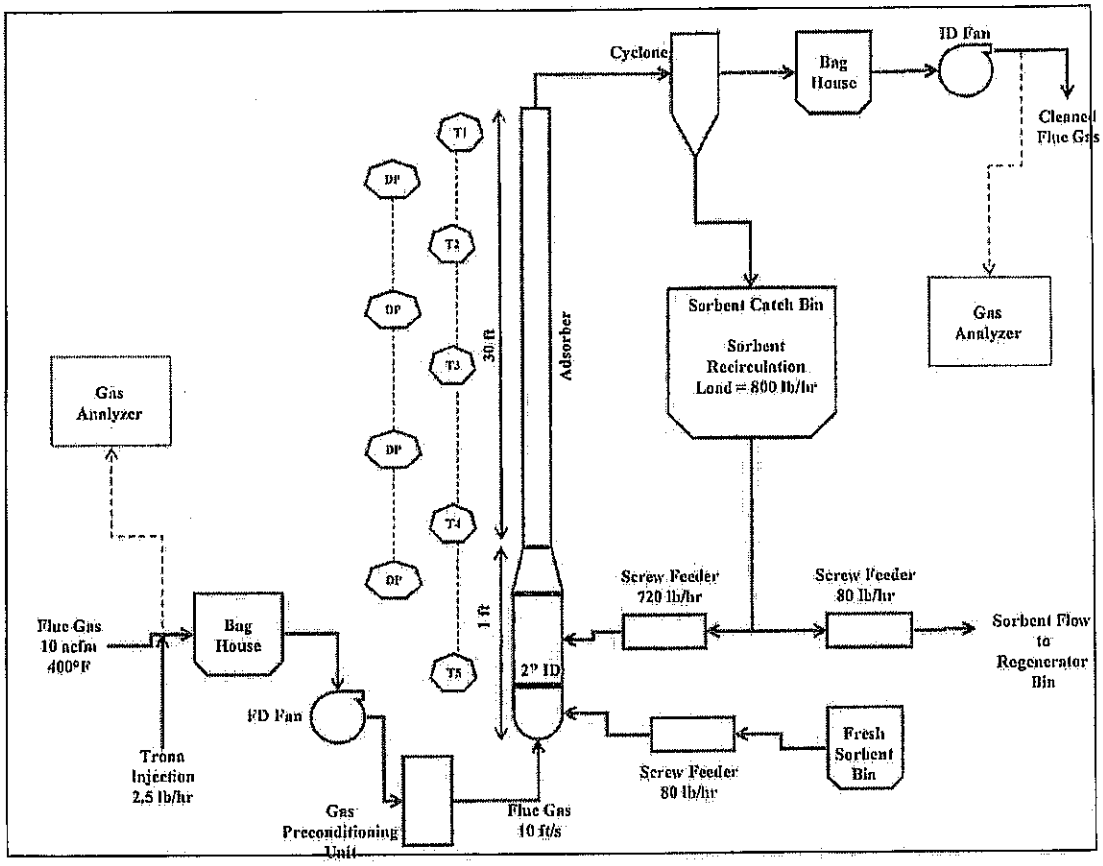



**Figure 2. Flue Gas Conditioning and Adsorber System.**

The sorbent regenerator will be designed and fabricated by Solex Thermal. The regenerator will consist of a dual sorbent feeding system complete with lock hoppers and rotary air valves, a $CO_2$/steam exhaust, condenser, baghouse for exhaust gases, heating unit, and a regenerated sorbent catch section. UND, Envergex and Solex will collaborate in designing the regenerator and integrating the feed/discharge systems, steam supply and $CO_2$/steam exhaust systems. Solex will manufacture the unit along with associated safety, measurements and control systems and ship to the UND site.

The adsorber, regenerator and associated sorbent and flue gas handling equipment will be installed at the UND steam plant. The continuous stream of flue gas from the steam plant will provide a high degree of flexibility in testing. The steam plant is located across the street from the School of Engineering and Mines. Further, associated instrumentation such as gas and steam flow meters, gas analyzers ($SO_2$ and $CO_2$), pressure gauges and thermocouples will be installed to monitor process conditions. Shakedown testing of the bench-scale system components will be conducted independently and as an integrated system. Testing will be conducted in a three phase program. Phase 1 testing will be on developing key information on the operation of the flue gas sampling and conditioning system that will allow for tailoring the flue gas composition. The system will have the ability to vary flue gas flow rates, trona injection rates ($SO_2$ levels), and flue gas conditions. Calibration curves and operating procedures will be developed for each of the units. Phase 2 will be geared toward testing the adsorber section. Sorbents with varying amounts of promoters, active components and support will be contacted with flue gas to allow for absorber system baseline performance testing. Sorbent injection rates and flue gas flow rates will be varied to allow for system performance testing. During phase 3, the performance of the regenerator will be tested. Sorbent flow, heating rates and final temperatures for regeneration will be varied to estimate residence times required to regenerate the sorbent. The next phase will encompass the overall system testing. Both batch and continual adsorption and regeneration steps will be performed.

***Task 5 - Parametric Testing and Updating of Technical, Economic and Environmental Health and Safety Assessment***

The testing will consist of an adsorption-heating/regeneration-cooling cycle. Flue gas will be introduced into the adsorber and the outlet $CO_2$ measured. A $CO_2$ breakthrough curve will be generated along with temperature measurements of the sorbent along the length of the adsorber. During regeneration, a known amount of heat will be delivered to the sorbent bed, and the $CO_2$ desorption and bed temperature monitored.

Sorbent specific heat and heat of adsorption as measured using the TGA/DSC analyzer along with the heat and material balances will be used to obtain a sorbent, $CO_2$ balance, $H_2O$ balance and the heat balance in the $CO_2$ recovery process. We will use measured temperatures, sorbent mass flow, specific heat data from TGA/DSC, heat input, and gas sensible and latent heats to perform an overall heat balance during each of the process steps. Table 1 provides a test matrix of the main variables.

Solid samples will be obtained throughout both adsorber and regenerator testing and analyzed for carbonate/bicarbonate content to confirm the heat and mass balance measurements. Solid samples will also be subjected to scanning electron microscopy and x-ray microanalysis to determine chemical composition and morphology.

Initially, the adsorber and regenerator (using $CO_2$-loaded samples from the adsorber) units will be tested separately. Subsequently, multi-cycle testing will be conducted to evaluate any deterioration in sorbent reactivity. The physical characteristics of the sorbent after multiple cycles will be determined to understand mechanical integrity.

**Table 1. Preliminary Adsorber and Regenerator Test Matrix.**

| Test | Test Ranges |
|---|---|
| Adsorber Temperature Range | 50°C- 90°C |
| Adsorber Gas and Solids Residence Time | Gas: 1-5 s; Solids Recirculation Rate Varied |
| Regenerator Residence Time | 1 - 30 minutes |
| Regenerator Pressure | Various |
| Regenerator Temperature/Heat Input | 120°C -200°C |
| Sorbent Cycle Times in Adsorber/Regenerator | Multiple Cycles |

Multiple test campaigns are planned for the adsorber and the regenerator and in combination. This will allow analysis of data and effective selection of new test conditions and operating strategy. In all, we anticipate about 30 days (6 weeks) of testing spread over the duration of the task.

Using the data generated from the bench-scale testing, it is anticipated that the superior performance of CACHYS™ sorbents will be established and the results used to project the process and equipment requirements for a given coal-fired power plant size, specifically a 500MWe plant. An updated technology and economic feasibility study will be conducted and a final report issued that detail the proposed CACHYS concept. Further, an updated environmental, health and safety assessment will be conducted to identify potential solids, air, and water emissions, and risks of the proposed CACHYS concept.

***Task 6 – Final Report***

A final report incorporating all results from the different project tasks will be submitted to DOE and project co-sponsors.

## DELIVERABLES

The primary deliverable of the entire project will be quarterly reports and a final report that will include a detailed explanation and supporting experimental and testing results that will be conducted to support the proposed CACHYS™ concept. The final report will identify the specific strategies applied in the capture of $CO_2$ from coal fired boilers, an updated technical and economic feasibility for the retrofitting of a carbon capture system to a 500MW plant, and an environmental health and safety assessment. Further, the quarterly reports as well as the final report will be provided for comments and revision.

## STANDARDS OF SUCCESS

The overall success of the project will be based on the ability to make progress in decreasing the cost of $CO_2$ capture. The DOE goals are to develop advanced $CO_2$ capture and separation technologies that can achieve at least 90% $CO_2$ removal at no more than a 35% increase in cost of electricity (COE) produced at the plant. This project's standard of success is based on the CACHYS™ technology to achieve DOE's goal.

## BACKGROUND

**The Problem** – In the US, coal-fired power plants represent about 50% of the electricity generated but contribute about 80% of the $CO_2$ emissions. Coal-fired plants represent a very large concentrated stationary emission source and are a more viable target to address the challenge of $CO_2$ emission mitigation compared to distributed emission sources such as transportation. There are essentially three approaches to reducing $CO_2$ emissions; burning less fossil fuel such as coal, improving the efficiency of energy conversion, and capturing and storing the $CO_2$ (CCS). This proposal focuses on the CCS option. In the CCS option, after the $CO_2$ is captured, it needs to be compressed to about 2200 psi for delivery to sequestration reservoirs.

