IPM Model – Revisions to Cost and Performance for APC Technologies

Mercury Control Cost Development Methodology

Final

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Systems Research and Applications Corporation

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Mercury Control Cost Development Methodology – Final

Technology Description

Activated carbon injection (ACI) is a viable technology for mercury (Hg) reduction on coal fired boilers. The ACI technology is fairly new but is gaining acceptance. Currently less than 10% of the U.S. coal fired boiler flue gas (based on power produced) is treated for Hg by ACI. Many domestic new and retrofit units require Hg control to meet operating permits in accordance with the limits set forward in state regulations and/or consent decrees. Due to the limits set forth by these regulations, and future legislation, mercury removal of greater than 90% will likely be required. Commercial experience has shown that ACI can meet a 90% reduction in total Hg in some cases.

It should be noted that with the addition of an ACI system, and capture of the carbon in the same particulate collector as the fly ash, beneficial use of the fly ash may be limited. The carbon may prevent sale of the fly ash to the cement markets. Even the “concrete friendly” activated carbons are not well accepted in the cement industry without prior testing by the fly ash purchaser.

Mercury Speciation

Mercury is contained in varying concentrations in different coal supplies. During combustion, mercury is released in the form of elemental mercury. As the combustion gases cool, a portion of the mercury transforms to ionic mercury. Ultimately, there are three possible forms of mercury:

- Elemental (Hg^0),
- Ionic or Oxidized (Hg^{++}), or
- Particulate.

The conversion of elemental mercury to the other forms depends upon several factors; cooling rate of the gas, presence of halogens or SO_3 in the flue gas, amount and composition of fly ash, presence of unburned carbon, and the installed air pollution control equipment.

Considering the interaction of the various parameters, ionic mercury can vary between 10% and 90% of the total mercury in the flue gas. Particulate mercury generally ranges from about 5-15% of the total mercury. The remainder is elemental mercury that typically makes up 10-90% of the total mercury.

Air Pollution Control Equipment Co-Benefits

SCR catalysts promote the oxidation of elemental mercury. However, the extent of oxidation through the SCR catalyst beds can be limited by other factors, such as low flue gas halogen concentrations and amount of catalyst available for Hg oxidation after the ammonia adsorption on surface is minimal. SCR systems may have the ability to convert some elemental mercury to ionic mercury depending on the halide content in the coal. The catalyst used in SCR systems is designed to facilitate the conversion of NO_x to N_2 and H_2O. The active ingredient used in SCR catalysts is vanadium pentoxide, which oxidizes sulfur dioxide (SO_2) to sulfur trioxide (SO_3) as well as elemental mercury to ionic mercury. Mercury oxidation is inhibited by ammonia injection. Typically, most of the mercury oxidation occurs in the last layer of catalyst where the concentration of ammonia is the lowest.

Another mechanism of mercury oxidation occurs across fabric filter elements in a baghouse. Unburned carbon in the fly ash accumulates in the filter cake on the filter elements. The unburned carbon oxidizes Hg^0 to Hg^{++} in the presence of chlorides in the flue gas. The degree of oxidation depends on the quantity of unburned carbon present in the filter cake. The ionic mercury converted in a baghouse could be captured by an FGD system downstream of the baghouse.

Through intimate contact of the flue gas with the filter cake on the fabric filters, mercury can be adsorbed on the carbon particles present in the fly ash. The mercury is bound to the particulates in the filter cake and the particulate mercury is removed at the same efficiency as the solids. For this reason, fabric filters can result in extremely high mercury capture depending on the unburned carbon concentration or can improve the capture with activated carbon injection.

Mercury Capture

The speciation of the mercury plays a significant role in its capture. Elemental mercury is insoluble in water. Therefore, Hg^0 is not collected in downstream FGD systems. Nor do particulate collectors remove elemental mercury. Elemental mercury can be removed with ACI or it must be converted to another form to be captured in downstream FGD systems.

Some flue gas constituents, especially SO_3, reduce the effectiveness of the ACI. With flue gas SO_3 concentrations greater than 5 - 7 ppmv, the carbon feed rate must be increased significantly to meet a high Hg removal and 90% mercury removal may not be feasible in some cases even with ACI. Based on commercial testing, the capacity of the activated carbon can be cut by as much as one half with an SO_3 increase from just 5 ppmv to 10 ppmv. Some utilities are testing the injection of alkali (typically Trona) before the ACI system to reduce the SO_3 concentration. For the purposes of this evaluation, no alkali injection was included. Any benefits from alkali injection would reduce the carbon feed rate and subsequently reduce the costs estimated in this study.

