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Modeling & Economic Evaluation of Trace Mercury Removal Using Palladium- Based Sorbents

February 2013

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Modeling & Economic Evaluation of Trace Mercury Removal Using Palladium-Based Sorbents

**A Preliminary Report
For DOE/NETL**

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List of Acronyms and Abbreviations

Acronym/Abbreviation	Definition
As	Arsenic
COE	Cost of Electricity
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
Hg	Mercury
IGCC	Integrated Gasification Combined Cycle
JM	Johnson Matthey
LCOE	Levelized Cost of Electricity
LTI	Leonardo Technologies, Inc.
MATS	Mercury and Air Toxics Standards
N ₂	Nitrogen
NETL	National Energy Technology Laboratory
NO _x	Nitrogen Oxide
O&M	Operation and Maintenance
ORD	Office of Research and Development
P	Phosphorus
Pd	Palladium
ppb _w	Parts per Billion by Weight
psia	Pounds per Square Inch Absolute
psig	Pounds per Square Inch Gauge
RTI	RTI International
SCR	Selective Catalytic Reduction
Se	Selenium
SV	Space Velocity
Syngas	Synthesis Gas
Trz	Troy Ounce
WGCU	Warm-Gas Cleanup
WGS	Water-Gas Shift

Summary

The development of warm-gas cleanup (WGPU) systems for synthesis gas (syngas) cleanup in integrated gasification combined cycle (IGCC) power plants has the potential to lower the costs of generating power. An important component of WGPU is the removal of mercury (Hg), present in coal, from the syngas. Carbon-based sorbents used for Hg removal are not suitable for high-temperature Hg removal in conjunction with the WGPU. The U.S. Department of Energy's National Energy Technology Laboratory's (DOE/NETL) Office of Research & Development (ORD) has been developing various sorbent alternatives to address the problem of high-temperature Hg removal. This study presents analysis of the capture of Hg from syngas streams as a polishing step to attain U.S. Environmental Protection Agency (EPA) Mercury and Air Toxics Standards (MATS) requirements for Hg (0.003 lb/GWh_{gross} for new IGCC plants) using palladium (Pd) adsorbent being tested by DOE/NETL in association with Johnson Matthey (JM).

For the present study, it was assumed that RTI International (RTI) WGPU would remove Hg to 5 parts per billion by weight (ppb_w) in the syngas and the Pd sorbent technology is used as a polishing step to achieve the EPA MATS requirements (0.003 lb/GWh_{gross}, equivalent to 2 ppb_w given RTI's process configuration and material flows). The incremental cost of Hg polishing and the additional capital cost needed were estimated for several scenarios/cases. These cases were differentiated by variance in the following parameters, which are important because they have direct impacts on additional capital costs (\$/kW) and in turn impacts on the levelized cost of electricity (LCOE):

- Pd cost (varied from \$4,000 to \$12,000/lb Pd).
- Gas hourly space velocity (SV) (varied from 500 to 13,500 h⁻¹).
- Pd loading (varied between 2 w/w% Pd and 5 w/w% Pd).
- Sorbent make-up rate (varied between 3%, 1%).

The ranges were chosen in order to reasonably reflect, in the cases which are analyzed, the actual fluctuations that have been observed in past experience in these important parameters that affect cost, e.g. the Pd cost has kept to within the \$4-12k/lb range in recent years. In the case of SV, the high and low points of the range are extremes beyond which costs would either be unreasonable, or increase in cost benefit would be negligible. For a typical case (i.e., using mid-range values of the parameters, including SV of 8,000 h⁻¹, 2% Pd loading, 3% make-up rate, \$9,500/lb Pd cost), the increase in LCOE due to the Pd polishing system is approximately 0.4% and the additional capital cost is ~\$10/kW. As a comparison, the incremental capital cost of conventional mercury removal in an IGCC plant is ~\$4 to 8/kW, and the increase in the LCOE is less than 0.4% ("Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity," DOE/2010/1397, Final Report, Revision 2, November 2010, National Energy Technology Laboratory). Results indicate that in the range of SVs from 3,500 h⁻¹ to 10,000 h⁻¹, the Hg polishing step is expected to function adequately and with increase of LCOE limited to about 1-2%. The use of a Pd sorbent-based polishing system to reduce trace Hg levels to the EPA MATS requirements for new IGCC power generation appears to be feasible and reasonably cost-effective.

