ABSTRACT

The overall goal of this three-phase/three-year program is to develop a novel, low-cost, high-capacity mesoporous carbon sorbent to remove CO\textsubscript{2} from high-sulfur-containing flue gas produced by coal-fired power plants. The development of this novel carbon sorbent offers the potential to reduce CO\textsubscript{2} emission from coal fired power plants by more than 90%, thus making coal one of the cleanest energy sources and expanding market share for coal in general and Illinois coal in particular in the US and global energy markets. In this project an assessment will be made of the viability of the mesoporous sorbent in removing CO\textsubscript{2} from high-sulfur flue gas generated by combustion of IL#6 coal.

A prototype sorbent system designed by TDA Research Inc. will be tested at Gas Technology Institute (GTI) on a slip-stream of flue gas generated by combusting IL#6 coal in a furnace to validate the ICCI criteria laid out in the RFP. Further objectives are to: a) initiate modification of an existing natural gas furnace at GTI to combust IL#6 coal for flue gas generation and completion of the design of a flue gas cleanup system, b) complete furnace modification and fabrication of the flue gas cleanup system, and c) integrate the TDA-designed prototype sorbent system with the modified furnace and cleanup system and operate the integrated system on a slip-stream of flue gas to validate the ICCI criteria.

In Phase I of the program GTI: a) identified and initiated modification of an existing natural gas furnace, b) completed evaluation of burner and coal feeder/hopper systems, c) designed a conceptual flue gas cleanup system, and d) identified potential suppliers of coal feedstock. In Phase II of the program GTI completed 80% of furnace modifications and 70% of cleanup system fabrication: acquired key furnace hardware components (burner, burner mount/extension, screw feeder, etc.) and finalized layout and bill-of-materials list for the flue gas cleanup system, sized reactors and heat exchangers for SO\textsubscript{x}/NO\textsubscript{x} and trace contaminant removal from flue gas. Furnace and cleanup skid fabrication could not be completed as planned due to unexpected delays in: a) vendor fabrication of the key hardware (for furnace modifications), and b) TDA’s testing of their cold flow visualization reactor system to obtain design parameters for the CO\textsubscript{2} capture prototype system fabrication (experienced in the final quarter of Year 2), impacted finalization of the cleanup componentry orientation and control strategy of the GTI flue gas cleanup skid designed for integration with the prototype system.
EXECUTIVE SUMMARY

The overall goal of this three-phase/three-year program is to develop a novel, low-cost, high-capacity mesoporous carbon sorbent to remove CO$_2$ from high-sulfur-containing flue gas produced by coal-fired power plants. The development of this novel carbon sorbent offers the potential to reduce CO$_2$ emission from coal fired power plants by more than 90%, thus making coal one of the cleanest energy sources and expanding market share for coal in general and Illinois coal in particular in the US and global energy markets. The overall project approach is given below.

- Develop, test and produce the CO$_2$ removal sorbent. (TDA)
- Design and fabricate a prototype sorbent system to capture CO$_2$ from flue gas derived from combustion of IL#6 coal and test at GTI. (TDA & GTI)
- Modify an existing natural gas furnace at GTI to accommodate combustion of IL#6 coal for flue gas generation. (GTI)
- Design and fabricate a flue gas cleanup system. (GTI)
- Integrate modified test furnace, flue gas cleanup and CO$_2$ sorbent systems. (GTI)
- Test integrated system and validate CO$_2$ capture effectiveness per DOE and ICCI criteria. (GTI)

In Phase II of the program, GTI completed 80% of furnace modifications and 70% of cleanup system fabrication: acquired key furnace hardware components (burner, burner mount/extension, screw feeder, etc.) and finalized layout and bill-of-materials list for the flue gas cleanup system, sized reactors and heat exchangers for SOx/NOx and trace contaminant removal from flue gas. Furnace and cleanup skid fabrication could not be completed as planned due to unexpected delays in: a) vendor fabrication of the key hardware (for furnace modifications), and b) TDA’s testing of their cold flow visualization reactor system to obtain design parameters for the CO$_2$ capture prototype system fabrication (experienced in the final quarter of Year 2), impacted finalization of the cleanup componentry orientation and control strategy of the GTI flue gas cleanup skid designed for integration with the prototype system. These will be completed by the end of first quarter of Year 3.

