

SORBENTS FOR MERCURY REMOVAL FROM COAL-DERIVED SYNTHESIS GAS

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ABSTRACT

Gasifiers convert coal into synthesis gas feed streams that can be used in advanced power cycles to generate electricity and in the production of a wide variety of chemicals. However, the coal-derived synthesis gas contains a myriad of trace contaminants that cannot be released to the environment if the syngas is burned to generate power or may poison the catalysts used in the downstream chemical manufacturing processes. Therefore, removal of these contaminants is critical for environmentally-friendly utilization of coal.

TDA Research Inc. (TDA) is developing a sorbent-based system that can reduce the concentration of the trace metal contaminants (i.e., mercury, arsenic, selenium and cadmium) to less than parts per billion levels in the coal-derived synthesis gas at elevated temperatures (260°C). This paper discusses the results of our sorbent tests and a preliminary cost assessment for the mercury removal system.

INTRODUCTION

The U.S. Department of Energy (DOE) is working to furnish the U.S. market place with a number of advanced, highly efficient and environmentally responsible coal-based processes that can overcome the economic and environmental impediments that limit the full utilization of coal. Advanced power generation cycles, such as the Integrated Gasification Combined Cycle (IGCC) are likely to replace conventional coal combustion due to their high efficiency. The commercialization of these advanced technologies depends on developing processes that eliminate the emission of contaminants in coal (e.g., sulfur, mercury). In this context, DOE funds the development warm gas clean-up systems to remove contaminants at elevated temperatures, since high temperature removal is essential for high efficiency. Recently, mercury was identified as a hazardous air pollutant in the Title III of the 1990 Clean Air Act Amendments and is now being regulated by the U.S. EPA. It has been singled-out with particular scrutiny because of its effects on humans and wildlife.

There are relatively few investigations on high temperature removal of mercury from the reducing gas environments encountered in gasification systems. Most of the early work in reducing environments focuses on removal of mercury from hydrocarbon streams in LNG/LPG plants to prevent mercury damage to process equipment. These are mostly sorbent-based

technologies capturing mercury via amalgamation, physical adsorption, chemical absorption and/or chemical reaction. It has been shown that expendable sorbents, such as activated carbon and aluminosilicates can to physically adsorb elemental mercury (Granite et al., 2000) at ambient temperature. However, due to the weak nature of the interaction (i.e., Van der Waal forces) that binds the mercury to the solid, application of these sorbents are limited to ambient temperatures. In several studies, mercury is stabilized over sulfur impregnated activated carbon supports. Although they bind mercury more strongly and can be operated above ambient temperatures, they are still limited to temperatures below 120°C (Chao, 1984). They become net sulfur generators at 260°C as they react with hydrogen and form hydrogen sulfide. Prior research also showed that removal of mercury is possible by amalgamation of mercury with metals (Constandi, 1992). The mercury amalgamation with noble metals such as silver and gold is well known. Porous silver and/or gold containing samples in the form of loosely packed wires or thin films coated over gauzes or monoliths have been tested with success. However, a wide application based on expendable gold or silver sorbents have never been materialized for obvious cost reasons. The volumes charge of these sorbents required per volume of trapped mercury mass is very high, increasing the cost of the precious metal to prohibitive levels. Copper in different forms has also shown to amalgamate with mercury (Sugier, 1978). Copper-based formulations are less active than gold or silver, but their low cost enable their use in some niche applications.

A coal gasifier may emit mercury in several different forms, primarily as elemental mercury (Hg^0), mercuric chloride (HgCl_2) and mercuric sulfide (HgS). Depending upon the conditions, these compounds may exist as gas or in the form of micro particles (i.e., aerosols) at concentrations in low ppb levels. At such low concentrations and high temperatures, the efficacy of the state-of-the art sorbents is severely compromised. The thermodynamic absorption capacity of these sorbents is significantly reduced at high temperature. As a consequence, large quantities of sorbent are required per unit mass of mercury removed increasing the cost of removal of mercury. Early studies recognize that it is more difficult to remove elemental mercury from a gas stream than oxidized mercury. Although some approaches oxidize mercury compounds and then absorb and stabilize them over a solid (sorbents) or liquid (scrubbing solutions), these are not practical options for the hot and highly reducing fuel gas streams.