Many commercial post-combustion $CO_2$ capture plants use chemical absorption processes with monoethanolamine (MEA)-based solvents. Hot potassium carbonate solutions have also been used as a $CO_2$ scrubber solvent (Benfield Process). In a typical process, flue gas contacts the MEA solution in an absorber. The MEA selectively absorbs the $CO_2$ and is then sent to a stripper. In the stripper, the $CO_2$-rich MEA solution is heated to release almost pure $CO_2$. The $CO_2$-lean MEA solution is then recycled to the absorber. Concerns about degradation and corrosion have kept the solvent strength relatively low (typically 20-30% amines by weight in water), resulting in relatively large equipment sizes and high solvent regeneration costs.

The first thing to note is that when a capture and compression system is added, the plant's overall thermal efficiency drops significantly, from about 38% to 29% (a *relative* decrease of 24%) (Herzog, 2009). This is due to the additional parasitic energy load from the $CO_2$ capture system. The parasitic load can be broken down into three components: (i) energy (steam) to break the chemical bonds between the $CO_2$ and the amine and to raise the temperature of the amine solution to the operating temperature of the stripper (~60%), (ii) $CO_2$ compression (~ 33%); and (iii) electricity to push the flue gas through the absorber (~5%). Existing amine-based liquid chemical absorption systems have a number of disadvantages including high parasitic steam loss due to solvent regeneration, sensitivity to sulfur oxides and oxygen, solvent loss due to vaporization, and high capital and operating costs.

An alternate process for $CO_2$ capture is the use of solid sorbents. Solid sorbents may have advantages because of potentially less energy requirements as the heat capacity of the carrier is several times lower than the water in the MEA-based solvent. Several classes of solid sorbents have been considered for low temperature CCS including carbon-based, supported amines, carbonate-based and zeolite sorbents. Each of these classes of sorbents has advantages and disadvantages. Carbon-based sorbents, which would fall in the physical adsorbent category, have a low energy for regeneration (< 10 kJ/mol $CO_2$) (Radosz et al. 2008). However, the $CO_2$ capacity is also low, and more sorbent must be heated during regeneration. In addition, more material would have to be moved, which is an important consideration in a full-scale system. Zeolites rely on their structure to act as a molecular sieve for gases. While zeolites exhibited a superior capability to remove $CO_2$ from dry simulated flue gas, in the presence of moisture, their performance was poor. To improve the $CO_2$ capture potential of zeolites, the effect of moisture must be addressed. (Siriwardane et al. 2001). Other solid sorbents that have shown considerable promise are supported amines (Sjostrom and Krutka, 2010). Most of these materials contained approximately 40–50 weight % amines; in several cases this was polyethyleneimine. The substrates included several silicas, clays and other high surface area supports. Heat of regeneration for the best amine-based sorbents were between 2000 and 3500 kJ/kg $CO_2$ and working capacity was between 3 and 9 wt%. All the materials exhibited a slow loss in capacity, which was attributed, in part, to reaction with $SO_2$ to form heat-stable salts, but also due to physical loss of the active component.

An example of the use of carbonate-based sorbents is the Dry Carbonate Process being developed by RTI (Nelson, 2009). The reaction inherent to this process is as follows:

$$Na_2CO_3(s) + CO_2(g) + H_2O(g) \rightarrow 2NaHCO_3(s) \quad \Delta H_r = -135 \text{ kJ/mole of } CO_2 \qquad [1]$$

Sodium carbonate captures $CO_2$ in the presence of water vapor to form sodium bicarbonate at temperatures around 60°C. By performing a moderate temperature swing to 120 to 140°C, the bicarbonate decomposes and releases a $CO_2$/steam mixture that can be converted into a pure $CO_2$ stream by condensation of steam. This process is ideally suited for coal-fired power plants incorporating wet flue gas desulfurization (WFGD) – due to the associated cooling and saturation of the flue gas and with minimal quantities of $SO_2$ and HCl, which can consume the carbonate sorbent to form non-regenerable sulfates and chlorides. There are however, significant challenges with processes based on dry solid carbonate sorbents:

1. The $CO_2$ sorption process above is strongly exothermic and requires significant cooling. Reaction equilibrium is negatively impacted if adsorption reactor temperatures are not controlled.
2. The high degree of exothermicity for the adsorption reaction also implies that the regeneration (reverse) reaction imposes an equivalent large energy penalty.
3. The dry sorption process requires an equimolar amount of water vapor for the forward reaction. This humidity is an energy consumer and has to be added in steps, making reactor design challenging.
4. The released water vapor from the regeneration step has to be condensed to separate it from the $CO_2$. This energy of condensation needs to be recovered and re-used to reduce the overall energy penalty.
5. Additionally, the $CO_2$ loading capacity of the solid sorbent needs to be maximized to minimize the large solids handling and circulation requirements.

The primary target for reducing costs for $CO_2$ capture and sequestration should therefore focus on reducing the energy of regeneration and maximizing the $CO_2$-carrying capacity of the sorbent/solvent, which is the focus of the proposed novel technology.

***The Solution and Proposed Concept*** – Capture of $CO_2$ by a hybrid sorption (CACHYS™) process is proposed as a novel alternative to the dry sorption process. The proposed CACHYS concept is based on the following underlying ideas:

1. The energy required during regeneration of the sorbent is minimized through having a proprietary additive and sorbent formulation.

2. Novel process chemistry and contactor conditions minimize sorbent-$CO_2$ heat of reaction, promote fast $CO_2$ capture, and use an effective and low cost method of heat management.
3. Low sorbent cost.

The proposed CACHYS™ concept consists of the components as follows:

A. A hybrid sorbent that can capture $CO_2$ from flue gases exiting a desulfurization scrubber. This hybrid sorbent is composed of the following components (i) Active alkaline components that react with $CO_2$ but with low heats of reaction; (ii) Additives to activate the alkali carbonate and promote fast reaction rates and low heat of reaction (iii) Porous, attrition-resistant support with large pore volumes with large capacity for active components and to increase reactivity by uniformly dispersing the active components; and (v) Binders to impart strength to the final sorbent particle.
B. Unique adsorber design and operation to regulate sorbent temperatures during adsorption
C. Regenerator operation that preserves the active form of the sorbent to ensure low heats of dissociation for $CO_2$ release.

We now describe the elements of our CACHYS™ technology. A schematic of the proposed hybrid sorption process is shown in Figure 3. The proposed CACHYS™ process can capture $CO_2$ from flue gases exiting a desulfurization scrubber with high sorption capacity, fast kinetics, and low regeneration energies. Flue gas from a typical PC boiler firing Illinois No. 6 coal with the associated pollution controls for NOx, PM, Hg, and SOx will typically have a composition as shown in Table 2.

**Table 2. Normal Flue Gas Composition after Pollution Controls (dry basis) (DOE FOA).**

| Dry Flue Gas Composition | Composition of Flue Gas Exiting FGD System |
|---|---|
| $CO_2$ | 15.9 vol% |
| $N_2$ | 81.3 |
| $O_2$ | 2.8 |
| NOx | ~ 80ppmv |
| Sox | ~ 45ppmv |
| Moisture | 17 vol% |
| PM | ~ 9ppmw |
| Hg | ~ 1.2ppbw |

In the proposed concept, flue gas from a desulfurization scrubber connected to a coal-fired boiler with relatively low $SO_2$ (~45 ppmv), high humidity and $CO_2$ (~15.9%) levels enters the adsorber section of the process.

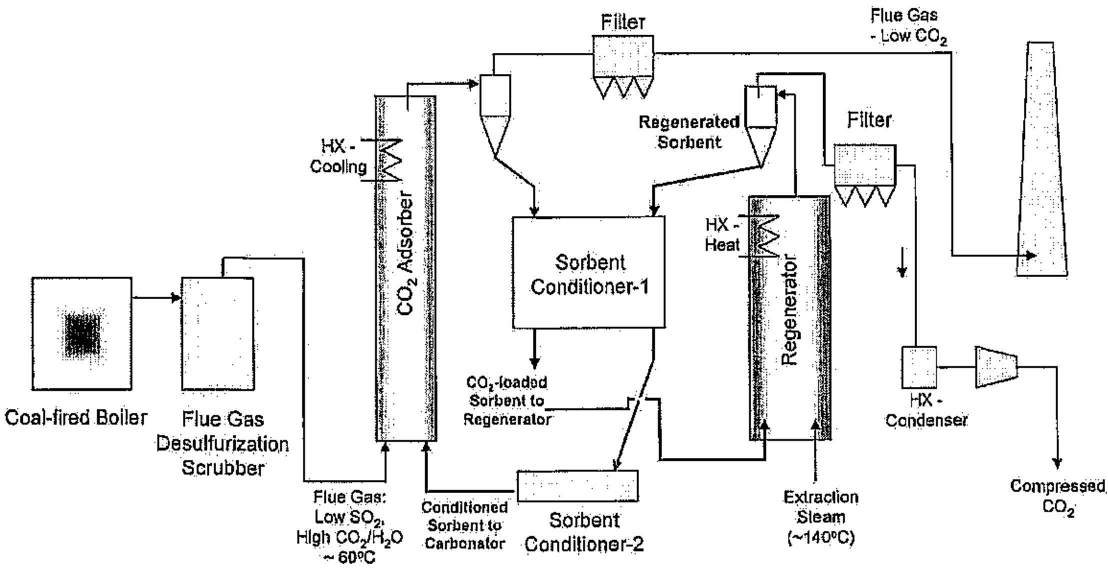



**Figure 3. Schematic of CACHYS™ process.**

I. **Adsorption:** It is anticipated that the adsorber will be a fluidized bed design or a transport reactor. Sorbent that can be fluidized (~100-1000 μm) sorbent is introduced into the adsorber and contacts the flue gas in a co-current manner. Adsorption of $CO_2$ is an exothermic process. The temperature in the adsorber is anticipated to be maintained at 60-80°.C The

$CO_2$-loaded, drier sorbent is separated with a cyclone and transferred to a sorbent conditioning system. A portion of the sorbent may be recycled to the adsorber,

II. **Sorbent Conditioning:** The second aspect of the process is that the $CO_2$-laden sorbent is conditioned before its introduction to the regenerator. The objective of the conditioning system is to tailor the sorbent properties to optimize its performance in the regenerator.