1. Introduction

This study estimates the cost of a trace mercury (Hg) removal system using palladium (Pd) sorbents in the context of an integrated gasification combined cycle (IGCC) power plant. In recent cost and performance baselines for bituminous coal-fueled IGCC plants (DOE/2010/1397; “Cost and Performance Baseline for Fossil Energy Plants, Vol. 1,” DOE/NETL-2007/1281, May 2007), raw synthesis gas (syngas) cleanup is accomplished through a sequence of quench and syngas scrubbing to remove particulates and solid matter, carbonyl hydrolysis, cooling and knockout of ammonia/sour water, conventional Hg removal using activated carbon adsorbent, and then a low-temperature acid gas removal system such as Selexol to remove the bulk of the sulfur in the syngas. In order to improve plant efficiency, there is interest in replacing the low-temperature gas cleanup with a high-temperature process that achieves comparable performance in gas cleanup without the penalty inherent in cooling the syngas to the low temperatures required in the Selexol process or other conventional sulfur removal technologies. A proprietary warm-gas cleanup (WGCU) technology has been developed by RTI International (RTI) which could have significant benefits over conventional syngas cleanup technologies. The RTI WGCU technology substantially modifies the cold syngas cleanup approach by:

- Eliminating scrubbing and quench cooling.
- Replacing Selexol with the RTI high-temperature sulfur removal and recovery technology.
- Replacing conventional low-temperature Hg removal with a high-temperature Hg removal technology.
- Adding incidental chloride removal, selective catalytic reduction (SCR) for control of the increased nitrogen oxide (NO_x) emissions due to increased ammonia passing through the gas cleanup train, and other design features to accommodate process impacts.

The feasibility of a proprietary WGCU technology developed by RTI and impacts on the cost of electricity (COE) were assessed previously (“Preliminary Feasibility Analysis of RTI Warm Gas Cleanup (WGCU) Technology,” Nexant, 2007). The RTI Hg removal technology could potentially lower the Hg content in the syngas to 5 parts per billion by weight (ppb_w), which is consistent with the goals stated in the RTI gas cleanup project (NETL Factsheet, “RECOVERY ACT: Scale-Up of High-Temperature Syngas Cleanup Technology, <http://www.netl.doe.gov/publications/factsheets/project/FE0000489.pdf>). However, an additional Hg polishing step, equivalent to the removal of ~60% of the mercury in the syngas from the WGCU operations, is needed to attain the new U.S. Environmental Protection Agency (EPA) Mercury and Air Toxics Standards (MATS) requirements for Hg (new IGCCs: 0.003 lb Hg/GWh gross power generation).

A possible solution for the Hg polishing step uses Pd sorbents in a fixed bed. The U.S. Department of Energy’s National Energy Technology Laboratory (DOE/NETL) and Johnson Matthey (JM) have developed alumina-supported Pd sorbents that enable high-temperature (>260°C) Hg removal. Based on preliminary bench-scale and syngas slip-stream testing at Southern Company’s pilot facility, this sorbent has the capability to perform the required Hg polishing (Granite et al., 2011). Results also indicate that the Pd sorbents may be suitable for bulk Hg removal from syngas streams. The Hg removal configuration analyzed in this study

consists of the RTI WGPU technology for bulk Hg removal from the syngas, followed by Pd sorbent polishing to attain EPA MATS requirements.

The approach taken in this study has been to develop a simplified model of the Pd sorbent-based Hg removal system, modify the IGCC baseline process including the RTI WGPU to integrate the Hg removal system, and perform cost calculations to determine the incremental capital and operating costs impacting the COE.

2. Process Description and Flow Diagrams

In the context of an IGCC plant, the Hg polishing system would be added directly following the bulk Hg removal in the WGPU step. The overall process diagram of the baseline IGCC plant, including the RTI WGPU and sulfur recovery systems followed by the Hg polishing system, is as depicted in Figure 1. This process configuration is essentially identical to the Case 4 process configuration from the RTI Nexant Report (Nexant, 2007), modified only by addition of the Hg polishing system with its incidental power and steam demands on the overall plant process.