Phase II Accomplishments

Furnace Modifications
1. Designed and fabricated a swirl burner to combust pulverized IL#6 coal for flue gas generation.
2. Designed and fabricated burner mount, furnace extension and stack.
3. Designed and fabricated a coal feeding system to the furnace for flue gas generation.
4. SIZED and procured an eductor for feeding the coal into the burner.
5. Sized and procured an orifice meter to measure flow rate of flue gas slip stream to the cleanup and TDA CO$_2$ capture system and a high-temperature filter to capture flue gas particulates.
6. Procured 5,000 pounds of pulverized IL#6 coal from GTI gasification group for flue gas generation.

Cleanup System Fabrication
1. Finalized cleanup system layout and skid dimensions: 6’L x 4’W x 6’H.
2. Generated a bill-of-materials list.
3. Sized fixed-bed reactors for SOx, NOx, and mercury/trace contaminant removal for demonstration testing (up to 500 hours).
   a. SO$_x$ 1.5 ft$^3$ (12” D x 24” L).
   b. NO$_x$ 0.2 ft$^3$ (12” D x 3” L).
   c. Mercury/trace contaminant 0.5 ft$^3$ (9” D x 20” L).

TDA CO$_2$ Capture Prototype System
1. Worked with TDA regarding design of the CO$_2$ capture prototype test unit for evaluation at GTI.
2. Reviewed P&ID and layout of the prototype test unit for integration with GTI furnace/flue gas cleanup system.
3. Determined prototype foot print: 6-ft W x 6-ft L x 16-ft H.

The complete details of Phase II accomplishments are given in the “Results and Discussion” section of this report. The work accomplished to date will provide a strong basis for successful completion of this program.
OBJECTIVES

The overall goal of this program is to develop a novel, low-cost, high-capacity mesoporous carbon sorbent to remove CO₂ from high-sulfur-containing flue gas produced by coal-fired power plants. Further objectives are to: a) initiate modification of an existing natural gas furnace at GTI to combust IL#6 coal for flue gas generation and completion of the design of a flue gas cleanup system b) complete furnace modification and fabrication of the flue gas cleanup system, and c) integrate the TDA-designed prototype sorbent system with the modified furnace and cleanup system and operate the integrated system on a slip-stream of flue gas to validate the ICCI criteria laid out in the RFP. This will be accomplished in a three-year/three-phase program.

Task 1 (in Phase II) objectives include the following:

- Complete modifications to an existing high-temperature test furnace in the GTI combustion facility to combust IL#6 coal for flue gas generation.
- Complete fabrication of a flue gas cleanup system.

INTRODUCTION AND BACKGROUND

Coal currently accounts for nearly 56% of US electric power generation. As the United States has 25% of world’s coal reserves, electricity generation from coal will play an important role in solving the Nation’s future energy needs (Tonks, 2007). With a projected 50% increase (from 300 GW to 450 GW) in electricity demand by 2030, the bulk of the electricity produced both in the United States and worldwide will continue to come from pulverized coal (PC) (Annual Energy Outlook 2007). CO₂ is a major greenhouse gas and plays a significant role in global climate change. Roughly one third of the US carbon emissions come from power plants. Because future government regulations are expected to require CO₂ capture, existing PC power plants will need to be retrofitted with a low-cost CO₂ capture technology.