III. **Regeneration:** The $CO_2$-loaded sorbent from sorbent conditioning system is transferred to a regenerator, which can be a moving bed or a bubbling fluid bed. One of the key elements of regenerator operation is that it be performed under process conditions that preserve the active component. Another unique aspect of the design is potential operation of the regenerator to further foster low regeneration heats of reaction. Heat transfer is provided in the regenerator to heat the sorbent to achieve the relevant regeneration temperatures, which are expected to be about 120-170°C. The regenerated sorbent particles are directed to sorbent conditioners prior to reintroduction into the adsorber.

A detailed technical basis of the proposed work, supporting data from previous research work, and heat and material balance calculations using ASPEN model for the CACHYS™ process are provided in Appendix D.

## QUALIFICATIONS

***Project Team***

***UND Institute for Energy Studies***

Dr. Steve Benson is the Director of the Institute for Energy Studies and a professor of Chemical Engineering at the University of North Dakota (UND). The Institute for Energy Studies was recently formed by the North Dakota State Board of Higher Education to facilitate the coordination energy education and research activities at UND that involves faculty, research staff, and students. Dr. Benson has over 25 years of experience of coal related research centering on coal, biomass, and petroleum energy conversion systems; air pollution control; and $CO_2$ separation and capture. Currently, Dr. Benson has active projects in trace metal transformation, ash formation, NOx control, mercury emissions control, and $CO_2$ separation and capture sequestrations. Prof. Benson has a well equipped laboratory and works with a very capable team of faculty/staff research engineers, equipment fabricators, and graduates students working on coal combustion and gasification related projects and has the capability of pilot-scale coal combustion and scrubber testing, sampling and analysis of combustion gases and ash, and mercury and trace element analysis.

Key UND team members include:

Dr. Michael Mann, Associate Dean for Research, School of Engineering and Mines, has extensive experience in fluidized bed combustion and gasification systems. Specifically he was involved in research projects; design, installation, and operation of a 1 $MW_{th}$ CFBC and a 250 lb/hr gasifier. In addition, he was a manager for project for the development of small power systems for Alaskan villages; and the development of a small-modular fluid-bed combustion system (0.5 to 5 MW)

Dr. Nanak Grewall, Professor of Mechanical Engineering, has conducted research programs to investigate the heat transfer in fluidized-bed coal combustors. He has designed and operated experimental facilities to measure spectral emissivity and investigated heat transfer between immersed horizontal tubes and liquid-solid fluidized bed.

Dr.Gautham Krishnamoorthy, Assistant Professor Chemical Engineering, expertise in heat transfer, reacting flow modeling and the use of computational fluid dynamic tools to study carbon capture technologies. He has extensive background in the development and implementation of algorithms in computational frameworks. As a heat transfer specialist at ANSYS Inc., he was at the interface of the consulting and development teams.

Mr. Charles Thumbi, Research Engineer, Department of Chemical Engineering and the Institute for Energy Studies, Mr. Thumbi is responsible for developing combustion and gasification models for combined heat and power systems using ASPEN and other software systems. He the lead engineering efforts in the design, construction and operation of the test equipment developed CACHYS Phase I STTR project. He has also performed combustion and gasification testing under laboratory settings.

*Envergex LLC*

Dr. Srivats Srinivasachar is President of Envergex LLC and also an adjunct faculty member of Chemical Engineering at the University of North Dakota (UND) and is a sub-contractor in this effort. Dr. Srinivasachar has an ongoing Department of Energy STTR project with UND (basis of proposed project) related to the capture of $CO_2$ from flue gases using solid sorbents. Dr. Srinivasachar holds 10 patents and has over 50 publications, several of these related to pollution control technology. He is a world class expert on the subject of mercury control. He is the inventor and developer of enhanced mercury control sorbents (ESORB®, patents pending) which have been tested in several full-scale boilers and are being commercialized. He scaled the product through pilot-scale evaluation and commercial-scale testing, including commercial-scale production of sorbents, and completed the successful demonstration of this technology at three full-scale plants.

***Burns & McDonnell***

Ms. Megan Parsons, P.E., Development Mgr. Ms. Parsons has over 10 years of experience in project development, providing feasibility evaluations for cogeneration, simple cycle, combined cycle, repowering, and coal fired generation options. Ms. Parsons is our $CO_2$ capture Business Unit Manager.

Mr. Tom Anderson, P.E., Process Lead. Mr. Anderson has over 30 years of experience in both power generation and process industry applications. Mr. Anderson specializes in process design and simulation for various process applications with expertise in distillation, gasification and carbon capture processes.

Mr. Steve Rottinghaus, P.E., Performance Manager /Consultant: As Manager of Development Engineering, Mr. Rottinghaus directs the technical development of energy related projects in Burns & McDonnell's Energy Division. In this capacity, he specializes in the preliminary design, feasibility, due diligence reviews and economic analysis of these projects. He has over 20 years of experience.

Mr. Eric N. Wenger, Industrial Hygienist, Mr. Wenger is a senior Industrial Hygienist with 15 years of consulting experience and has completed the comprehensive exam for professional certification (CIH).

Ms. Diana Marquez, Environmental Scientist Ms. Marquez has sixteen years of experience in human health risk assessment, vapor intrusion, RCRA corrective action, CERCLA project management, environmental site assessment, and hazardous waste management

Mr. Steven D. Jansen, Safety Engineer, Mr. Jansen serves Burns & McDonnell in the Design/Build Division as a Corporate Safety & Health Specialist. He has over 30 years of demonstrated ability and

experience in the management and oversight of safety and health and industrial hygiene programs

Mr. Mark Scoville, TSCA Specialist, Mr. Scoville is a sub-consultant commonly contracted by Burns & McDonnell to support TSCA audit work. He has over 28 years experience in performing Toxic_Substance Control Act (TSCA) audits.

Burns & McDonnell has unique qualifications to support the feasibility evaluations and EH&S assessments that include:

Understanding of Power Generation Facilities - As an EPC contractor and detailed design engineering firm in the power industry, Burns & McDonnell has in depth knowledge of all aspects of power generation facilities including coal plants for which this development is targeted. As such, we understand the impact of the carbon capture facilities on the plant (steam extraction, heat integration, auxiliary power consumption, etc.) and the plant's impact on the carbon capture (flue gas conditions and constituents including potential contaminants).

Experience with $CO_2$ Capture Technologies - Burns & McDonnell has been involved with and performed numerous feasibility studies on carbon capture applications for coal generation facilities including conventional Rankine cycle plants and Integrated Gasification Combined Cycle facilities. These feasibility studies range from high level feasibility assessments to general economic and technical impact of the application of new technologies to full blown Front End Engineering and Design (FEED) studies of application to existing coal plants. Our FEED experiences include involvement on Basin's Antelope Valley Station post combustion carbon capture retrofit, Tenaska's proposed Trailblazer new coal facility post combustion carbon capture, Duke's Edwards Port IGCC facility pre-combustion carbon capture, and a FEED study for post-combustion retrofit on another existing large coal plant for a confidential client.

*Solex Thermal*

Solex Thermal Science Inc. is a privately held company that specializes in the design and procurement of equipment used for heating, cooling and drying of bulk solids. Solex holds several patents for its exclusive heater, cooler and dryer technologies designed for use with bulk solids such as sugar, fertilizer, chemicals, plastics, biosolids, minerals, and many other types of grains, crystals and powders.

Mr. Igor Makarenko, Application Manager, joined Solex in 2010. Igor manages Solex high temperature and special applications which involves developing new product lines. Prior to joining Solex, he had 13 years of operation management and 5 years of project management experience in grain and oilseeds processing industry.

Ms. Ashley Byman, Vice President, Research & Development, joined Solex in 2001 and has 8 years experience in the powder and bulk solids processing industry. Ashley manages Solex R&D projects which involves developing new product lines and enhancing the capabilities of current product offerings. Prior to joining Solex, Ashley spent 7 years in the oil and gas industry working on mechanical and acoustical analysis of gas compressors involving finite element analysis and vibration troubleshooting. He is a graduate of the University of Saskatchewan and holds a degree in Mechanical Engineering.