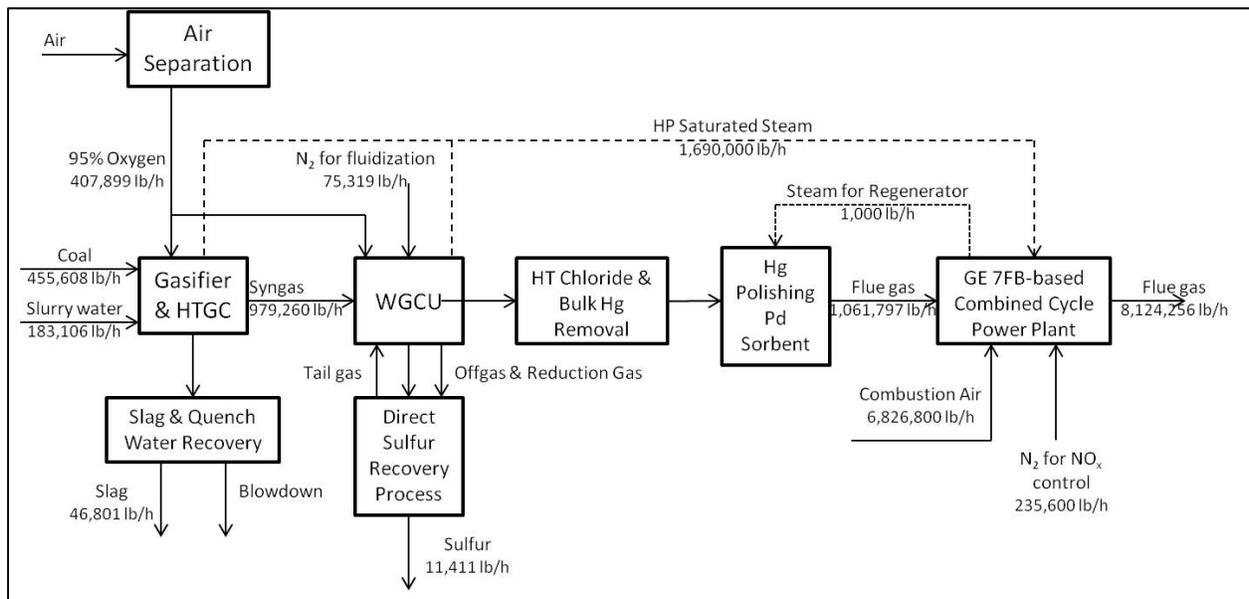


Figure 1: Block Diagram of IGCC Plant with RTI Warm-Gas Cleanup and Addition of Pd Sorbent-Based Polishing Unit

DOE has previously investigated the use of the JM Pd sorbents to remove Hg from coal gasification syngas. Detailed calculation procedures for determining extent of Hg removal using the Pd sorbents have been defined, accompanied by economic analysis to quantify costs of the Hg removal. The calculations assume a typical process arrangement for the sorbent-based Hg removal system; this is depicted in Figure 2. The basic process configuration of the Pd sorbent system consists of four Pd sorbent fixed beds, two of them online and two in offline or regeneration mode. The online sorbent beds may be kept in operation cleaning syngas until Hg/trace breakthrough reaches the allowable limit. At this point, the syngas is rerouted to the other two regenerated beds. The exhausted beds are then regenerated by blowing hot carrier gas (nitrogen) through the beds, which strips most of the trace metals away. The carrier gas is

cooled and passed through the disposable sorbent beds, removing the trace metals from the regenerator gas, which is then compressed, reheated, and cycled back. The regenerator gas is heated by steam of suitable quality to reach the required regenerator gas temperature of 400-550°C; this steam is withdrawn from the plant steam cycle.