For the existing PC plants, the CO₂ capture and separation will most likely be carried out by post-combustion CO₂ scrubbing/capture or oxy-combustion. In both these approaches, the challenge for flue gas CO₂ capture is to minimize the increase in the cost of electricity. Removal, compression, and sequestration of CO₂ are expensive and also consume a large amount of energy and capital because the power plant exhaust is at ambient pressure and the CO₂ is diluted with nitrogen (10- to 15-vol% CO₂ in the flue gas). Any carbon-capture method must concentrate the CO₂ and compress it through a pressure ratio of 100 to 1,000. There is minimum theoretical energy requirement to recover 90% of the CO₂ at 1.0 atm (i.e., concentrate flue gas CO₂ from 10% to 100%) and then compress it to 2,200 psi. Assuming an isothermal compression, the theoretical energy requirement is calculated to be about 9.4% (3% for the theoretical minimum plant power loss to concentrate the CO₂ in flue gas to a pure stream at 1 atm plus 6.4% for compressing the CO₂ to 2,200 psi). With an additional 4% penalty for transportation and sequestration, the CO₂ recovery and its sequestration will reduce the plant output by at least 13.5%.
Currently, many post-combustion methods are being investigated. Examples include aqueous sorbents (e.g., amines like monoethanolamine and diethanolamine, carbonates), physical adsorbents (e.g., molecular sieves by pressure swing), physical solvents (e.g., Selexol), cryogenic coolers, and membranes. A key contributor to the energy consumption of the CO$_2$ capture system is the heat input needed for the regeneration step (Nsakala, 2001). Because the regeneration of most solvents or sorbents is carried out at low temperatures (either to avoid a large temperature swing or because of the instability of the getter material at elevated temperatures), the recovery of this energy input is usually not economical and the heat input for the sorbent regeneration is likely not recoverable.

The chemical solvent or chemical sorbent processes that remove CO$_2$ by forming a covalent bond suffer from a particularly large efficiency penalty because of the large heat input required to support sorbent regeneration. For example, Research Triangle Institute (RTI) is developing a process using a regenerable, sodium-based chemical absorbent to remove CO$_2$:

$$2\text{NaHCO}_3(s) \leftrightarrow \text{Na}_2\text{CO}_3(s) + \text{CO}_2(g) + \text{H}_2\text{O}(g)$$

The heat of reaction of the decomposition of the sodium bicarbonate phase is 29.9 kcal per mole of CO$_2$ removed. The energy required for the regeneration represents 27 to 37% of the energy output of the power plant (system integration to recover some of this energy to avoid such a prohibitive penalty would be required). The amine solvents have a similar efficiency disadvantage, and as shown in the NETL report (NETL, 2005) the CO$_2$ capture and compression using amines raises the cost of electricity for a newly built supercritical PC power plant by 84%, from 4.9 cents/kWh to 9.0 cents/kWh and result in a very high CO$_2$ capture cost: $68/ton of CO$_2$ avoided (Klara, 2007).

Although oxy-combustion of coal is projected to cost less in the range of $36 to $52 per ton of CO$_2$ avoided (McDonald, 2007), the cryogenic separation system is much more complex than post combustion technologies and is more capital intensive. Thus, there is a need for a sorbent process that uses a physical adsorbent where the CO$_2$ is weakly bonded to the surface and can be regenerated relatively easily without applying a large energy input. The sorbent must also achieve a high capacity and show very fast adsorption and regeneration kinetics to ensure a small sorbent inventory and reduced capital investment.

TDA has previously developed a novel mesoporous carbon adsorbent to remove CO$_2$ from coal syngas (pre-combustion removal). Unlike the chemical sorbents, this sorbent relies on a relatively weak binding of the CO$_2$ molecule to the surface sites rather than forming a strong covalent bond. Thus, the sorbent requires only a modest heat input for the regeneration process. As measured by DSC (Figure 1), releasing one mole of CO$_2$ from the sorbent requires less than 4.7 to 5.3 kcal/mol depending on surface coverage of CO$_2$. This heat of adsorption is similar to Selexol solvents, which is still significantly high to provide selective CO$_2$ adsorption in the presence of other flue gas components (e.g., H$_2$O and N$_2$) even at relatively high temperatures (up to 200°C).
This novel adsorbent is a high surface area mesoporous carbon grafted with surface adsorption sites. Previously, TDA patented (US 7,541,312) a method to prepare a new carbon structure with uniformly distributed wide pores (20 Å average). TDA has also developed variants of these materials substituted with functional groups that can bind CO₂. These carbons can be prepared using low-cost precursor materials, while employing a simple, scalable, and high-throughput manufacturing process. A low-carburization temperature (~600°C) is selected to ensure the stability of the active groups on the sorbent surface. This yields a relatively low surface area for an activated carbon typically fired at higher temperatures, but the resulting surface area is still in excess of 450 m²/g, which is sufficient for surface adsorption of CO₂. In addition, the sorbent contains mesopores that are widely accessible and promote rapid gas diffusion. TDA successfully used these mesoporous carbons as ultracapacitor electrodes, where the mesopores facilitate easy access for liquid electrolytes.