TDA Research, Inc. (TDA) is developing a low-cost, high capacity, regenerable sorbent that can remove mercury from coal-derived synthesis gas. Unlike the commercial sorbents that are used to remove mercury compounds from hydrocarbon streams, TDA's sorbent operates at high temperature (i.e., 260°C). Since mercury's affinity to any surface is extremely low at elevated temperatures, to avoid unacceptably high replacement and disposal costs, the sorbent is operated in a regenerable manner. In the process, mercury in the coal gas is removed by an absorbent system. The regeneration of the sorbent is carried out at slightly higher temperatures (285-300°C). Once the regeneration is complete, the sorbent is ready for reuse. An effective sorbent for this application must be able to withstand volume changes associated with absorption of mercury, while maintaining its structure and mechanical integrity under the conditions encountered in the high temperature, high pressure environment. In the DOE Phase II SBIR project, TDA is developing a high-capacity absorbent that meets all these requirements. This article summarizes the preliminary results of the development efforts.

RESULTS AND DISCUSSIONS

Sorbent Preparation

During the course of the project, more than 50 different sorbent formulations were prepared using different sources of active materials, inert substrates and additives (i.e., clays, binders). We first screened these formulations according to their physical properties, including porosity, surface area, crush strength of the pellet. In the selection of proper active material and support, the material costs were also taken into consideration. Our choice of substrate materials included conventional supports such as γ -alumina, titania, silica, activated carbon and boehmite [$\text{AlO}(\text{OH})_3$]. All these materials satisfied the criteria of being low-cost and high surface area (150 to 580 m^2/g as measured by the manufacturers). The active material precursors and inert substrates were combined using TDA's geode technology, enabling the incorporation of large quantities of active material into the final sorbent pellet, without plugging the pores of the substrate material and reducing its porosity. The best formulations with desired physical properties were tested for their mercury absorption capacities under simulated reaction conditions in an automated testing apparatus.

Sorbent Screening

Sorbent Testing Apparatus: The test apparatus was built at TDA to specifically measure sorbent performance for trace contaminant removal (Figure 1). The sorbent reactor consists of a 2.5 cm-OD quartz reactor tube that contains a frit at its mid-point to support pellets of 1/32" to 1/8" in diameter. A Mellen tube furnace surrounding the reactor is used to control the temperature. The gas streams of CO , H_2 , CO_2 , and N_2 were introduced through Porter mass flow

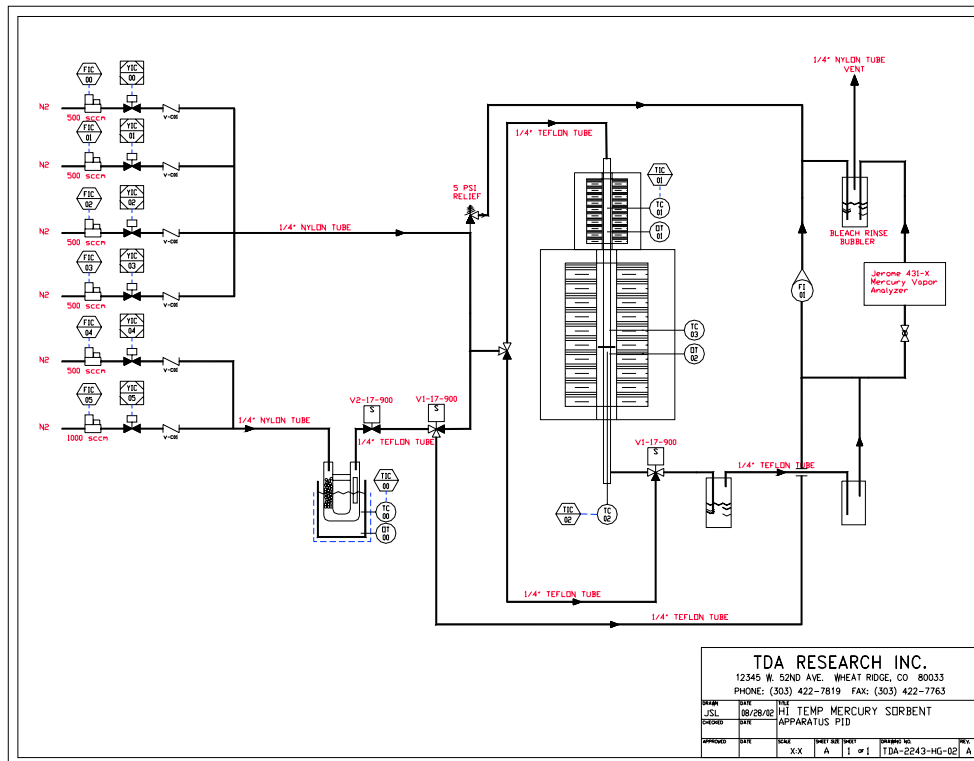


Figure 1. Process and instrumentation diagram of the test unit.

controllers. Mercury is generated using a permeation tube (VICI) immersed in a temperature-controlled mineral oil bath in a glass container. A sweep gas from the container (containing mercury vapor) was diluted to achieve the desired Hg concentration at the reactor inlet. The mercury concentration in the feed gas can be adjusted by increasing the temperature of the bath. The generator uses an ampule containing liquid mercury, which consists of a membrane permeable to mercury vapors. At higher temperatures, permeation rate increases (Figure 2).