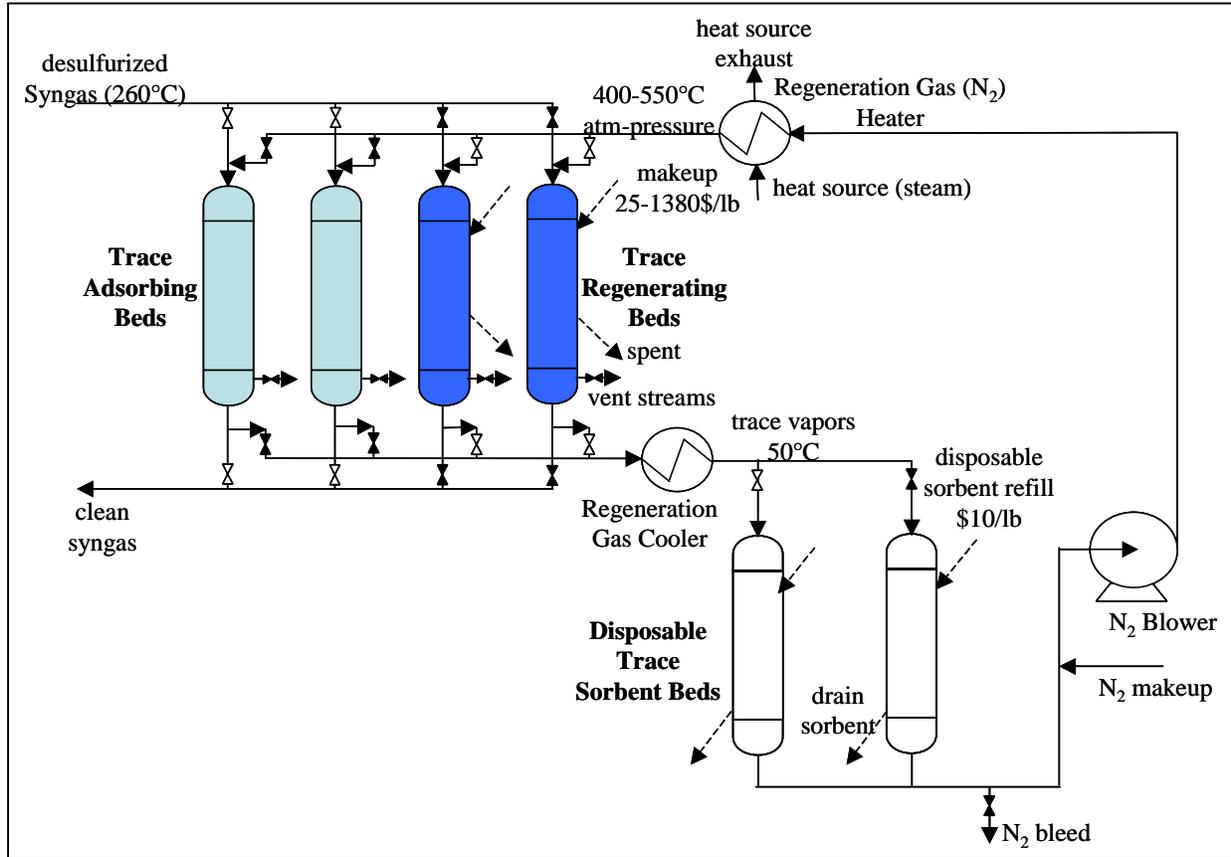


Figure 2: Pd Sorbent Unit Process Flow Diagram

As expected, there are considerable differences in gas flow rates, Hg concentrations and key operating conditions (pressure) between the current application (Hg polishing using Pd sorbents) and previous DOE analysis that considered bulk-removal of Hg using the RTI WGPU technology. In this study, a new set of assumptions about parameters governing the performance of the Pd sorbent unit in the IGCC plant context was developed for the concept of Hg polishing to very low levels. In this context, analysis of how the levelized cost of electricity (LCOE) is affected by the Pd cost, Pd loading in the sorbent, gas hourly space velocity (SV), and sorbent make-up rates has been performed. Given the substantial changes in equipment sizes, rates, and fluctuations in Pd value in recent years, equipment and other capital costs (adsorber pressure vessels constitute an important capital cost element in addition to the sorbent cost) were also updated. The impact of steam consumption, electric loads, and pressure drop due to the Pd sorbent system on power plant performance was quantitatively accounted.

3. Design Rationale for Case Studies

3.1. Description of Case Studies

The most significant parameters affecting the cost of Hg capture are the cost of Pd sorbent, the amount of sorbent in the bed (inversely proportional to the SV), sorbent make-up rate, and the quantity of Pd in the sorbent. The Nexant RTI 2007 Report was used as a basis for LCOE calculations¹. Various cases were devised, summarized in Table 1, to examine the effects of these parameters.

Table 1: Summary of Various Cases

	Pd Sorbent Loading, w/w%²	Pd Price, \$/lb	Space Velocity, h⁻¹	Make-Up Rate, wt% Bed
Case 1a	2	9,500	500 to 13,500	3
Case 1b	2	4,000 to 12,000	8,000	3
Case 2a	2	9,500	500 to 13,500	1
Case 2b	2	4,000 to 12,000	8000	1
Case 3a	5	9,500	500 to 13,500	3
Case 3b	5	4,000 to 12,000	8,000	3
Case 4a	5	9,500	500 to 13,500	1
Case 4b	5	4,000 to 12,000	8,000	1

The base case was designed, in which mid-range values of the parameters are selected and which is expected to represent a reasonable, typical case. This case assumes 2% w/w Pd/alumina sorbent, with an SV of 8,000 h⁻¹, Pd cost of \$9,500/lb (~\$651/troy oz.[trz]), and a sorbent make-up rate of 3%. SVs of 500 to 13,500 h⁻¹ were chosen because preliminary studies revealed that the adsorber volume and cost would increase significantly below 500 h⁻¹. Very little change in adsorber volume was observed with SVs in excess of 15,000 h⁻¹. Palladium sorbent costs were approximated to be those of the pure metal. Pure Pd costs spanning a three+-year (2010-2013) time period were used to obtain the range of variation for Pd cost. Recent pilot plant tests at Southern Company used a 2 w/w% Pd sorbent with an SV of 1,704 h⁻¹; accordingly, 2% and 5% Pd sorbents were used. Bed make-up rates were varied from 3% to 1% of the bed weight. Discussions with NETL indicated that 40% Hg content (wt Hg/wt Pd) at 40% breakthrough was reasonable. The adsorber beds were sized to be 10-feet in diameter for reasonable superficial gas velocities and pressure drops lower than 4%.

3.2. Extent of Hg Capture Needed to Satisfy EPA MATS

The RTI WGPU process was assumed to remove Hg to 5 ppbw in the clean syngas to the turbine. The EPA MATS requirement for Hg emissions is 0.003 lb/GWh gross power output (2 ppbw). For the Nexant RTI Case 4 chosen as the power plant for this study, the gross power output is ~766 MW. Accordingly, the Hg emissions without a polishing step would be 6.93e-3

¹ Case 4, ~641 MW net power, 6.47 cents/kWh LCOE with RTI warm-gas cleanup to 5 ppbw Hg.

² Hg content in bed at 40% breakthrough, is assumed to be 40% wt Hg/wt Pd in all cases.

lb/GWh. Therefore, the extent of Hg removal needed to meet EPA MATS is ~57%. This implies that the Hg breakthrough in the beds would be approximately 40% (~60% capture).