TDA is collaborating with MeadWestvaco, the largest supplier of wood-based specialty carbon products, to produce these new materials in large scale. Their preliminary cost analysis suggests the carbon sorbent can be synthesized at $1.2 per lb when produced at large-scale, including all energy and labor costs. The manufacturing process emits 0.95 lb of carbon per lb of sorbent, but based on a useful life of 100,000 cycles, each lb of sorbent will eliminate 545 lb CO₂. A detailed life cycle analysis will be carried out in the following phases of this project. The carbon sorbent can be prepared as strong pellets with crush strength greater than 3.4 lb/mm (Table 1).

In the previous DOE project, TDA demonstrated mesoporous carbon sorbents can achieve greater than 20-wt% CO₂ capacity (lb of CO₂ per lb of sorbent) at the high CO₂ partial pressures present in IGCC applications. In multiple-cycle tests, it was shown the sorbent maintained stable capacity for over 2,000 cycles.
In addition to the extensive data on carbon capture from syngas generated by coal gasification (pre-combustion), experiments were also carried out to demonstrate the capability of this novel sorbent for flue gas CO$_2$ removal. Preliminary testing was carried out of the mesoporous carbon sorbent in a fixed-bed system and the sorbent achieved high CO$_2$ capacity and high removal efficiency. Heat effects during adsorption are very mild for the sorbent: the bed temperature rises by only 5-8°C during CO$_2$ adsorption. The sorbent achieved a CO$_2$ loading of 4.5% wt. CO$_2$ at 30°C and 2.5 psia CO$_2$ partial pressure (Figure 2). Tests were also conducted at higher temperatures where the sorbent achieved a CO$_2$ loading of 2.6% wt. CO$_2$ at 55°C and 1.9 psia CO$_2$ partial pressure.

Multiple-cycle testing was carried out at different temperatures, space velocities and partial pressures of CO$_2$; throughout these tests the sorbent did not exhibit any degradation. A typical working capacity of 4-6% wt. CO$_2$ was obtained at 30°C and 2.5 psia CO$_2$ at 55°C. The impact of CO$_2$ partial pressure on the sorbent capacity at various temperatures is shown in Figure 3.

Figure 4 shows the results from the multiple cycle tests. More than 220 cycles were conducted using simulated flue gas and the sorbent maintained its capacity, achieving a working capacity over 4% wt. CO$_2$ at 30°C both at the beginning and the end of the 220-cycle test.

<table>
<thead>
<tr>
<th>Table 1. Sorbent Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
</tr>
<tr>
<td>Crush strength</td>
</tr>
<tr>
<td>Shape</td>
</tr>
<tr>
<td>Pore volume</td>
</tr>
<tr>
<td>Surface area</td>
</tr>
<tr>
<td>Heat of adsorption</td>
</tr>
<tr>
<td>Maximum CO$_2$ capacity</td>
</tr>
<tr>
<td>Operating CO$_2$ capacity</td>
</tr>
</tbody>
</table>

![Graph showing CO$_2$ Concentration vs. Time for Adsorption and Desorption processes.](image-url)
Tests were also carried out using a moisture-containing (15% H₂O) simulated flue gas stream and similar capacity was observed as in isothermal cycling; the sorbent achieved a working capacity of 1.5% wt. CO₂ at 60°C in the presence of 15% H₂O. The sorbent achieved even higher working capacity of 2% wt. CO₂ working capacity under desorption in steam at 120°C (Figure 5). It is important to note that even though some water adsorbs onto the sorbent, as shown in experiments with and without water vapor, the water does not compete with the CO₂ (apparently, the CO₂ adsorption occurs at different sites). The water adsorption isotherms were measured in the TGA at various temperatures (Figure 5). It was found H₂O adsorbs and desorbs at the same temperature easily and the H₂O capacity at 60°C is almost constant up to 3% vol. H₂O at 0.6% wt. H₂O.