Ms. Farah Salaria recently joined Solex Thermal Science as the Vice President, Product Development. Farah comes to Solex with extensive knowledge in the area of plate heat exchangers and centrifugal separation equipment. She has worked in oil and gas, water and waste treatment as well as the chemical and the fertilizer industries. Farah holds a degree in Chemical Engineering.

*Facilities*

The UND campus has 3 coal fired (sub-bituminous/lignite) stoker boilers that provide steam for district heating. The coal fired boilers are of a spreader stoker configuration. Coal firing rates of the boilers range from summer lows of approximately 8,000 lb/hr to winter highs of 30,000 lb/hr. Flue gas generated from each of the coal boilers is routed through bag houses for particulate control. We will use this flue gas in our bench-scale testing.

The UND department of Chemical Engineering has a 19kW pilot scale entrained flow combustion system capable of firing coal and biomass, a 5 kW natural gas fired combustor, and a 10 kW gasification system. The combustion systems can be integrated with a baghouse for particulate control and a wet scrubber system for sulfur control. The flue gas from these systems can be used to study $CO_2$ capture. UND currently uses a 1 kg fixed bed reactor system to capture $CO_2$ using solid sorbents. The reactor system is equipped with a steam generator for sorbent regeneration. This reactor system has been used to test the adsorption and regeneration behavior of several solid sorbents. These conversion systems are all equipped with the following flue gas analyzers that can continuously sample flue gas:

- Non-dispersive Infrared Absorption Spectroscopy for $SO_2$ and $CO/CO_2$ analysis using the Teledyne Analytical Instrument-IR 7000 and the Liston Scientific Enviromax respectively.
- Paramagnetic type $O_2$ Analyzer - using the Teledyne analytical instrument-3000M series.
- A Datatest Model DT 5000 NOx analyzer that utilizes chemiluminescence technology for precise continuous measurement of the NOx.

UND Chemical Engineering also has a simultaneous thermogravimetric/differential scanning calorimeter (TGA/DSC). Simultaneous measures of weight loss or gain and exothermic and endothermic reactions/transformations associated with decomposition and adsorption processes can made as a function of temperature and atmosphere.

A sand bed reactor is available for measuring reaction rates and will be reconfigured for testing to support this project.

The School of Engineering and Mines has a scanning electron microscope equipped with an energy dispersive x-ray microanalysis system that will be utilized to examine the microstructural features of the sorbent before and after exposure to flue gas.

## VALUE TO NORTH DAKOTA

North Dakota produces over 30 million tons of lignite annually. North Dakota's economy depends on lignite production and use. Lignite combustion produces more $CO_2$ per Btu of energy as compared to other coals, thus a low-cost effective means of separating $CO_2$ will be critical to ensure lignite's future use if regulations limit $CO_2$ emissions in the future.

## MANAGEMENT

The team assembled to perform the proposed work includes the Institute for Energy Studies (IES) of the University of North Dakota, Envergex LLC, Burns & McDonnell, Solex Thermal, Allete, Minnesota Power, SaskPower, and the Lignite Energy Council. The team brings together the expertise required to effectively perform the proposed work to determine the technical and economic feasibility of the technology that will lead to a commercial system to capture $CO_2$. The project is led by Drs. Benson and Srinivasachar the principal investigators of the project. Dr. Benson will be the program manager and the overall lead and will be the contact person for the University of North Dakota and will be responsible for managing resources and project schedule. Dr. Srinivasachar will lead and coordinate the scientific and engineering aspects of the project. Drs Benson and Srinivasachar have a long history of working together on projects and programs associated with coal combustion and associated environmental control systems. Dr. Benson will coordinate meetings and conference calls with the NETL and other project co-sponsors as well as communications with project participants. The activities of the various components of the project are divided by task and the tasks will be implemented and completed by each task leader.

Project meetings and conference calls will be held on a weekly basis to review project timeline, upcoming milestones/deliverables, costs and challenges associated with the completion of the projects. Microsoft Project management tools will be utilized. Project review meetings with sponsors will also be held on a quarterly basis to ensure communication and discussion of accomplishments, plans and management of project risks. Meet with industry co-sponsors to update them on technical progress and seek input on commercial scale-up and applicability.

Figure 4 shows the management structure for the project that is designed to manage the project by task with key individuals identified to lead the specific areas. The Tasks will be performed by teams of the individuals listed in Figure 5. Cost management will be coordinated by the Administrative management who will be responsible for tracking all costs for each of the project tasks.

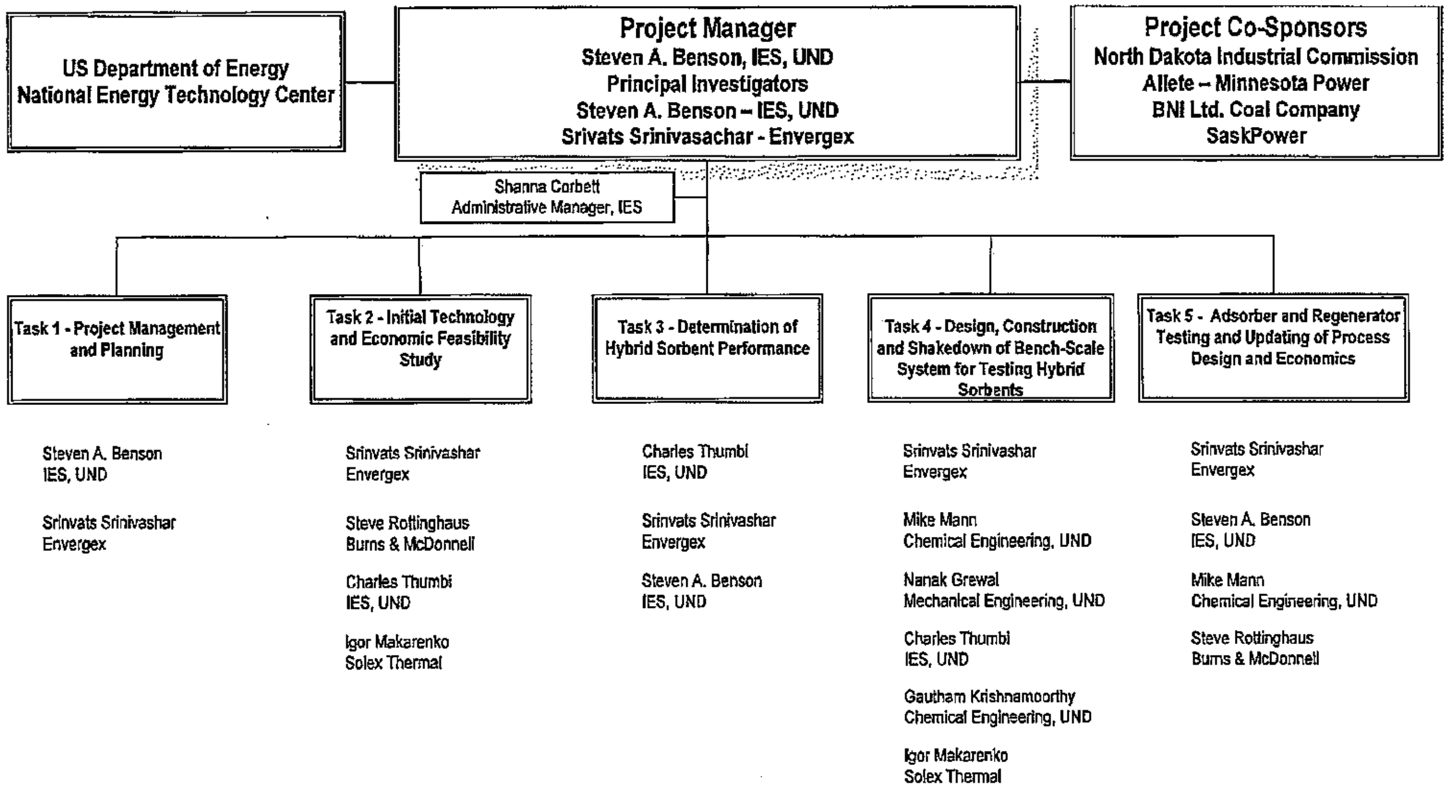
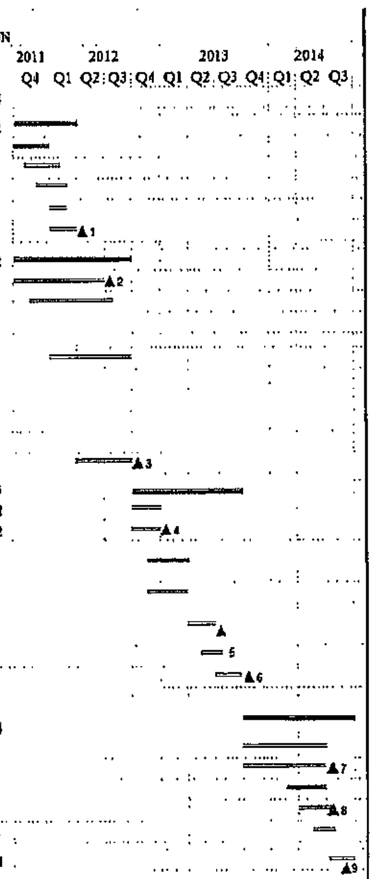