After mixing in a manifold, the gas stream was preheated above the dew point of water to prevent condensation. The mixture then passed through a saturator where water was mixed into the feed stream by a peristaltic pump. The saturator design allowed complete evaporation of the liquid and ensured good mixing of the gases prior exiting the device. After mixing, the preheated feed mixture was directed into the reactor. Feed gases could also bypass the reactor through a valve combination and flow directly to an analytical system for accurate measurement of the feed gas composition. With the setup, it was possible to generate feed streams of simulated coal-derived syngas and pass them over sorbent formulations at desired rates.

The mercury concentration at the outlet of the reactor bed was continuously monitored with an on-line Jerome 431X analyzer. An SRI Model 8610A gas chromatogram (GC) was used to measure concentrations of the other reaction gases (i.e., CO, H₂, CO₂). After exiting the analyzer, the effluent gas stream was scrubbed by a strong NaOH/oxidizer solution to capture any remaining mercury and to prevent its release to the atmosphere. The apparatus was fully automated and ran without an operator for long periods of time, including overnight. We used Control CB software on this apparatus to control test conditions, log analytical data, and to safely shut down the apparatus in case of a malfunction.

Testing Procedure: We carried out experiments to measure the pre-breakthrough and saturation mercury absorption capacity of the sorbents. In the breakthrough tests, we measured the pre-breakthrough absorption capacity of the sorbent. The breakthrough is defined at 90% mercury removal (i.e., the point when the mercury concentration at the bed exit exceeds 90% of the inlet Hg concentration). Pre-breakthrough capacity is a good indicator of the rate of removal of mercury, however, it is also important for the sorbent to absorb large quantities of mercury as possible even after the breakthrough. Either in a fixed-bed or moving-bed reactor configurations, a large fraction of the sorbent bed is operated beyond the breakthrough, approaching or reaching to saturation. Thus, the screening tests were designed to address both criteria.

In these tests, coal-derived synthesis gas mixtures were simulated by blending certified mixtures of H₂, N₂, CO, H₂, and CO₂ (Air Gas, Inc., Colorado Springs, CO). Prior to each

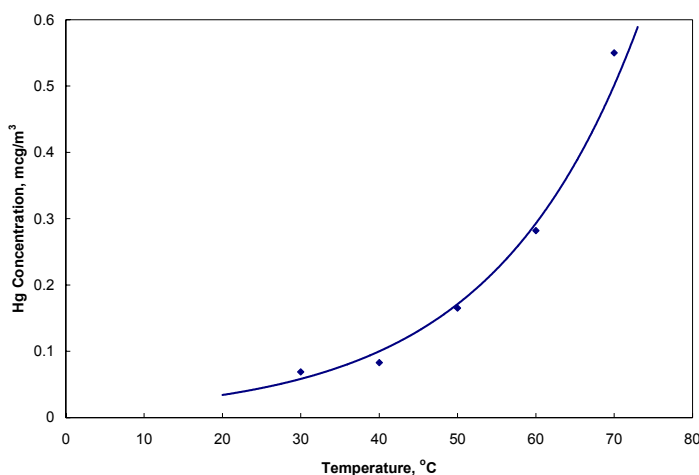


Figure 2. Hg concentration of the feed gas as a function of generator temperature.

test, the mercury analyzer was calibrated and mercury concentration was measured at the reactor inlet via a reactor by-pass line. Once a stable baseline for the inlet mercury level was established, gas flow was directed through the bed. In every test, a known quantity of sorbent was placed in the reactor. Each test started with heating the reactor to desired temperature under nitrogen flow. After the temperature was stabilized, mercury laden gas stream was introduced into the sorbent bed.