Figure 3. Impact of CO₂ Pressure on Working Capacity

Figure 4. CO₂ Capacity in Parametric Tests and Multiple Cycle Tests in the Fixed-Bed Flow Reactor (T= 30-120°C)
During the multiple-cycle testing the space velocity was also varied and demonstrated that the sorbent has high CO\textsubscript{2} removal efficiency and faster rates of adsorption and desorption (Figure 6), indicating the sorbent could be used with fast adsorption and desorption cycles that provide very high sorbent utilization (i.e., productivity).

The sorbent was also shown to adsorb CO\textsubscript{2} in the presence of moderate amounts of SO\textsubscript{2} and NO without any change in performance. Figure 7 shows the effect on CO\textsubscript{2} capacities under isothermal cycling at 55°C in a 78-ppmv SO\textsubscript{2} and 200-ppmv NO containing flue gas stream.

A systems analysis has also been conducted based on the mass and energy balances of a 433,300 kW\textsubscript{e} plant, specifically, AEP’s Conesville Unit #5 (Ramezan, 2007). For this analysis, a working capacity of 2.0-wt\% CO\textsubscript{2} (from preliminary bench-scale data shown in Figure 4) was employed for the mesoporous carbon sorbent. The major power requirements are listed in Table 2 below.
Figure 7. Effect of Flue Gas Contaminants SO₂ and NO

Table 2. Power Requirements for TDA’s CO₂ Capture System

<table>
<thead>
<tr>
<th>Description</th>
<th>Power, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of power to compress steam</td>
<td>-28,875</td>
</tr>
<tr>
<td>Parasitic power losses</td>
<td>-6,979</td>
</tr>
<tr>
<td>Power loss from compression to CO₂ &amp; H₂O to 3.0 atm</td>
<td>-8,839</td>
</tr>
<tr>
<td>Power loss from compression to CO₂ &amp; H₂O to 9.0 atm</td>
<td>-8,509</td>
</tr>
<tr>
<td>Power loss from compression to CO₂ &amp; H₂O to 36 atm</td>
<td>-11,875</td>
</tr>
<tr>
<td>Power loss to condense CO₂ and pump</td>
<td>-6,914</td>
</tr>
<tr>
<td>Total net power required for CO₂ capture</td>
<td>-71,991</td>
</tr>
<tr>
<td>Plant initial power</td>
<td>433,300</td>
</tr>
<tr>
<td>Net plant power with CO₂ capture</td>
<td>361,309</td>
</tr>
<tr>
<td><strong>Net Plant Power Reduction with CO₂ capture</strong></td>
<td><strong>16.61%</strong></td>
</tr>
</tbody>
</table>

The net plant power output was estimated to be reduced to 361,309 kW with this CO₂ capture sorbent (Table 2). In comparison, the output was reduced to 303,317 kW in the baseline CO₂ capture case using amines (DOE/NETL-401/110907). The net plant power output was reduced by 16.6% with TDA’s CO₂ capture system compared to a 30% loss for an amine system. These results suggest the sorbent has the potential to reduce the cost of CO₂ removal from flue gases.
These preliminary results obtained to date with this material (Figure 4) for flue gas CO\textsubscript{2} removal suggest that this sorbent needs further optimization to meet the below ICCI criteria:

- A demonstrated, continuous capture efficiency of at least 90% from a flue gas stream at 65°C containing at least 250-ppm sulfur and 10% H\textsubscript{2}O.
- A demonstrated capture efficiency of at least 10-wt% CO\textsubscript{2} after 20 regeneration cycles.
- A regeneration energy of less than 4500-kJ/kg CO\textsubscript{2} (1900-Btu/lb CO\textsubscript{2}).