In contrast to elemental mercury, ionic mercury is highly water soluble. In dry FGD systems, the ionic mercury is captured in the injected lime slurry. Dry FGD systems evaporate the liquid phase, allowing the ionic mercury to be removed with the solid by-product in the baghouse. In wet FGD systems, ionic mercury is soluble in the liquid. The captured mercury leaves the system with the purge water or the mercury can bind with the solid phases in the FGD slurry and leave with the solid by-product. Recent commercial data indicates that some of the ionic mercury captured by the wet FGD can be reduced to the elemental form and be re-emitted to the stack under certain circumstances. Extensive testing is on-going to determine the mechanism for re-emission and to develop additives to mitigate the problem. For the purposes of the cost estimation, a wet FGD additive that eliminates re-emission is modeled as an additional variable operating cost.

Particulate mercury is removed very efficiently from the flue gas by the particulate control device. Therefore, it is desirable to convert as much mercury as possible to particulate mercury. High SO_3 levels have been shown to inhibit the binding of ionic mercury to fly ash or carbon. Low halogen levels in the coal will also inhibit formation of particulate mercury by first inhibiting formation of ionic mercury. Activated carbon and addition of halogens increase the conversion of elemental and ionic mercury to particulate mercury.

Establishment of Cost Basis

Commercial experience indicates that wet or dry FGD systems can capture up to 90% of the ionic mercury. SCR catalysts can convert much of the elemental mercury to ionic mercury in the presence of halogens. When an SCR exists and there are relatively high halogen concentrations in the flue gas, about 90% of the mercury will be ionic mercury. Therefore, the maximum capture by an FGD following an SCR would be around 80% of the total mercury if there is no re-emission.

Bituminous coals will have relatively high halogen concentrations in the flue gas. So flue gas mercury from bituminous coals that is treated by an SCR could be approximately 90% ionic mercury. ACI is not required when an FGD system exists downstream of an SCR for bituminous fuels and the required total mercury removal is less than 80%. To ensure full wet FGD co-benefit capture, costs are included to provide slurry additives that inhibit re-emission of the mercury. Both capital and variable O&M costs were included for the slurry additive injection system. If a total mercury removal of greater than 80% is required, an ACI system must be installed and no slurry additives are required. However, alkali injection may be required for SO_3 control to meet the removal requirements with ACI. No costs were included for alkali injection.

Mercury Control Cost Development Methodology – Final

PRB and lignite coals have relatively low halogen concentrations. For those fuels, coal additives are required to promote ionic mercury speciation. With an SCR followed by an FGD and coal additives included, a maximum of 80% total mercury removal could be achieved without an ACI system. Coal additives, for PRB and lignite fuels, are included in the cost estimate when an SCR and an FGD system exist and the total mercury removal is less than 80%. In that case, an ACI system should not be required. The coal additive costs include capital, variable O&M and a one time royalty fee associated with the injection process. If a removal of greater than 80% of the total mercury is required, an ACI system would need to be installed and no coal additives may be required.

When an ACI system is required, the design carbon feed rate will dictate the size of the ACI equipment and the resulting capital costs. The carbon feed rate is a function of required removal, particulate collection device, and in some cases state regulations.

A consistent basis was established to calculate the carbon feed rate. The activated carbon rate was based on the use of brominated carbon. Current industry experience indicates that 5 pounds of carbon injected for every 1,000,000 acfm of flue gas will ensure adequate mercury capture and is a common design target for systems with an ESP. When a baghouse is used to capture the carbon, a reduced feed rate of 2 pounds of carbon injected for every 1,000,000 acfm is generally acceptable. No co-benefit removal was considered in the carbon feed rate. No additional alkali injection was included to remove SO_3 or other inhibitors. In summary:

- 5 lb per 1,000,000 acfm carbon feed rate with an ESP
- 2 lb per 1,000,000 acfm carbon feed rate with a baghouse
- Flue gas rate established after the air preheater
- No co-benefit or other unit operations considered
- No alkali injection considered

To account for all of the variables, the capital cost was established based on the actual anticipated activated carbon feed rate, not the plant power rating. Cost data for several ACI systems was reviewed and a relationship was developed for the capital costs of the system on a carbon feed rate basis.

Another capital cost impact from ACI systems is often the addition of a baghouse to capture the carbon. A baghouse can be required for several reasons:

- The existing ESP cannot remove the additional particulate load associated with the activated carbon injection.
- A new baghouse should be installed whenever flue gas conditioning (SO_3 injection) is required for the existing ESP. Use of flue gas conditioning

indicates that the existing ESP is marginally acceptable for the current solids load and the additional ACI load would result in excessive particulate emissions.