The critical experimental need is to demonstrate the operation of the sorbent under representative conditions (i.e., elevated temperatures and pressures). However, evaluation of sorbents at such conditions is difficult because mercury interacts with all types of metal tubing (e.g., stainless steel). The inert materials such as quartz or Teflon cannot be operated effectively at the combination of elevated temperatures and pressures (i.e., $T=300^{\circ}\text{C}$, $P=40$ bar). In our reactor design, quartz was the material of choice, with Teflon lines to deliver the feed gases to the reactor and reactor effluent to the analysis system. Using all quartz and Teflon parts (tubes, unions, fittings etc.) ensures minimal mercury absorption on the system components. Although with this design, it was possible to simulate high temperature operation, the reactor could not be operated at typical gasifier operation pressures (i.e., 20-50 bar). We simulated the pressure effect by increasing the mercury partial pressure in the gas stream (i.e., 10 ppb Hg at 50 bar will have the similar effect on the performance of the sorbent as 500 ppb Hg at 1 bar). Although high pressure operation affects the mass transfer characteristics (i.e., pore diffusion), these are anticipated to be minor and will be addressed at the later stages of the project.

Diagnostic Tests: Prior to testing of the sorbent, we carried out several diagnostic tests to measure the effects of dead volume and other reactor components (i.e., tubing) on the breakthrough time and mercury outlet concentrations. The time elapsed from introducing mercury into the manifold and its detection in the gas monitor was less than a minute under representative operation conditions, this lag is small compared to the duration of the tests. Once the blank reactor tests were completed, we loaded the reactor with inert alumina pellets (high surface area and high porosity) to measure the effect of typical substrate material used to support the sorbents. We tested the inert pellets with mercury inlet concentrations ranging from 1.0 to $5.0\ \mu\text{g}/\text{m}^3$ and observed that the high surface area substrates (i.e., alumina or silica) have very little or no affinity for mercury, essentially acting as inerts for the mercury absorption process. These tests allowed us to use these materials as a diluent in the reactor during the tests where small quantities of sorbent materials were mixed with inerts to prevent the reaction gases from channeling through the bed.

Test Profile: Figure 3 presents a typical test profile, in which the mercury concentration at the reactor outlet is presented as a function of time. At the beginning of the test, Hg concentration in the feed gas was measured by flowing the gases through reactor bypass line to the analyzer (in this particular run, it averaged at approximately at $0.18\ \mu\text{g}/\text{m}^3$). The gas flow was then diverted through the reactor, and tests were carried out at 260°C and near ambient pressure (3.0 psig). The mercury level at the reactor exit dropped sharply due to removal by the sorbent. Mercury breakthrough occurred after 400 minutes of operation. Mercury flow was maintained for another 1,000 minutes, at a gas hourly space velocity (GHSV) of $37,500\ \text{h}^{-1}$, following breakthrough to measure the saturation capacity of the sorbent. Once the mercury concentration eluding from the bed exceeds a pre-determined concentration, the automated system initiated a shutdown

sequence, stopping the mercury gas flow, purging all the mercury from the system with nitrogen and heating the sorbent bed to 285-300°C to carry out the regeneration of the sorbent. The small increase in temperature and the swing in the Hg concentration facilitated sorbent regeneration. We tripled the gas flow during regeneration to ensure the Hg levels were maintained within the detection range of the analytical instrument. Sorbent regeneration proceeded rapidly and all the mercury absorbed during the absorption step was recovered during regeneration step, verified with a close mercury balance in the absorption and regeneration steps (i.e., amount of mercury absorbed were in good agreement with the amount of mercury desorbed). In select tests, some of the samples were recovered without undergoing regeneration, so we could carry out chemical and physical characterization tests. Some samples were shipped to a local independent laboratory, Hazen Research, to analyze the mercury content. The chemical analysis results and our calculations based on the breakthrough profile were in very close proximity ($\pm 5\%$).