In the current DOE project, up to nine different formulations of the original mesoporous carbon sorbent will be prepared and tested by TDA along with the original formulation for CO\textsubscript{2} removal from a simulated high-sulfur-containing flue gas. Based on the ICCI criteria goal, GTI will test the sorbent’s effectiveness for CO\textsubscript{2} capture using the high-sulfur flue gas generated by the combustion of IL#6 coal.

**EXPERIMENTAL PROCEDURES**

The overall research approach to accomplish the set ICCI criteria for CO\textsubscript{2} capture from a high-sulfur containing flue gas (~250-ppm SO\textsubscript{2}) derived by combusting IL#6 coal and using TDA mesoporous carbon sorbents is as follows: a) initiate modification of an existing natural gas furnace to combust IL#6 coal for flue gas generation and complete the design of a flue gas cleanup system in year 1 (Phase I), b) complete furnace modification and fabrication of flue gas cleanup system in year 2 (Phase II) and c) integrate the TDA designed prototype sorbent system with modified furnace and cleanup system and operate the integrated system on a slip-stream of flue gas in year 3 (Phase III) to validate the ICCI criteria laid out in the RFP.

Based on the test results, a preliminary engineering and cost analysis will be carried out by TDA and GTI to identify commercialization opportunities for this novel CO\textsubscript{2} removal sorbent in existing power plants fired with Illinois coal.

The data generated in this work will serve as a basis for a large-scale slipstream demonstration test (1-5 MWe), the successful results of which are critical in stimulating strong commercial interest in using this new CO\textsubscript{2} capture technology. Because of the current support from the DOE/NETL and existing collaboration with a major manufacturing partner (MeadWestvaco Corp), the commercialization of the new technology will be rapid once the demonstration tests are successful.

**RESULTS AND DISCUSSION**

In Task 1 (in Phase II) of this program GTI performed the work described below.

1. Test Setup

A typical boiler with pollution controls and associated flue gas compositions requirements upstream of the CO\textsubscript{2} capture process are shown in Figure 8 and Table 3.
Based on this scheme, GTI devised and evaluated a conceptual design of a test setup (Figure 9) comprising a furnace and flue gas cleanup sections to accomplish the slip-stream testing of the prototype TDA CO$_2$ capture sorbent. Based on consultations with TDA, the pollution control sequence was altered from that shown in Figure 8. Following is a detailed description of the test setup.

![Figure 8. Typical PC Boiler with Pollution Controls](source.png)

**Table 3. Flue Gas Compositions after Pollution Controls**

<table>
<thead>
<tr>
<th>Illinois #6 Coal</th>
<th>Flue Gas</th>
<th>Feed to TDA CO$_2$ Capture System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Basis</td>
<td>Wet Basis</td>
</tr>
<tr>
<td>Moisture</td>
<td>11 wt%</td>
<td>CO$_2$</td>
</tr>
<tr>
<td>Carbon</td>
<td>64</td>
<td>N$_2$</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.5</td>
<td>O$_2$</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.2</td>
<td>NO$_x$</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.3</td>
<td>SO$_x$</td>
</tr>
<tr>
<td>Sulfur</td>
<td>2.5</td>
<td>Moisture</td>
</tr>
<tr>
<td>Oxygen</td>
<td>6.9</td>
<td>PM</td>
</tr>
<tr>
<td>Ash</td>
<td>9.7</td>
<td>Hg</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.15 ppm</td>
<td>Hg, ppbw</td>
</tr>
</tbody>
</table>

*250 ppmv ICCI criteria*
Figure 9. Flow Diagram of Integrated System (Furnace, Flue Gas Cleanup and TDA CO₂ Capture Subsystems)
Furnace Modifications

GTI identified an existing natural gas furnace for modifications to combust IL#6 coal for flue gas generation and CO₂ capture testing.