**Figure 4. Overall project management structure for the proposed project**

## PROJECT TIMETABLE

The schedule of tasks and milestones is shown in Figure 5.

| TASK/ SUBTASK | TASK DESCRIPTION | PLANNED COMPLETION |
|---|---|---|
| 1 | **Project Management Plan** | 9/30/2014 |
| 2 | **Initial Technology and Economic Feasibility Study** | 3/31/2012 |
| 2.1 | Identification of major process equipment | 1/15/2012 |
| 2.2 | Material and energy balances | 2/15/2012 |
| 2.3 | Stream tables generation | 3/15/2012 |
| 2.4 | Cost estimation for process equipment and consumables | 3/31/2012 |
| 2.5 | Initial technology and economic feasibility study report | 3/31/2012 |
| 3 | **Determination of Hybrid Sorbent Performance Metrics** | 9/30/2012 |
| 3.1 | Sorbent selection, formulation, and development | 7/31/2012 |
| 3.2 | Testing using pressurized TGA/DSC | 8/31/2012 |
| | Acquisition, installation, and training | 5/31/2012 |
| | Testing (Eqm.loading; heats of adsorption/desorption) | 8/31/2012 |
| 3.3 | Testing of sorbent physical properties | 9/30/2012 |
| | Bulk and true density measurements | 8/31/2012 |
| | Size distribution measurements | 8/31/2012 |
| | Estimation of particle void fraction and packing density | 8/31/2012 |
| | Measurement of crush strength and estimation of attrition | 8/31/2012 |
| 3.4 | Testing of sorbents - modified fixed bed reactor | 9/30/2012 |
| 4 | **Design, Construction, and Shakedown of Bench-Scale** | 9/30/2013 |
| 4.1 | Design of bench scale absorber unit | 10/31/2012 |
| 4.2 | Design of bench scale regenerator unit | 11/30/2012 |
| 4.3 | Construction of absorber unit, flue gas conditioning equipment and solid handling system | 3/31/2013 |
| 4.4 | Construction of regenerator and subsystems | 3/31/2013 |
| 4.5 | Installation and integration of absorber and regenerator sections, and instrumentation with UND coal fired boiler | 6/30/2013 |
| 4.6 | Shakedown testing of absorber and regenerator | 7/31/2013 |
| 4.7 | Optimization of absorber and regenerator test units | 9/30/2013 |
| 5 | **Absorber and Regenerator Testing and Process Design/Economics Updating** | 9/30/2014 |
| 5.1 | Adsorber testing | 5/31/2014 |
| 5.2 | Regenerator tesing | 5/31/2014 |
| 5.3 | Multi-Cycle testing | 5/31/2014 |
| 5.4 | Updating of process design and economics | 6/30/2014 |
| 5.5 | Determination of process environmental health and safety items | 9/30/2014 |
| 6 | **Final Report** | 9/30/2014 |




**Milestone List**

1. Initial technology feasibility report
2. Optimized Sorbent Selection Completed
3. Hybrid Sorbent Performance Metrics Verified/ Feasibility Report; Go/No-go decision point
4. Design of bench-scale system completed
5. Bench-scale System Installed
6. Bench-scale System Shakedown Testing Completed
7. Adsorber and Regenerator Testing Completed
8. MultiCycle Testing of Bench-Scale System Completed
9. Project Final Report

**Figure 5. Task List, Schedule and Milestones for the Proposed Project.**

## BUDGET

The budget and budget notes for the overall project is included in Appendix B.

## MATCHING FUNDS

Matching funds are provided by Allete- BNI, SaskPower, University of North Dakota, and U.S. Department of Energy. Letters of commitment are attached in Appendix C.

## TAX LIABILITY

No outstanding tax liabilities to the state of North Dakota.

## CONFIDENTIAL INFORMATION

Confidential information is contained only in Appendix D.

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# APPENDIX A

# RESUMES OF KEY PROJECT MANAGER AND KEY PERSONNEL

**STEVEN A. BENSON, Professor of Chemical Engineering**

*Research Areas of Expertise*

Dr. Benson's principal areas of interest and expertise include development and management of complex multidisciplinary research programs that are focused on solving environmental and energy problems associated with the utilization of renewable and fossil fuel resources. These programs include: 1) technologies to improve the performance of combustion/gasification and associated air pollution control systems; 2) transformations and control of trace elements in combustion and gasification systems; 3) carbon dioxide separation and capture technologies from combustion and gasification derived gases, 4) advanced analytical techniques to measure the chemical and physical transformations of inorganic species in gases; 5) computer-based models to predict the emissions and fate of pollutants from combustion and gasification systems; 6) advanced materials for power systems; 7) impacts of power system emissions on the environment; 8) harvesting diffuse energy resources; 9) national and international conferences and training programs; and 8) state and national environmental policy.

*Education*

| | | |
|---|---|---|
| Minnesota State University | Chemistry | B.S. 1977 |
| Pennsylvania State University | Fuel Science | Ph.D. 1987 |

*Professional Experience*

| | |
|---|---|
| 2010 – present | Director, Institute of Energy Studies, University of North Dakota |
| 2008 – present | Professor, Chemical Engineering, University of North Dakota |
| 1999 – 2008 | Senior Research Manager/Advisor, Energy & Environmental Research Center, University of North Dakota (EERC, UND). |
| 1994 – 1999 | Associate Director for Research, EERC, UND. |
| 1991 – Present | President, Microbeam Technologies Incorporated. |
| 1989 – 1991 | Assistant Professor of Geological Engineering, Department of Geology and Geological Engineering, UND. |
| 1986 – 1994 | Senior Research Manager, Fuels and Materials Science, EERC, UND. |
| 1984 – 1986 | Graduate Research Assistant, Fuel Science Program, Department of Materials Science and Engineering, The Pennsylvania State University, |
| 1983 – 1984 | Research Supervisor, Distribution of Inorganics and Geochemistry, Coal Science Division, UND Energy Research Center |
| 1979 – 1983 | Research Chemist, U.S. Department of Energy Grand Forks Energy Technology Center, Grand Forks, North Dakota. |
| 1977 – 1979 | Chemist, U.S. Department of Energy ,Grand Forks Energy Technology Center, Grand Forks, North Dakota. |

*Synergistic Activities*

- Senior Research Manager/Advisor Energy & Environmental Research Center, Dr. Benson was responsible for leading a group of about 30 highly specialized group of chemical, mechanical and civil engineers along with scientists whose aim is to solve problems on combustion and gasification system performance, environmental control systems, the fate of pollutants, computer modeling, and health issues for clients worldwide (PI on over $13 million).

- Current Research Support: "Advances in the Fundamental Understanding of Coal Combustion Emission Mechanisms", DOE EPSCoR IIP/ND EPSCoR , $2,500,000, 7/06 – 7/09; "Lignite Gasification Technology Summary Report", DOE and Lignite Energy Council, $100,000.
- Lignite Energy Council, Distinguished Service Award, Research & Development, 1997; College of Earth and Mineral Science Alumni Achievement Award, Pennsylvania State University, 2002; Lignite Energy Council, Distinguished Service Award, Research & Development, 2003; Lignite Energy Council, Distinguished Service Award, Government Action Program (Regulatory), 2005; Lignite Energy Council, Distinguished Service Award, Research & Development, 2008.
- Five Patent Applications: "Method and Apparatus for Capturing Gas phase Pollutant," 2005; "Removal and Recovery of Deposits from Coal Gasification Systems," 2007; Activated Carbon Production Plant," 2008; "Method for Improving Mercury Capture in Particular from Sulfur Bearing Gases," 2008; An Apparatus for Improving Water Quality by Means of Gasification, 2007.
- Provided testimony to the United States Senate Committee on the Environment and Public Works – Mercury emissions control at coal-fired power plants - 2008 and 2005.

***Selected Topical Reports/Special Issues***

- Controlling Mercury Emissions for Utilities Firing Lignites from North America, North Dakota Industrial Commission, 2007, 376 p.
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**MICHAEL D. MANN, Professor and Chair of Chemical Engineering, Associate Dean for Research**

**Research Areas of Expertise**

Dr. Mann's principal areas of interest and expertise include performance issues in advanced energy systems firing coal and biomass; renewable and sustainable energy systems with a focus on integration of fuel cells with renewable resources through electrolysis; production of fuel and specialty chemicals from crop oils; and development of energy strategies coupling thermodynamics with political, social, and economic factors. Dr. Mann is co-director of SUNRISE, UND's research group focused on the development and implementation of sustainable energy resources.