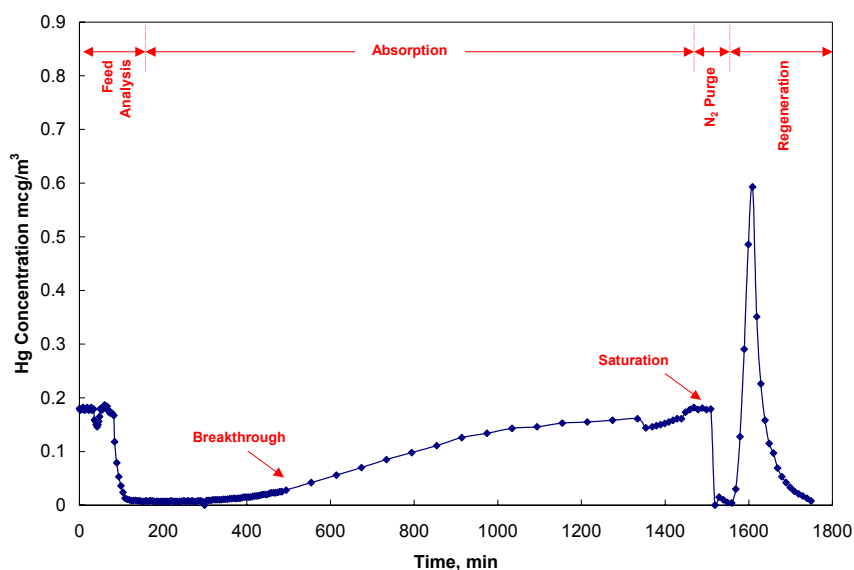


Figure 3. Typical test profile.

Parametric Tests

Once we completed the screening of the sorbent samples to identify the single-best formulation, we carried out parametric tests to measure the effect of operation parameters (i.e., temperature, space velocity) on sorbent performance. The results of the initial screening experiments and parametric tests are published in detail elsewhere (Alptekin et al., 2003). After an effective formulation was identified and the optimum operating conditions were determined, we tested the performance of the sorbent in long duration tests through 40 consecutive absorption/regeneration cycles.

Long-term Durability Test

We carried out a 40-cycle test to demonstrate the long-term cyclic capacity of the sorbent. We flowed a simulated synthesis gas mixture containing $3.0 \mu\text{g}/\text{m}^3$ of mercury (to simulate the effects of a high pressure syngas) at 18.0 psia and 260°C. We passed a $\text{H}_2/\text{CO}/\text{CO}/\text{H}_2\text{O}/\text{N}_2$ gas mixture over the sorbent at a molar ratio of 20/10/5/10/55 at a gas hourly space velocity of $50,000 \text{ h}^{-1}$ (STP) corresponding to a 0.072 sec gas/solid contact time.

At the start of each cycle, the inlet mercury concentration was measured by sampling through reactor bypass line. Once a stable inlet concentration established, the gases were flown over the sorbent bed. Each cycle, as the gas flow was diverted to the bed, the mercury level dropped sharply to zero indicating that all the mercury was absorbed by the sorbent, providing 100% mercury removal. We continuously monitored the mercury breakthrough profile at the reactor exit and stopped the gas flows when mercury concentration exceeded 10% of the inlet Hg concentration, removing about 98% of the mercury over each run. Regeneration was carried out using a combination of pressure swing (i.e., running a 2% H₂/He mixture without any mercury) accompanied by a mild temperature swing, increasing the bed temperature to 285°C.

The regeneration conditions were maintained until we observed no mercury being released from the sorbent bed. We maintained these conditions for 40 consecutive absorption and regeneration cycles. The sorbent exhibited a stable mercury absorption capacity of 0.023% wt. (lbs of mercury absorbed per lbs of sorbent) at 260°C. We did not record the data in between cycle #21 and cycle #35, because the mercury analyzer was temporarily unavailable. However, cycling tests were continued using the absorption/regeneration times measured in earlier cycles. When the analyzer was brought back on line, we observed that the sorbent performance was unchanged.