4. Calculation Methodology

A spreadsheet-based model of the Pd sorbent process was developed to account for the new operating conditions and parameters. It is restricted to cases with only Hg adsorption (no co-adsorption of arsenic [As], selenium [Se], phosphorus [P] is considered). The capital and operating & maintenance (O&M) costs of capturing Hg are estimated using bed residence time, Pd price, Pd sorbent weight%, Hg content at breakthrough, and make-up rate as primary input parameters in the spreadsheet. Process simulations for the IGCC plant indicated that the exhaust gas composition and conditions following the turbine are independent of the extent of water-gas shift (WGS) reaction occurring in the Pd sorbent beds. Because plant performance and cost calculations would not be affected, we assumed 0% WGS in the adsorber. The only concern may be that the syngas temperature (288°C at the inlet) may increase further due to WGS, leading to decreased adsorption of Hg at higher bed temperatures.

4.1. Cost of Sorbent

The cost of the Pd sorbent-based Hg removal unit is dominated by the cost of the sorbent itself, because it incorporates a significant quantity of Pd metal with recent spot prices as high as ~\$750/trz (January 2013). However, sorbent fabrication and ongoing refining costs to maintain the sorbent in working order also contribute to capital and O&M costs, respectively, associated with this unit. The amount of Pd initially required for the four sorbent vessels is used to calculate the sorbent cost. This estimate includes ~20% storage/excess sorbent capacity stored onsite.

4.2. Effects of Gas Residence Time, Superficial Velocity, and Pressure Drop

The volume of gas contacted per unit mass of adsorbent, SV/X_{Pd} where SV is the space velocity, and X_{Pd} is the weight percentage of Pd in the sorbent, is a primary parameter affecting the cost of Hg capture. Given a specific value for X_{Pd} , and assuming no mass transfer limitations, higher SV s lead to lower initial sorbent costs. Minimizing the amount of sorbent requires higher gas velocities through the material and/or shorter gas residence times (higher SV s). In applications where a large volume of syngas volumetric flow with low inlet Hg concentrations exists, the required amount of sorbent to provide adequate Hg capture capacity might be relatively low. However, this corresponds to very short gas residence times in the sorbent bed ($\ll 1$ second) in which mass transfer constraints might not allow sufficient capture of Hg. Increasing residence time by decreasing the cross-sectional area of the sorbent beds increases pressure drop in the sorbent beds and the associated energy penalty. Acceptable pressure drop has been assumed to be 4% of the inlet gas pressure. Testing of the Pd sorbent for Hg capture in Southern Company tests (“Palladium Sorbents for High Temperature Capture of Mercury, Arsenic, Selenium and Phosphorus from Fuel Gas,” presented at West Virginia University Seminar, Evan J. Granite, Henry W. Pennline, Erik C. Rupp, John P. Baltrus, Dennis C. Stanko, Bret H. Howard, Chris Guenther, Jenny Tennant – NETL; Hugh Hamilton, Stephen Poulston, Liz Rowsell, Wilson Chu, Andrew Smith – Johnson Matthey; Tony Wu, Subhash Datta, Bob Lambrecht, John Wheeldon –

Southern Company, October 2011) provides some guidance on required operating conditions and parameters (SVs of 1,500 to 3,700 h⁻¹, 150 to 200 pounds per square inch gauge [psig]).

Even a small pressure drop attributable to a Hg polishing sorbent unit could have a negative impact on the overall efficiency of a gas turbine cycle. In the recent baseline IGCC plant Case 1 (as described in the [NETL Bituminous Baseline report](#)), the GE advanced F class turbine is noted to have a requirement for gas feed at 450 pounds per square inch absolute (psia). In this case, syngas was expanded to 460 psia to generate some power before the gas turbine. In earlier baseline (NETL 2007) IGCC plant cases (which Nexant adopted as a baseline for their original analysis), advanced turbines of that time had somewhat lower pressure ratios, which in turn corresponded to lower syngas inlet pressures. Accordingly, the RTI WGPU Case 4 plant cycle analysis had the syngas pressure entering the turbine at 414.7 psia, which was likely just sufficient for turbine operability at that time. In other words, there was no syngas expander present because the gasifier operated at a significantly lower pressure, and after gas cleanup the syngas was already depressed to a suitable gas turbine inlet pressure (414.7 psia). A recent discussion with the GE turbine manufacturer³ confirmed that significant fuel gas pressure drop occurs in the turbine valving, piping, controllers and injection nozzles, and accordingly the pressure specified for the gas turbines (450 psia in the NETL bituminous baseline report [DOE/2010/1397], 414.7 psia in the Nexant 2007 study) must be maintained. Accordingly, in the present analysis, a penalty is taken in the form of a compression duty for recompressing the syngas exiting the adsorbers to the original pressure (414.7 psia), to compensate for any pressure drop due to the Hg polishing unit. If the Nexant study were updated in accordance with latest NETL baseline, reflecting the availability of more advanced turbines and higher gasifier pressure along with a syngas expander upstream from the turbine, then pressure drop associated with addition of the Hg polishing unit would be accounted for by a lower inlet pressure to the expansion turbine (which would result in lower attained turbine output).