- Gathered parts available in-house: furnace end cap, furnace thermal load (Figure 10), data acquisition components/modules, and flue gas stack sections (Figure 11).
- Designed (GTI), fabricated (American Metal Installers, Villa Park, IL) and refractory lined (JP Larsen, Alsip, IL) flue gas stack extension (Figure 11).
- Designed and fabricated a swirl burner (Department of Mechanical Engineering, Brigham Young University, Provo, UT) to combust IL#6 coal for flue gas generation (Figure 12).
- Designed and fabricated burner mount and furnace extension (Figure 13).
- Winger, Inc. (Crystal, MN) designed and fabricated a coal feeding system to the furnace for flue gas generation (Figure 14).
- Sized and procured an eductor for feeding pulverized IL#6 coal into the burner (Figure 14).
- Sized and procured an orifice meter to measure flow rate of flue gas slip stream to the cleanup and TDA CO₂ capture system and a high-temperature filter to capture flue gas particulates (Figure 15).
- Procured thermocouples and thermocouple fittings, pipe fittings for the slip stream connection at the bottom of the furnace and sight glasses for the furnace extension.
- Procured 5,000 pounds of pulverized IL#6 coal from GTI gasification group for flue gas generation.

Figure 10. Various Views of Furnace End Cap and Thermal Load
Figure 11. Flue Gas Analyzer, Data Acquisition Components/Modules, Flue Gas Stack Sections and New Stack Extension

Figure 12. Swirl Coal Burner Assembly (top) and Burner in Operation (bottom)
Figure 13. Burner Mount/Furnace Extension

Figure 14. Coal Screw Feeder (L) and Eductor (R)
The cleanup system consists of the following subsystems: heat exchangers, particulate matter (PM), SOx, NOx and trace contaminant control. Also, an induced draft (ID) fan is included in the system to overcome pressure drops in the respective subsystems.

- Finalized cleanup system layout (Figure 9) and skid size (6’L x 4’W x 6’H).
- Generated a bill-of-materials list (Table 4).
- Sized fixed-bed reactors for SOx, NOx, and mercury/trace contaminant removal for demonstration testing (up to 500 hours). A representative reactor is shown in Figure 16.
  - SOx 1.5 ft³ (12” D x 24” L).
  - NOx 0.2 ft³ (12” D x 3” L).
  - Mercury/trace contaminant 0.5 ft³ (9” D x 20” L).
- Selected 5S/10S stainless pipe & fittings (from Robert-James Sales, Inc., Oak Forest, IL) for reactor fabrication.
- Selected heat exchangers (available in-house) and band heaters (Chromalox) for temperature control.

GTI completed 80% of furnace modifications and 70% of flue gas cleanup system fabrication. Unexpected delays in: a) vendor fabrication of the key hardware, and b) in part, testing of coal flow visualization reactor system by TDA to obtain parameters for the design of their CO₂ capture prototype system experienced in the final quarter of Year 2, respectively, impacted furnace modifications and finalization of the cleanup componentry orientation and control strategy of the flue gas cleanup skid. These will be completed by the end of first quarter of Year 3.

2. TDA CO₂ Capture Prototype System

GTI worked with TDA on the design of the CO₂ capture prototype test unit, shown in Figure 17, for evaluation at GTI. GTI reviewed the P&ID and layout of the prototype test unit for integration with the GTI furnace/flue gas cleanup system. The team determined the prototype foot print to be 6-ft W x 6-ft L x 16-ft H (Figure 17). In order to obtain
design data for the fabrication of the CO$_2$ prototype system, TDA also constructed a cold flow unit (Figure 18). However, equipment related issues delayed testing (still continuing) and data generation that impacted completion of the final design of the TDA prototype system.