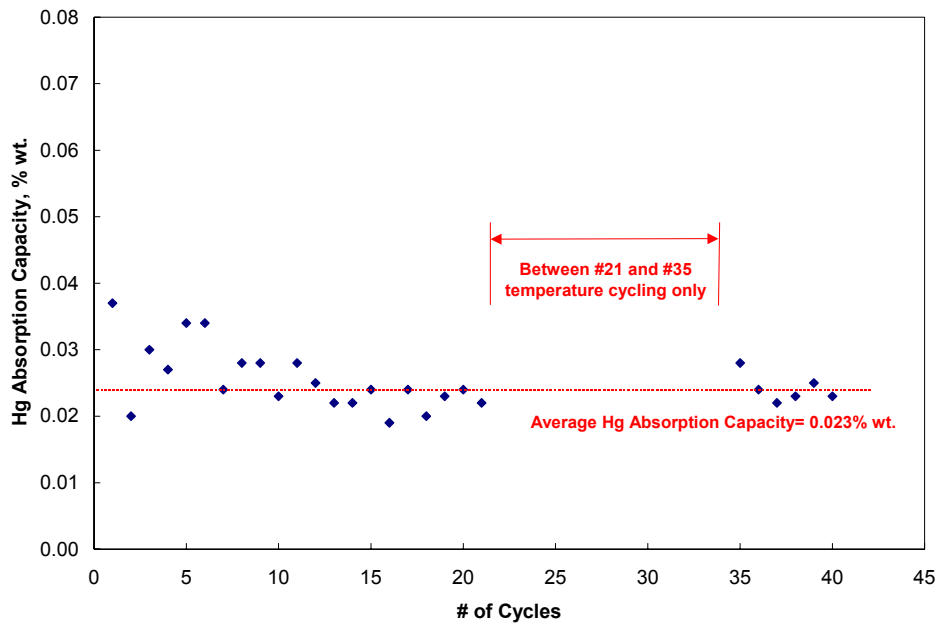


Figure 4. Multiple-cycle testing. $T_{\text{absorption}} = 260^{\circ}\text{C}$, $T_{\text{regeneration}} = 280^{\circ}\text{C}$, Hg inlet conc. = $3.0 \mu\text{g}/\text{m}^3$, Hg breakthrough conc. = $0.3 \mu\text{g}/\text{m}^3$, GHSV = $50,000 \text{ h}^{-1}$.

A comparison of the mercury breakthrough profiles for cycle #10 and cycle #40 also shows that the mercury removal efficiency remained above 98% throughout the test (the regeneration data are not included for clarity). These results clearly demonstrate that the sorbent maintains its absorption capacity over cycling.

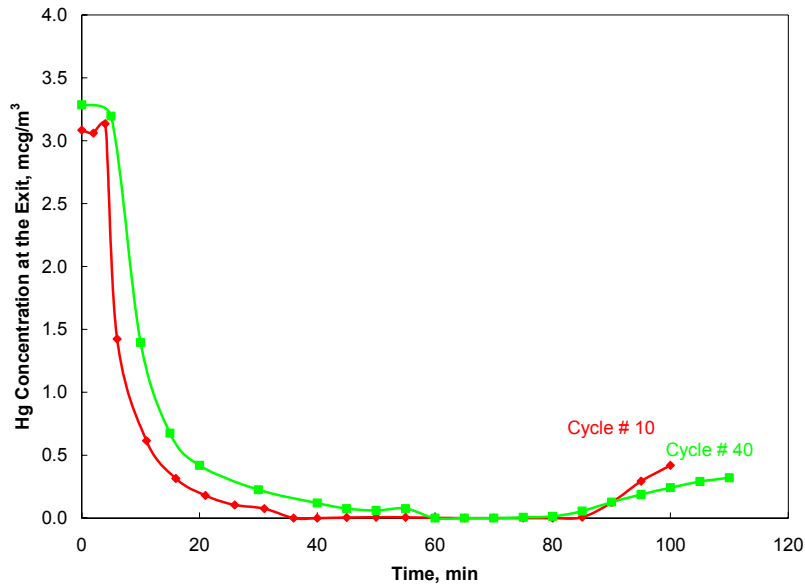


Figure 5. Breakthrough profiles for cycle #10 and cycle #40. $T_{\text{abs}} = 260^{\circ}\text{C}$, $T_{\text{reg}} = 280^{\circ}\text{C}$, Hg inlet conc. = $3.0 \mu\text{g}/\text{m}^3$, GHSV = $50,000 \text{ h}^{-1}$.

In separate tests, we also demonstrated that the sorbent is also tolerant to up to 20 ppmv sulfur in the syngas (typical sulfur concentration following a warm temperature sulfur removal system).

System Analysis and Cost Assessment

Based upon the experimental results, we carried out a preliminary system analysis in which we sized all major process equipment and their estimated costs. In this preliminary assessment, we used the following approach:

- 1) Select a basis of operation
- 2) Integrate the sorbent-based mercury control system with the rest of the components in the power generation system
- 3) Carry out mass and heat transfer balances across each unit
- 4) Estimate the size and installed costs of major components
- 5) Estimate the annual operating and maintenance costs
- 6) Using a capital recovery cost and annual O&M costs, calculate the annualized cost of removal of mercury on a unit mass basis

We initiated the cost analysis work by first identifying the basis of operation (i.e. plant size). In current industrial practice, the IGCC power plants tend to be very large since they greatly benefit from the economies of scale (the cost of electricity goes down as the capital cost per MW decreases). In this analysis, we used the Clean Coal Technology Demonstration Plant at Polk County, Florida as the basis of operation; a 250 MW_e IGCC power plant with the operation parameters provided in Table 1.