**Education**

| | | |
|---|---|---|
| Mayville State University | Chemistry, Mathematics | B.A., 1979 |
| University of North Dakota | Chemical Engineering | M.S., 1981 |
| University of North Dakota | Business Administration | M.B.A., 1987 |
| University of North Dakota | Energy Engineering | Ph.D., 1997 |

**Professional Expeience**

| | |
|---|---|
| 2008 | Interim Dean, School of Engineering and Mines, University of North Dakota |
| 2006-*present* | Professor, Department of Chemical Engineering, University of North Dakota |
| 2005-*present* | Chair, Department of Chemical Engineering, University of North Dakota |
| 1999-2006 | Associate Professor of Chemical Engineering, University of North Dakota |
| 2000-2005 | Director, Engineering Doctoral Program, University of North Dakota |
| 1999-*present* | Senior Research Advisor, Energy& Environmental Research Center (EERC) |
| 1994 – 1999 | Senior Research Mgr, Advanced Processes and Technologies, EERC, UND. |
| 1985 – 1994 | Research Manager, Combustion Systems, EERC, UND. |
| 1981 – 1985 | Research Engineer, Wastewater Treatment and Reuse, EERC, UND |

**Selected Publications**

- Hrdlicka, J.A., Seames, W.S., Mann, M.D., Muggli, D.S., and Horabik, C.A., "Mercury oxidation in flue gas using gold and palladium catalysts on fabric filters", *Engineering Science and Technology*, (2008), 42 (17), pp. 6677-6682.
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**Patents**

- 60/642,678 with Seames and D.S. Muggli, "Mercury Oxidation of Flue Gas using Catalytic Barrier Filters", January 2005.
- 5,546,875, "Controlled Spontaneous Reactor System", 1996 (method to upgrade properties of low-rank coals)
- 6,053,954, "Methods to Enhance the Properties of Hydrothermally Treated Fuels", 2000

**SRIVATS SRINIVASACHAR, President Envergex LLC.**

**Research Areas of Expertise**

- Expertise in energy and environmental engineering, power plant systems, and cross-industry products
- Current focus on identifying new business opportunities, setting vision, developing business plans, and implementing strategies for new products/processes
- Successfully executed projects for multiple clients with multi-industry, cross-functional, and international project teams – exceeding performance goals, ahead of schedule and with cost efficiency
- Strong experience in generating financing with industry and government
- Led product and process development groups. Managed large multi-contractor projects
- Obtained multiple patents and published over 50 technical papers

**Education**

| | | |
|---|---|---|
| 2003-2004 | Boston University, School of Management<br>Boston, MA<br>**Master of Business Administration** | |
| 1981-1986 | Massachusetts Institute of Technology<br>MA<br>**Sc.D. degree in Chemical Engineering** | Cambridge, |
| 1976-1981 | Indian Institute of Technology<br>**Bachelor of Technology, Chemical Engineering** | Madras, India |

**Professional experience**

*Present* *President, Envergex LLC* *Sturbridge, MA*

- President

  Pursuing commercial production and supply of low cost and high performance activated carbon-based sorbents for mercury control. Working with partners to set up a venture for low-cost manufacturing of these sorbents.

  Continuing to develop and test formulations and treatment methods to maximize the performance of mercury sorbents for different coals and air pollution control system configurations

  Received from the US Patent and Trademarks office registration of trademark for mercury sorbents, ESORB-HG®, in March 2009 (Registration Number: 3589943)

  Manufactured and supplied commercial quantities and successfully demonstrated ESORB-HG® sorbent to several utility customers at full-scale, and responded to commercial bid requests for sorbent supply

Awarded a Small Business Innovation Research grant in June 2007 from DOE for a project for a novel method for reducing mercury re-emission from wet flue gas desulfurization (FGD) scrubbers.

Developed a business plan for coal and biomass to liquids venture to commercialize technology developed at a university

Teamed with University of North Dakota Energy & Environmental Research Center and a utility partner to perform process design, preliminary engineering, and plant capital and O&M costing to implement an innovative technology for activated carbon manufacturing integrated to a power plant

Developed a technical and business strategy to increase manufacturing process energy efficiencies at a major building materials company

***1993 – 2006 ALSTOM Power, Inc./ABB Combustion Engineering, Inc., Windsor, CT***

- Technical Manager, Environmental Control Technology (March 2003-2006)
  Developed new product for control of mercury emission from coal-fired power plants. Set product strategy, positioned the differentiated product competitively, secured intellectual property, developed business plan, established partnership with component suppliers and external research organizations, led product development team, identified and successfully executed 3 commercial demonstration projects, scaled the product through laboratory, pilot and commercial scale, obtained industry, government and internal funding ($ 13 million)
- Principal Consulting Engineer, New Product Business Development (Oct. 1999 to March 2003)
- Environmental Group Leader, (Oct. 1997 – Sept. 1999)
  Minimizing pollutant emissions from a new gasification-based power plant technology
- Senior Consulting Engineer, (1994 – 1997)

***1986-1993 Physical Sciences Inc. Andover, MA***

- Manager, Environmental Remediation and Resource Utilization (1992-93)
  Directing R&D for an emerging business area. Negotiated with strategic partner for funding. Secured and managed an EPA Superfund project to remediate heavy metal-contaminated soils.
- Principal Research Scientist (1986-92)
  Principal Investigator on a multi-million dollar university-industry project. Created test methods and software for electric utilities to evaluate savings with various fuel switching options and predict fuel quality impacts on slagging and fouling in coal-fired power plants

**Patents**

U.S. Patent 6,848,374-Control of Mercury Emissions from Solid Fuel Combustion
U.S. Patent 6,749,681-Method of Producing Cement Clinker and Electricity
U.S. Patent 6,601,541-Method of Producing Steam and Calcined Raw Meal
U.S. Patent 6,089,171-Minimum Recirculation Flame Control Pulverized Solid Fuel Nozzle Tip
U.S. Patent 6,089,023-Steam Generator System Operation
U.S. Patent 5,556,447 and 5,245,120-Process for Treating Metal-Contaminated Materials

**Selected Publication List**


1. Benson, S.A., Crocker, C.R., Hanson, S.K., McIntyre, K.A., Just, B.J., Raymond, L.J., Pflughoeft-Hassett, D.F, Srinivasachar, S., Barry, L.T. and Doeling, C.M., "JV Task 115- Activated Carbon Production from North Dakota Lignite – Phase IIA," Final Report, U.S. Department of Energy Cooperative Agreement No. DE-FC26-98FT40321, June 2008
2. Kang, S.K., Srinivasachar, S. and Brickett, L.A., " Full-Scale Demonstration of Mer-Cure™ Technology for Mercury Emissions Control in Coal-Fired Boilers, " 31st International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, FL May 2006
3. Srinivasachar, S. and Kang, S.K., "Field Demonstration of Enhanced Sorbent Injection for Mercury Control," DOE-NETL Program Review Meeting, July 2005, Pittsburgh, PA
4. Srinivasachar, S. and Kang, S.K., "Field Demonstration of Enhanced Sorbent Injection for Mercury Control," Quarterly Report October-December 2005, DOE-NETL, Pittsburgh, PA
5. Senior, C.L., Bool, L.E., **Srinivasachar, S.**, Pease, B.R. and Porle, K., "Pilot-Scale Study of Trace Element Vaporization and Condensation during Combustion of a Pulverized Sub-bituminous Coal," Fuel Processing Technology, 63(2-3), 149-165, 2000
6. Liu, B.B., **Srinivasachar, S.**, and Helble, J.J., "The Effect of Chemical Composition on the Fractal-Like Structure of Combustion-Generated Inorganic Aerosols," Aerosol Science and Technology, 33(6), 459-469, 2000
7. Pease, B.R., **Srinivasachar, S.**, Porle, K., Haythornthwaite, S. and Ruhl, J., "Ultra-high Efficiency ESP Development for Fine Particulate and Air Toxics Control – Phase I and II: Mercury Removal Investigations," Proc. – 15th Annual International Pittsburgh Coal Conference, 1580-1598, 1998