5. Results and Discussion

5.1. Effect of Hg Polishing System on Plant Power

The Hg removal system affects plant power output in three main respects: (1) the pressure drop of the syngas through the sorbent vessels for which an energy penalty is taken; (2) the power to operate the regeneration gas circulating blower; and (3) the steam to heat the regeneration gas, which is taken from the main plant steam cycle, causing a decrease in steam turbine output. In order to calculate these accurately, a process model of the IGCC plant was developed in a process simulator, in which syngas flows, steam flows, the gas turbine, steam turbine, and Hg sorbent unit including the regenerator were modeled to a sufficient extent to determine impacts of the Hg polishing system on plant net output. The results of the plant simulation in terms of key impacts of the Hg removal system on plant power are shown in Table 2.

³ Telephone conversation with Jeff Goldmeer (jeffrey.goldmeer@ge.com) of GE Power early February 2012.

Table 2: Effect of Pressure Drop Caused by Hg Polishing System on Net Power Generated

	Baseline Plant	Pd Bed, SV=13,500 h ⁻¹	Pd Bed, SV=4,500 h ⁻¹	Pd Bed, SV=1,500 h ⁻¹	Pd Bed, SV=500 h ⁻¹
Pressure Drop Penalty, MW	None	0.21	0.63	1.94	6.28
N₂ Blower Penalty, MW	None	0.02			
Steam Turbine Output, MW	316.7	316.6			
Net Plant Power, MW	641.0	640.8	640.5	639.8	637.3

The energy penalty from the pressure drop through the Hg vessels is by far the most significant impact. It increases into the several MW range for lower SV values. The 1,000 lb/hr of 538°C steam withdrawn from the steam cycle causes a loss of about 100 kW in the gross output of the steam turbine; it is relatively insignificant because the total steam flow in the cycle is more than 1,000,000 lb/hr. The power to operate the nitrogen (N₂) blower, which provides 2,000 lb/hr of N₂ at 525°C for the regeneration cycles, is negligible at about 20 kW.

5.2. Analysis of Levelized Cost of Electricity

The increase in the LCOE of the IGCC plant and the incremental capital cost (\$/kW) were estimated for all cases, and are shown in Figure 3 and Figure 4. In general, higher values of gas hourly SV and lower Pd costs and loadings lead to lower increases in the LCOE.

As the SV is varied from 500 to 13,500 h⁻¹, keeping the cost of Pd constant at \$651/trz, with 2% wt Pd sorbent, and 3% make-up rate, the percentage increase in LCOE is ~0.3% to 4.3% (Figure 3). The incremental capital cost of the system (including the cost of the sorbent and the cost of the adsorber vessels) increases from ~\$7/kW at SV = 13,500 h⁻¹ to \$104/kW at SV = 500 h⁻¹. Similarly, with 5 wt% Pd sorbent and 3% make-up rate, the increase in LCOE is 0.6% (SV = 13,500 h⁻¹) to 10.7% (SV = 500 h⁻¹), and the incremental capital cost increased from ~\$13/kW (SV = 13,500 h⁻¹) to \$257/kW (SV = 500 h⁻¹). Very little change in the percentage of LCOE increase with the make-up rate for a sorbent utilization value of 40% (wt Hg/wt Pd) in the adsorbers is observed. From Figure 3 it is clear that the optimal values for the gas hourly SV would be ~3,500 to 13,500 h⁻¹.