The average concentration of the coal used in the particular plant location is estimated as 100 ppb on weight basis (Rutkowski et al, 2002). After the gasification step, mercury is diluted to 52 ppbw. Using 90% mercury removal criterion, we allowed 5.0 ppbw mercury leaving the sorbent

bed at breakthrough. Based on 80% plant capacity factor and 90% removal efficiency, we estimated 130.5 lbs of mercury to be removed on an annual basis. Chemical process engineering approaches were used for flow sheet development and analysis. Based upon the mass and heat transfer calculations carried across each unit, we calculated the cost of major process equipments. In the costing the units, we followed the procedures provided by Association for Advancement of Cost Engineering (AACE) for a Level 5 cost analysis. Level 5 analysis, although limited in scope, provides a good understanding of the economic feasibility of the system on a preliminary basis and is widely accepted as a reasonable indicator for showing whether the concept has merits deserving a more detailed analysis. The first step in calculating the direct costs was to size the major equipment items and formulate the bare equipment costs (manufactured selling costs). The bare equipment costs are determined using cost curves, and consulting size/cost charts. Vendor costs were not obtained. We then included a factored estimating methodology to build upon the bare equipment costs. These factors determined the amount of labor to set the equipment, distributive or bulk material and costs for buildings, foundation, piping electrical and instrumentation.

Reactor size and cost: We estimated the size of the sorbent reactors based upon sorbent performance and absorption capacity at a gas/solid contact time 0.072 sec at STP (i.e., ~2.0 sec at the empty reactor volume-based residence time at process conditions). To estimate the size of the reactors we used the specifications provided by “Chemical Plant Design and Economics Handbook” by Peters and Timmerhaus (1982). These reactors are externally insulated to maintain desired operation temperatures with minimum heat leakage. Based upon the upper temperature and pressure limits, we selected Carbon Steel A285 for the construction material. We then calculated the bare equipment cost based upon material and used a factor for labor and installation reflecting 2002 dollar values. We calculated the costs for the reactor housing, end caps, external insulation, internal piping (for solid transfers and gas distribution), short-term storage vessels and particulate filters on a bare cost basis, and then applied a factor (115% of the bare material cost) for installation and delivery. Cost of the reactors is estimated to be \$369,423.

Sorbent Inventory Costs: The sorbent cost and the sorbent life (i.e., mercury absorption capacity of the sorbent) are the two determinants of the sorbent replacement costs. We anticipate that sorbent can be manufactured at a cost approximately \$5/lb. This includes the cost of materials as well as the fabrication costs. We calculated the cost of the sorbent required during the process start-up. In the analysis, we calculated the volume of the sorbent required in each reactor and the amount retained in the short-term storage vessels. Estimating the packing density of the pellets in these locations and the density of the sorbent itself, we identified the amount of sorbent required as start-up inventory. Based upon the reactor volume, the sorbent amount

Table 1. Plant parameters.

Syngas, kmol/h	8546
Syngas MW, kg/kmol	21.04
Syngas, kg/h	179808
Temperature, oC	260
Pressure, psia	900
Hg Concentration, ppbw	52
Hg Removed, kg/h	0.0094
Sorbent life, cycles	1
Plant availability	95%
Plant Operation, hr	8322
Cycle Time, h	8322
Mercury loading, kg Hg/kg sorbent	0.0016
Sorbent Requirement, kg/h	6
Sorbent Replacement, kg/year	48632
Syngas, scf/h	6,757,816
Syngas, slh	191381349
Sorbent Density, kg/L	1.02
Sorbent Volume, L	47678
Space Velocity, h-1	4014

required is estimated as 25,320 lb for the initial charge-up. The total initial capital investment in the sorbents is estimated about \$126,150.

Capital Investment Requirement

Based upon the installed equipment costs, we calculated the capital investment requirement for the overall system based upon year 2002 values. We estimated the total capital requirement as approximately \$1.325 million dollars. Table 2 summarizes the costs involved with the capital items. We assumed a 30% cost for the facilities and a 2-month allowance in early design for the working capital.

Table 2. Total capital requirement.

DIRECT COSTS SUMMARY (2002 PRICES)			
	Equipment	Labor	Total
Sorbent Reactors	369.4	7.4	376.9
Heat Exchange Equipment	197.3		197.3
Gas Circulation Equipment	22.5		22.5
Sorbent Storage/ Transfer Equipment	73.0		73.0
TOTAL DIRECT COSTS	662.2	7.4	669.7
INDIRECT COSTS (Percentage of direct labor)		50%	3.7
TOTAL DIRECT AND INDIRECT COST			673.4
ENGINEERING (percentage of direct costs)		5%	33.7
OVERHEAD & ADMINISTRATION (percentage of direct costs)		8%	53.9
CONTINGENCY		18%	121.2
FEE (percentage of on-site costs)		5%	33.7
TOTAL PLANT COST			915.8
STARTUP COST (percentage of direct costs)		3%	20.1
SPARE PARTS (percentage direct equipment costs)		5%	33.1
INITIAL SORBENT/ CHEMICALS INVENTORY			126.2
FACILITIES		30%	202.0
LAND		see note	0.0
WORKING CAPITAL (2 months of annual operating cost)			28.7
TOTAL CAPITAL REQUIREMENT			1325.9