# APPENDIX B
# Overall Project Budget and Budget Notes

BUDGET OUTLINE

F&A (INDIRECT COST) RATE FOR PROPOSAL = 38.00%

| SPONSOR | TOTAL UND | TOTAL SASK POWER | TOTAL ALLET MNPOWER BNI COAL | TOTAL LIGNITE ENERGY COUNCIL | TOTAL BURNS & MCDONNELL | TOTAL COST SHARE ALL BUDGET PERIODS | TOTAL DOE ALL BUDGET PERIODS | TOTAL PROJECT COST ALL BUDGET PERIODS |
|---|---|---|---|---|---|---|---|---|
| SALARIES - REGULAR | 31,056 | 5,624 | 10,851 | 38,240 | 0 | 85,771 | 431,537 | 517,308 |
| SALARIES - GRADUATE STUDENTS | 0 | | | 0 | | 0 | 124,086 | 124,086 |
| SALARIES - UNDERGRADUATE STUDENTS | | | | | | 0 | 23,260 | 23,260 |
| SALARIES - FACULTY | 47,380 | 7,879 | 16,184 | 62,365 | 0 | 133,808 | 192,712 | 326,520 |
| FRINGE BENEFITS-REGULAR | 12,422 | 2,250 | 4,341 | 15,296 | | 34,308 | 172,615 | 206,923 |
| FRINGE BENEFITS-GRADUATE STUDENTS | | | | 0 | | 0 | 4,200 | 4,200 |
| FRINGE BENEFITS-UNDERGRAD STUDENTS | | | | | | 0 | 2,326 | 2,326 |
| FRINGE BENEFITS-FACULTY | 14,214 | 2,364 | 4,855 | 18,709 | | 40,142 | 57,814 | 97,956 |
| | | | | 0 | | | 0 | 0 |
| TOTAL PERSONNEL | 105,073 | 18,116 | 36,232 | 134,610 | 0 | 294,030 | 1,008,549 | 1,302,580 |
| | | | | 0 | | | | 0 |
| TRAVEL | | 3,587 | 0 | 11,613 | | 15,200 | 42,776 | 57,976 |
| COMMUNICATIONS-PHONE | | | | 0 | | 0 | 1,800 | 1,800 |
| COMMUNICATIONS-POSTAGE | | | | 0 | | 0 | 300 | 300 |
| INSURANCE | | | | 0 | | 0 | 0 | 0 |
| RENTS/LEASES-EQUIPMENT & OTHER | | | | 0 | | 0 | 0 | 0 |
| RENTS/LEASES-BUILDING/LAND | | | | 0 | | 0 | 0 | 0 |
| OFFICE SUPPLIES | | 0 | 0 | 1,591 | | 1,591 | 1,929 | 3,520 |
| PRINTING-COPIES, DUPLICATING | | | | 0 | | 0 | 1,098 | 1,098 |
| REPAIRS | | | | 0 | | 0 | 0 | 0 |
| UTILITIES | | | | 0 | | 0 | 0 | 0 |
| SUPPLIES-IT SOFTWARE | | | | 0 | | 0 | 0 | 0 |
| SUPPLY/MATERIALS-PROFESSIONAL | | 0 | 0 | 18,596 | | 18,596 | 23,923 | 42,519 |
| SUPPLIES-MISCELLANEOUS | | | | 0 | | 0 | 0 | 0 |
| IT EQUIPMENT <$5,000 | | | | 0 | | 0 | 0 | 0 |
| OTHER EQUIPMENT <$5,000 | | | | 0 | | 0 | 0 | 0 |
| FEES-OPERATING FEES & SERVICES | | | | 15,283 | | 15,283 | 32,450 | 47,733 |
| FEES-PROFESSIONAL FEES & SERVICES | | | | 0 | | 0 | 0 | 0 |
| FEES-SUBCONTRACTS (see Note 1 below) | | | | 0 | | 0 | 0 | 0 |
| Envergex | | | | 0 | | 0 | 796,100 | 796,100 |
| Burns & McDonnell | | | | 0 | 0 | 0 | 240,000 | 240,000 |
| Solex-Thermal | | | | 16,510 | | 0 | 270,000 | 270,000 |
| TOTAL FEES-SUBCONTRACTS (see Note 1 below) | | | | | | | 1,306,100 | 1,306,100 |
| PROFESSIONAL DEVELOPMENT | | | | | | | 0 | 0 |
| FOOD AND CLOTHING | | | | | | | 0 | 0 |
| WAIVERS/SCHOLARSHPS/FELLOWSHPS | | | | 16,510 | | 16,510 | 24,490 | 41,000 |
| TOTAL OPERATING | 0 | 3,587 | 0 | 63,594 | 0 | 50,671 | 1,434,866 | 1,485,536 |
| | | | | 0 | | | | |
| EQUIPMENT >$5,000 | | 45,050 | 100,000 | 82,753 | | 227,803 | 57,212 | 285,015 |
| IT EQUIPMENT >$5,000 | | | | 0 | | 0 | 0 | 0 |
| | | | | 0 | | | | |
| TOTAL EQUIPMENT | 0 | 45,050 | 100,000 | 82,753 | 0 | 227,803 | 57,212 | 285,015 |
| | | | | 0 | | | | |
| TOTAL DIRECT COST | 105,073 | 66,753 | 136,232 | 280,956 | 0 | 589,014 | 2,500,627 | 3,089,640 |
| | | | | 0 | | | | |
| F&A (INDIRECT COST) * | 39,928 | 8,247 | 13,768 | 69,044 | 0 | 130,986 | 451,373 | 582,360 |
| 3RD PARTY IN-KIND COST SHARE | | | | | 0 | | | |
| Burns & McDonnell | | | | | | 18,000 | | |
| Solex-Thermal Science | | | | | | | | |
| TOTAL IN-KIND | | | | | | | | |
| TOTAL COST | 145,000 | 75,000 | 150,000 | 350,000 | 0 | 738,000 | 2,952,000 | 3,690,000 |

NDIC Share Detail - Lignite Energy Council

BUDGET OUTLINE

F&A (INDIRECT COST) RATE FOR PROPOSAL = 38.00%

| DESCRIPTION | YEAR 1 | YEAR 2 | YEAR 3 | TOTAL |
|---|---|---|---|---|
| SALARIES - REGULAR | 0 | 22,284 | 15,956 | 38,240 |
| SALARIES - OTHER | 0 | 0 | 0 | 0 |
| SALARIES - FACULTY | 0 | 33,775 | 28,590 | 62,365 |
| FRINGE BENEFITS | 0 | 19,046 | 14,959 | 34,006 |
| TOTAL PERSONNEL | 0 | 75,105 | 59,505 | 134,611 |
| TRAVEL | 11,613 | 0 | 0 | 11,613 |
| COMMUNICATIONS-PHONE | 0 | 0 | 0 | 0 |
| COMMUNICATIONS-POSTAGE | 0 | 0 | 0 | 0 |
| INSURANCE | 0 | 0 | 0 | 0 |
| RENTS/LEASES-EQUIPMENT & OTHER | 0 | 0 | 0 | 0 |
| RENTS/LEASES-BUILDING/LAND | 0 | 0 | 0 | 0 |
| OFFICE SUPPLIES | 750 | 841 | 0 | 1,591 |
| PRINTING-COPIES, DUPLICATING | 0 | | 0 | 0 |
| REPAIRS | 0 | 0 | 0 | 0 |
| UTILITIES | 0 | 0 | 0 | 0 |
| SUPPLIES-IT SOFTWARE | 0 | 0 | 0 | 0 |
| SUPPLY/MATERIALS-PROFESSIONAL | 10,000 | 0 | 8,596 | 18,596 |
| SUPPLIES-MISCELLANEOUS | 0 | 0 | 0 | 0 |
| IT EQUIPMENT <$5,000 | 0 | 0 | 0 | 0 |
| OTHER EQUIPMENT <$5,000 | 0 | 0 | 0 | 0 |
| FEES-OPERATING FEES & SERVICES | 0 | 0 | 0 | 0 |
| FEES-PROFESSIONAL FEES & SERVICES | 15,283 | 0 | 0 | 15,283 |
| FEES-SUBCONTRACTS (see Note 1 below) | 0 | 0 | 0 | 0 |
| PROFESSIONAL DEVELOPMENT | 0 | 0 | 0 | 0 |
| FOOD AND CLOTHING | 0 | 0 | 0 | 0 |
| WAIVERS/SCHOLARSHPS/FELLOWSHPS | 0 | 16,510 | 0 | 16,510 |
| TOTAL OPERATING | 37,646 | 17,351 | 8,596 | 63,593 |
| EQUIPMENT >$5,000 | 0 | 0 | 0 | 0 |
| IT EQUIPMENT >$5,000 | 0 | 0 | 0 | 0 |
| TOTAL EQUIPMENT | 82,753 | 0 | 0 | 82,753 |
| TOTAL DIRECT COST | 120,399 | 92,456 | 68,101 | 280,957 |
| F&A (INDIRECT COST) * | 14,305 | 28,860 | 25,879 | 69,044 |
| TOTAL COST | $ 134,704 | $ 121,316 | $ 93,980 | $ 350,000 |

Budget Summary

Salaries-Faculty: Salary of $62,365 is included for UND faculty working on research as described in the scope of work. A 5% annual increase in base salary is included in the salary total over the three year project. The funds requested may include summer salaries and/ or academic year salaries.

Salaries-Regular: Salary of $38,240 is included for UND administrative staff, research engineer, or technical assistant. A 5% annual increase in base salary is included in the salary total over the three year project. UND administrative staff will assist in setting up travel, manage the accounts and maintain the budget. The research engineer and technical assistant will work on research and related task described in the scope of work.

Fringe Benefits: are estimated at 30% of salary of UND faculty and 40% for UND staff. Amounts shown for fringes are estimates determined by historical data and provided for proposal evaluation purposes only. Actual fringe benefit costs will be charged to the grant according to each employee's actual benefits.

Travel: totaling $11,613 will include expenses to travel on project related trips.

Office Supplies: totaling $1,591 are included to be used over the course of the project and may include items such as pens, pencils, paper clips, printer paper and toner cartridges, notebooks, post-it notes, computer discs, presentation materials, duplicating charges, and other miscellaneous items required to complete the project.

Lab Supplies: totaling $18,596 is included for related supplies required to complete the scope of work.

Professional Fees or Other Direct Costs: totaling $15,283 is included for analytical testing needed to complete the scope of work.

Tuition Remissions: totaling $16,510 is included for tuition support for our Graduate Research Assistants that will assist with project related research..

Equipment: totaling $82,753 is included for the purchase of major equipment related to this project.

Indirect Costs: The indirect cost rate of 38% included in this proposal is the federally approved rate for the University of North Dakota. Indirect costs are calculated based on the Modified Total Direct Costs (MTDC), defined as the Total Direct Costs of the project less individual items of equipment greater than $5000, subcontracts in excess of the first $25,000 for each award, and tuition remission.