Table 4. Flue Gas Cleanup System Bill-of-Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Potential Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace shell</td>
<td>1</td>
<td>Existing in GTI inventory</td>
</tr>
<tr>
<td>Furnace burner support</td>
<td>1</td>
<td>American Metal Installers (Villa Park, IL) / J.P. Larson (Alsip, IL)</td>
</tr>
<tr>
<td>Furnace end cap</td>
<td>1</td>
<td>Existing in GTI inventory</td>
</tr>
<tr>
<td>Burner</td>
<td>1</td>
<td>BYU Precision Machining Lab (Provo, UT)</td>
</tr>
<tr>
<td>Coal feeder</td>
<td>1</td>
<td>Winger Inc. (Crystal Lake, MI)</td>
</tr>
<tr>
<td>Venturi distributor &amp; house</td>
<td>1</td>
<td>Fox Valve Development (Dover, DE), Schuette &amp; Koering (Trevose, PA)</td>
</tr>
<tr>
<td>Furnace cooling tube bundle</td>
<td>1</td>
<td>GTI / American Metal Installers (Villa Park, IL)</td>
</tr>
<tr>
<td>Ceramic tube (in-furnace particle control)</td>
<td>1</td>
<td>Coorsite (Golden, CO)</td>
</tr>
<tr>
<td>Furnace stack extension</td>
<td>1</td>
<td>American Metal Installers (Villa Park, IL) / J.P. Larson (Alsip, IL)</td>
</tr>
<tr>
<td>UV sensor flame relay</td>
<td>1</td>
<td>Existing in GTI inventory</td>
</tr>
</tbody>
</table>

**Flue Gas Cleanup Subsystem**

- Upstream heat exchanger: 1 GTI / American Metal Installers (Villa Park, IL)
- Cyclone: TBD
- Particulate filter: 1 Pull Corp. (New York, NY), Matt Corp. (Farmington, CN)
- SO$_x$ removal adsorbent: 45-90 lb TDA Research, Inc. (Wheat Ridge, CO)
- NO$_x$ removal catalyst: 0.2 lb TDA Research, Inc. (Wheat Ridge, CO)
- Carbon adsorbent (trace contaminant removal): 50 lb NUCON (Columbus, OH) / Calgios (Pittsburgh, PA) / Nort (Marshall, TX)
- Steam generator: 1 Various
- Pipe and tube: 100 ft McMaster Carr (Elmhurst, IL) / American Metal Installers (Villa Park, IL)
- SO$_x$, NO$_x$, and carbon vessels: 3 American Metal Installers (Villa Park, IL)
- Induction (ID) fan: 1 McMaster Carr (Elmhurst, IL)
- Orifice meter: 1 Pyronics (Cleveland, OH)
- ID fan speed control: 1 AutomationDirect (Cannonville, GA)
- Insulation: 20 lb McMaster Carr (Elmhurst, IL)
- Thermocouples: 20 Wilson Industries (Lake Elmo, CA) / Lesman Instrument Co. (Bensenville, IL)
- Data Acquisition: 1 unit Existing in GTI inventory
- Manual and automated ball valves: 2 McMaster Carr (Elmhurst, IL)

Figure 17. TDA CO$_2$ Prototype Capture Test Unit
CONCLUSIONS AND RECOMMENDATIONS

In Phase I of this project GTI completed 80% of furnace modifications and 70% of flue gas cleanup system fabrication. Furnace and cleanup skid fabrication could not be completed as planned due to unexpected delays in: a) vendor fabrication of the key hardware (for furnace modifications), and b) TDA’s testing of their cold flow visualization reactor system to obtain design parameters for the CO₂ capture prototype system fabrication (experienced in the final quarter of Year 2), impacted finalization of the cleanup componentry orientation and control strategy of the GTI flue gas cleanup skid designed for integration with the prototype system. These will be completed by the end of first quarter of Year 3.

Research activity in the next year (Phase III) will be concentrated on validating the prototype CO₂ capture system using ICCI criteria. Before commencing the validation testing, GTI will conduct a hazard and operability analysis (HAZOP) and safety review of the unit for extended operation, develop test protocols and data collection requirements in consultation with ICCI and perform gas sampling and analyses per ICCI specifications.
REFERENCES


DISCLAIMER STATEMENT

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