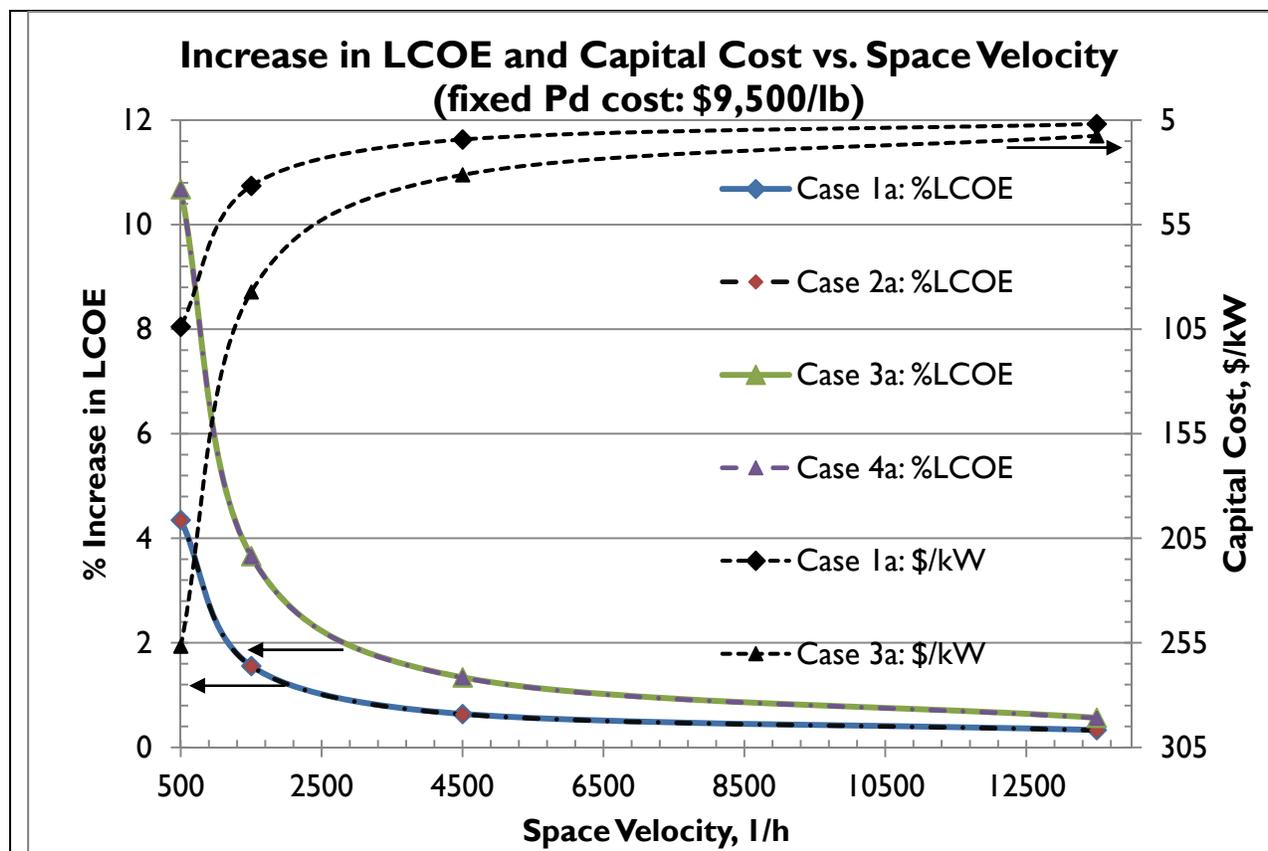


Figure 3: Effect of Varying Space Velocity on Increase in LCOE and Capital Cost for 2% wt Pd Sorbent (Case 1a, Case 2a) and 5% wt Pd Sorbent (Case 3a, Case 4a) and Make-Up Rates of 3% (Case 1a, Case 3a) and 1% (Case 2a, Case 4a). The palladium cost was fixed at \$9,500/lb (\$651/trz).

Figure 4 represents the effect of the cost of Pd on LCOE and the capital cost with 2 wt% and 5 wt% Pd sorbents and 3% and 1% sorbent make-up rates, with a fixed SV of $8,000 \text{ h}^{-1}$. As the cost of Pd is increased from \$274/trz (\sim \$4,000/lb) to \$823/trz (\sim \$12,000/lb), the percentage increase in LCOE increases from 0.3% to 0.5% for 2 wt% Pd sorbent with 3% make-up rate, and from 0.5% to 1% for the 5 wt% Pd sorbent with 3% make-up rate, respectively. The incremental capital cost of the adsorbers (Pd sorbent, vessel cost) is increased from \$6 to \$11/kW for the 2% Pd sorbent, and from \$10 to \$23/kW for the 5 wt% Pd sorbent, respectively. Decreasing the sorbent make-up rate decreases the increase in LCOE, but to an insignificant extent. Changes in sorbent make-up rate do not affect the incremental capital cost in all cases.

For the base case, the performance of the Hg polishing sorbent system (\sim 0.4% increase in LCOE, \sim \$10/kW incremental capital cost for the base case SV = $8,000 \text{ h}^{-1}$, \$9,500/lb Pd, 2 w/w% Pd sorbent, 3% make-up rate) is comparable to that of the carbon-based, low-temperature Hg adsorbers ($<$ 0.4% increased LCOE, \$4 to \$8/kW)⁴. Therefore the Hg polishing system holds significant promise to lower the cost of Hg capture from warm syngas streams.

⁴ See DOE/NETL-2007/1281.