Note - Cost of land is not included

Operating and Maintenance Expenses

The operating and maintenance costs are presented in Table 3. These expenses include labor and supervision costs, and maintenance labor and supplies. Due to the similarities between these systems, we used the labor costs as indicated by Rutkowski and coworkers (2002) and applied the same fractions as they used in their analysis for supervision, maintenance supplies, taxes and administration and overhead. We also estimated other cost items for our process such as the sorbent replacement cost, sorbent disposal cost, power costs. We estimated the sorbent replacement frequency and associated costs based upon the performance result; an overall absorption capacity of 0.92% wt.= 0.023% per cycle*40 cycles is used to calculate the replacement requirement. Annual sorbent replacement cost and disposal cost is estimated as \$70,924 and \$3,546 (based upon \$500/ton of hazardous material removal cost), respectively. We then calculated the levelized cost of capital (i.e., capital recovery cost) over the unit quantity mercury removed based upon TDA's process using a 15% fixed charge rate. The cost of capital recovery is added to the O&M expenses to calculate the annualized cost for the mercury removal system. Dividing this value to the annual amount of mercury removed, we estimated the cost of removal of mercury as \$2,995/lb.

The reported cost for mercury removal is far lower than those reported for the state-of-the-art mercury abatement technologies applied to the pulverized coal combustion power plants. A recent EPA study submitted to the congress in 2000 predicts that the cost of removal of mercury from pulverized coal combustion plants is a minimum of \$17,400 per lb of mercury removed with activated carbon injection with spray cooling (the most promising technology for mercury removal from flue gases) and \$37,000 for carbon beds. A recent DOE study sets the near-term goal for the cost of mercury control technologies at a baseline cost of \$50,000-70,000/lb (Feely, 2003).

CONCLUSIONS

TDA's sorbent achieves a high mercury absorption capacity at 260°C under simulated conditions. The bench-scale test results clearly demonstrate that:

- 1) TDA's sorbents exhibit a high capacity for mercury absorption
- 2) The sorbent is tolerant to sulfur
- 3) The sorbent is regenerable and maintains its absorption capacity over 40 absorption/regeneration cycles
- 4) Effect of mercury removal to the cost of electricity using our sorbent-based high temperature cleaning process will be negligible. Based on an electricity cost of 35 mills/kWh, the increase in the cost of electricity will be less than 1%.

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Table 3. Operating and maintenance expenses.

PLANT PARAMETERS		
Plant net capacity, MW		250
Hg level before removal, ppbw		52.0
Hg level after removal, ppbw		5.0
Capacity factor		80%
Hg removed, lbs/year		130.50
Sorbent loading, %wt.		0.92%
CAPITAL COST (\$)		
Total Capital Costs (TCC)	\$	1,325,863
TCC, \$/kW		5.30
OPERATING & MAINTENANCE COSTS (\$/year)		
Operating labor*	\$	4,380
Supervising labor*	\$	657
Maintenance labor*	\$	2,409
Maintenance material	1% of TCC \$	13,259
Sorbent replacement cost	\$	70,924
Sorbent replacement	14,185	
Sorbent Cost, \$/lb	5.00	
Sorbent Disposal Costs	\$	3,546
Disposal cost, \$/ton	500	
Power Costs	\$	31,357
Fan power for gas circulation	\$ 16,640	
Compensate for pressure drop	\$ 14,717	
Overhead	\$	12,423
Taxes, insurance and admin. costs	4% of TCC \$	53,035
Total O&M Costs	\$	191,989
Capital recovery cost	\$	198,879
Capital recovery factor	15%	
Total annual costs	\$	390,868
Cost of Mercury Removal, \$/lb	\$	2,995
* same as Rutkowski et al., 2002		
Operating labor: 1 hour/shift @ \$20/h		
Supervision: 15 percent of the operating labor		
Maintenance costs: 0.5 hour/shift @ 10% wage premium over labor wage		
Power cost: Using 4 psi pressure drop and 35 mills per kWh		
Overhead Costs: 60 percent of operating labor and maintenance costs		

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