# APPENDIX C
# Letters of Commitment

**NATIONAL ENERGY TECHNOLOGY LABORATORY**
Albany, OR • Morgantown, WV • Pittsburgh, PA

U.S. DEPARTMENT OF ENERGY

August 19, 2011

Dr. Barry Milavetz
The University of North Dakota
264 Centennial Drive Stop 7134
Twamley Hall Room 105
Grand Forks, ND 58202-7134

Dear Dr. Milavetz,

Evaluation of your application titled "Evaluation of Carbon Dioxide Capture from Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents" received in response to Funding Opportunity Announcement DE-FOA-0000403, titled "*Bench-Scale and Slipstream Development and Testing of Post-Combustion Carbon Dioxide Capture and Separation Technology for Application to Existing Coal-Fired Power Plants*" has been completed in accordance with the application review information contained in the announcement.

After a careful review of your application, I am pleased to inform you that your application has been selected for negotiations leading to award. Please submit the following documentation by August 29, 2011:

- Representation of Limited Rights Data, available at http://management.energy.gov/documents/RepresentationofLimitedRightsData.doc;
- Copy of your organization's most recent Government Indirect Rate Agreement (If your organization does not have a recent Government Indirect Rate Agreement, please follow the guidelines for "PMC 400.2: Sample Indirect Rate Proposal" available at http://www.netl.doe.gov/business/forms-far.html); and
- Any application updates (Statement of Project Objectives revisions; Project Management Plan revisions; key personnel changes; third party changes; etc.).
- 424A Budget Information-Non-Construction Program, available at http://energy.gov/sites/prod/files/SF424Aexcel_0.pdf

In order to meet our mutual goal of accomplishing an award in a timely manner, you will need to work with the National Energy Technology Laboratory (NETL) Project Officer to prepare the finalized Statement of Project Objectives and the revised Project Management Plan as soon as possible. All of the required documentation identified above is to be submitted directly to the Contract Specialist, via e-mail, with a copy to the Project Officer.

The Contract Specialist from the Acquisition and Assistance Division who will be handling the administrative portion of your application is Ashley Scekeres, who can be reached by telephone at 412-386-4857 or via e-mail at Ashley.Scekeres@NETL.DOE.GOV. The NETL Project Officer from the Project Management Division who will be handling the technical aspects of your application is Andrew Jones, who can be reached by telephone at 412-386-5531 or via e-mail at Andrew.Jones@NETL.DOE.GOV.

On behalf of the Department, I would like to express a sincere appreciation of your interest and participation in this program.

Sincerely,

Brittley K Robbins

Brittley K. Robbins
Contracting Officer
Acquisition and Assistance Division

cc: Dr. Steven Benson
University of North Dakota

UNIVERSITY OF UND NORTH DAKOTA

DEPARTMENT OF CHEMICAL ENGINEERING
HARRINGTON HALL ROOM 323
241 CENTENNIAL DRIVE STOP 7101
GRAND FORKS ND 58202-7101
PHONE (701) 777-4244
FAX (701) 777-3773
chem_e@mail.und.edu

September 23, 2011

National Energy Technology Laboratory
U.S. Department of Energy
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236

Dear Contracting Officer Laukatis,

This letter confirms $145,000 in cost share from the University of North Dakota School of Engineering and Mines committed to DOE project Evaluation of $CO_2$ Capture from Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents (CACHYS$^{TM}$).

The School of Engineering and Mines commits support for a research engineer time as cost share during budget period 1. The estimated value of the salary, benefits, and indirect costs for this engineer is $60,000.

The School of Engineering and Mines also commits to support a portion of the salaries for Steve Benson, Michael Mann, Gautham Krishnamoorthy, Nanak Grewal. The estimated value of the salary, benefits, and indirect costs for these personnel over the 3 year duration of this project is $85,000.

If you have any questions, please feel to contact me at michael.mann@engr.und.edu or at 701-777-3852.

Sincerely

Michael D. Mann

Michael Mann, Ph.D.
Associate Dean for Research
School of Engineering and Mines

Barry Milavetz, Ph.D.
Associate VP for Research
Research, Development and Compliance

BNI COAL

Wade Boeshans, General Manager - BNI

minnesota power

Allan S. Rudeck, Jr., Vice President - MP Generation

March 15, 2011

Dr. Steven A. Benson
Director
Institute for Energy Studies
School of Engineering and Mines
University of North Dakota
Harrington Hall Room 323
241 Centennial Drive Stop 7101
Grand Forks, ND 58202

Re: Support of the proposal entitled "Capture of $CO_2$ by Hybrid Sorption Process (CACHYS™)" submitted in response to DE-FOA-0000403 "Bench-Scale and Slipstream Development and Testing of Post-Combustion Carbon Dioxide Capture and Separation Technology for Application to Existing Coal-Fired Power Plants"

Dear Dr. Benson:

ALLETE, along with it's operating division Minnesota Power and its subsidiary BNI, is pleased to support the proposal from the University of North Dakota (UND) and Envergex LLC to develop a process (CACHYS™) that will efficiently capture $CO_2$ from large coal fueled power plant flue gas and regenerate a pure $CO_2$ stream with a lower operating cost than current methods. We understand the goal of the technology is 90 percent $CO_2$ removal at no more than 35 percent increase in the cost of electricity which would be achieved through the development of a new sorbent that will require 80 percent less energy to regenerate than that for an absorption process using conventional amines (30% MEA).

We further understand that the work to further this technology concept will consist of a combination of bench-scale testing and sub-pilot testing. The sub-pilot scale test unit may be installed as a slipstream at UND's coal-fired steam plant to verify the potential of this carbon capture technology.

Developing low cost and high efficiency technologies for $CO_2$ capture is a key to meeting future $CO_2$ emissions targets as well as providing additional markets for North Dakota lignite-derived materials. ALLETE has a very strong interest in supporting the development and commercialization of the CACHYS™ technology and intends to negotiate with ENVERGEX LLC for certain rights to the technology. ALLETE is pleased to provide a total of $150,000 in cost-share for the thirty month project, subject to project award by US Department of Energy and pursuant to good faith negotiations and final review.

If you have questions and require additional information please contact Dwight Anderson at (218) 355-3539.

Sincerely,

Wade Boeshans
*General Manager BNI*

Allan S. Rudeck, Jr.
*Vice President Minnesota Power Generation*

cc. Srivats Srinivasachar, Envergex LLC

**SaskPower**
Powering the future

**Operations Support**
2001 Powerhouse Drive
Regina, SK S4N 0A1
Phone (306) 566-2290
Fax (306) 566-3348

2011 March 17

Dr. Steven A. Benson
Director
Institute for Energy Studies
School of Engineering and Mines
University of North Dakota
Harrington Hall Room 323
241 Centennial Drive Stop 7101
Grand Forks, ND 58202

Re: Support of the proposal entitled "Capture of $CO_2$ by Hybrid Sorption Process (CACHYS™)" submitted in response to DE-FOA-0000403 "Bench-Scale and Slipstream Development and Testing of Post-Combustion Carbon Dioxide Capture and Separation Technology for Application to Existing Coal-Fired Power Plants"

Dear Dr. Benson:

*SaskPower* is pleased to support the proposal from the University of North Dakota and Envergex LLC to develop the CACHYS™ process that will efficiently capture $CO_2$ from power plant flue gas and regenerate a pure $CO_2$ stream at a lower cost than current methods. The goal of the technology to achieve 90 percent $CO_2$ removal aligns with SaskPower's anticipated requirement to remove this amount of $CO_2$ from our plants in the near future. In addition, the targeted limit of increasing the current cost of electricity by no more than 35 percent represents considerable savings compared to conventional $CO_2$ control technologies. We understand CACHYS™ is based on using a novel solid phase sorbent that will have a high $CO_2$ loading capacity and a process that results in 80% less regeneration energy penalty compared to amine absorption solvents. In addition the increased reaction kinetics of the CACHYS™, should allow for somewhat smaller $CO_2$ capture systems with reduced capital cost and parasitic power for operations.

We understand, that at this stage of technology development, work will focus on the feasibility and technical process details of the CACHYS™ process and will largely consist of a combination of bench-scale testing and sub-pilot testing, taking advantage of the specialized capabilities of UND. We recognize that further work is likely required at a larger scale to confirm the commercial viability of CACHYS™. SaskPower would consider being involved in this larger scale work should this proposed project meet its goals.

Developing low cost and high efficiency technologies for $CO_2$ capture is a key to meeting future $CO_2$ emissions targets. We believe that CASHYS™ technology has the potential to lead to a lower cost method to capture $CO_2$ from coal-fired systems. Therefore, *SaskPower* is pleased to provide a total of $75,000 ($25,000 per year for 3 years) or 2 % of the total project cost in cost-share for the thirty-six month project, subject to project award by US Department of Energy, achieving a project agreement with appropriate commercial provisions through good faith negotiations and final review.

Please feel free to contact me if you have questions and require additional information.

Sincerely,

David W. Smith

Supervisor, Environmental Initiatives

cc. Blake Taylor
Manager, Operations Support

Srivats Srinivasachar
President, Envergex LLC