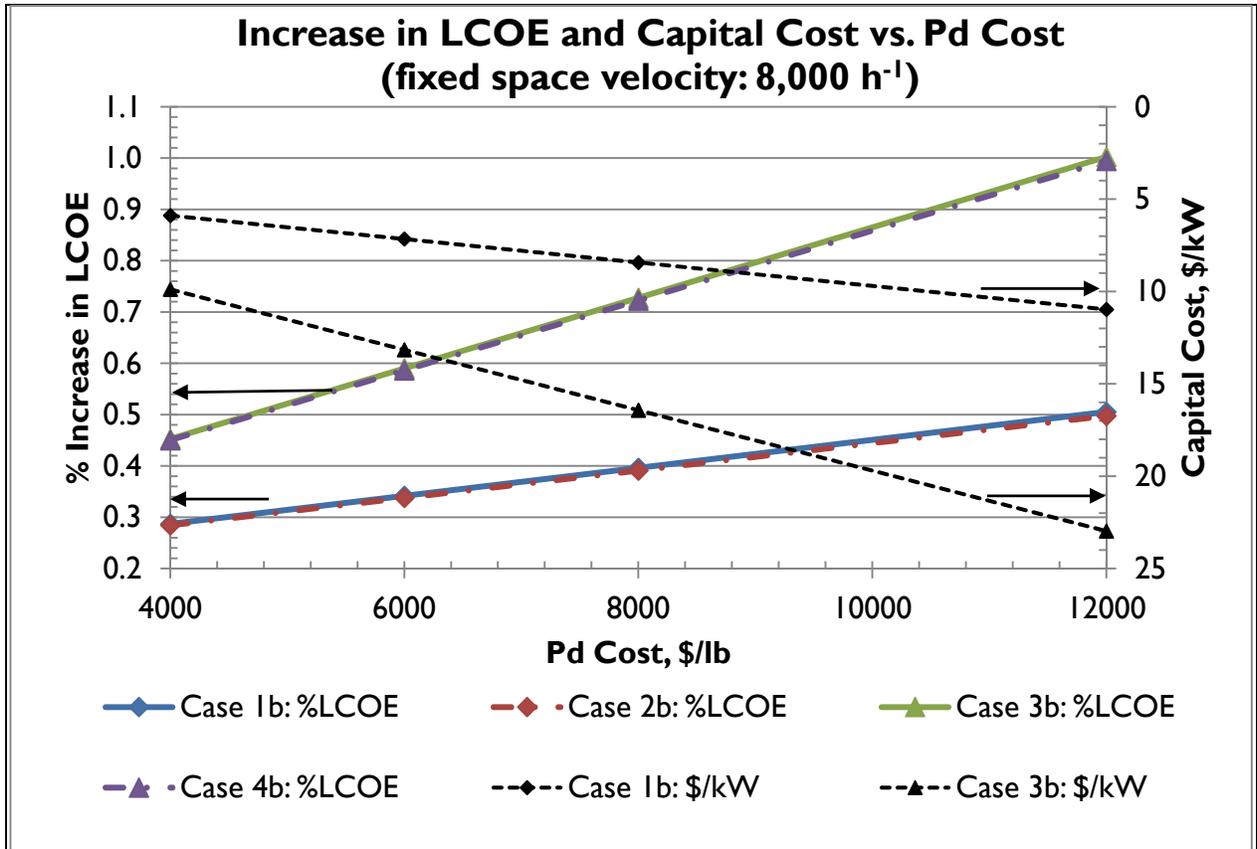


Figure 4: Effects of Pd Cost on Increase in LCOE and Capital Cost for 2% wt Pd Sorbent (Case 1b, Case 2b) and 5% wt Pd Sorbent (Case 3b, Case 4b) and Make-Up Rates of 3% (Case 1b, Case 3b) and 1% (Case 2b, Case 4b). The gas hourly space velocity was fixed at 8,000 h⁻¹.

6. Summary

In this analysis, a number of assumptions, based on experimental results and other studies, were made about Pd sorbent operating characteristics and constraints. To decrease the uncertainty associated with those assumptions, parameters such as Pd cost, SV, sorbent composition, and sorbent make-up rate were varied over possible ranges while observing the effects on performance and costs.

Preliminary results from this study indicate that a Pd sorbent-based polishing system in an IGCC plant with WGPU could be used to reduce trace Hg levels to the new EPA MATS requirements for IGCC power generation in a cost-effective manner. For gas hourly SVs greater than 3500 h⁻¹, COE is elevated less than 2% by addition of the Hg polishing step. For SVs greater than 10,000 h⁻¹, the COE increase continues to improve marginally, but it is likely that Hg mass-transfer limitations may limit the performance of the Pd sorbent system at these higher SVs (high gas velocities and low gas residence times) in the sorbent beds. Accordingly, for a range of SVs from 3,500 h⁻¹ to 10,000 h⁻¹, the Hg polishing step is expected to function adequately and with increase of LCOE limited to about 1-2%. As a comparison, the incremental capital cost of conventional (95%) Hg removal in an IGCC plant is ~\$4 to \$8/kW, with less than 0.4% increase in the LCOE (DOE/2010/1397).

Cost of the Pd sorbent-based polishing system is strongly affected by the cost of the sorbent, which in turn depends primarily upon the cost of Pd. Large and unpredictable fluctuations in the cost of Pd will necessarily have a corresponding impact on the capital cost of a system, as illustrated by case studies in which the price of Pd was varied. For higher SVs, less sorbent and less Pd are required, though as previously discussed there will be practicable limits on how far this can be taken.

Further testing of the Pd sorbent at actual conditions and trace Hg levels in the IGCC Hg polishing scenario would be highly desirable to confirm the assumptions and results of this study. In addition to the use of Pd-based sorbent for polishing (i.e., reducing Hg levels from 5 ppbw to 2 ppbw), the sorbent could also be used for bulk Hg removal from syngas. Finally, the present analysis was restricted to cases assuming only Hg adsorption, so the effects of additional adsorption of arsenic [As], selenium [Se], and phosphorus [P] were not explored. Nevertheless, these may have significant impact on Hg adsorption capacity/characteristics, and so future work should extend to consider the overall behavior of Pd sorbents for simultaneous removal of Hg and these additional pollutant species.

7. References

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