- PRB coals tend to be low in chloride; therefore, most of the flue gas mercury is elemental mercury. Installation of a baghouse can result in varying degrees of oxidation of the elemental mercury through contact with the unburned carbon in the fly ash. The oxidized mercury may be captured in downstream FGD systems. Mercury oxidation does not proceed at the same rate through an ESP.

A polishing baghouse with an air-to-cloth (A/C) ratio of 6.0 should be considered when the baghouse is installed after an existing particulate capture device that will remain in service to capture the majority of the fly ash. The ACI system would be installed downstream of the existing particulate capture device and upstream of the new baghouse. The design has two benefits. First, a smaller capital investment is required for a polishing baghouse when compared to a full sized baghouse. Second, any beneficial use of the fly ash can be maintained.

A full sized baghouse, with an A/C ratio of 4.0, should be specified when the baghouse will be the primary particulate collection device for the fly ash and activated carbon. The lower A/C ratio will provide better bag life with the high inlet particulate loading expected for the single particulate capture device in the process.

Capital costs were developed for the baghouse addition. The option to include a 4.0 A/C or a 6.0 A/C baghouse or not to include a baghouse is left to the user of the cost algorithm. Cost data from the S&L current database of projects, for several different baghouse installations, was reviewed and a relationship was developed for the capital costs of the system on a flue gas rate basis. The capital costs include:

- Duct work modifications,
- Foundations,
- Structural steel,
- ID fan modifications or new booster fans, and
- Electrical modifications.

Methodology

Inputs

Several input variables are required in order to predict the total future retrofit costs:

- Type of coal,
- Unit size,

- Unit heat rate, and
- Baghouse addition option and required size.

A retrofit factor that equates to difficulty in construction of the system must be defined.

Outputs

Total Project Costs (TPC)

First the base installed cost for the complete ACI system is calculated (BMC). Then a base installed cost for the baghouse (as applicable) is calculated (BMB). However, if an ACI system is not needed because of the existing equipment co-benefit capture, some form of additive addition may be required. If a wet FGD is used to remove 90% of the ionic mercury, slurry additives may be required. A base module price for the slurry additives would be included in the capital estimate (BMF). If PRB or lignite is fired, and the total mercury removal is less than 80%, then additional halogens must be added to the coal. The installed capital cost for the coal additive system is included as applicable (BMA). The base installed costs include:

- All equipment;
- Installation;
- Buildings;
- Foundations;
- Electrical; and
- Average retrofit difficulty.

The base installed costs are then increased by:

- Engineering and construction management costs at 5% of the BM cost;
- Labor adjustment for 6 x 10 hour shift premium, per diem, etc., at 5% of the BM cost; and
- Contractor profit and fees at 5% of the BM cost.

A capital, engineering, and construction cost subtotal (CECC) is established as the sum of the BM and the additional engineering and construction fees.

Mercury Control Cost Development Methodology – Final

Additional costs and financing expenditures for the project are computed based on the CECC. Financing and additional project costs include:

- Owner's home office costs (owner's engineering, management, and procurement) at 5% of the CECC; and
- Allowance for Funds Used During Construction (AFUDC) at 0% of the CECC and owner's costs as ACI projects are expected to be completed in less than a year.
- With the addition of a baghouse, 6% of the CECC is added to account for AFUDC based on a complete project duration of 2 years.
- If coal additives are required, based on the type of fuel, existing equipment, and total mercury removal; then a one time royalty fee must be added to the total project cost (C2). The royalty fee is added to the bottom line project cost with no burden allowances.

The total project cost is based on a multiple lump sum contract approach. Should a turnkey engineering procurement construction (EPC) contract be executed, the total project cost would be 10 to 15% higher than what is currently estimated.

Escalation is not included in the estimate. The total project cost (TPC) is the sum of the CECC and the additional costs and financing expenditures.

Fixed O&M (FOM)

The fixed operating and maintenance (O&M) cost is a function of the additional operations staff (FOMO), maintenance labor and materials (FOMM), and administrative labor (FOMA) associated with the ACI installation. The FOM is the sum of the FOMO, FOMM, and FOMA.

The following factors and assumptions underlie calculations of the FOM:

- All of the FOM costs were tabulated on a per kilowatt-year (kW-yr) basis.

- In general, 1 additional operator is required for an ACI system. The FOMO was based on one additional operation staff member.

- The fixed maintenance materials and labor is a direct function of the process capital cost (BM).

- The administrative labor is a function of the FOMO and FOMM.

Variable O&M (VOM)

Variable O&M is a function of:

- Reagent use and unit costs;
- Waste production and unit disposal costs;
- Additional power required and unit power cost; and
- Bag and cage replacement as applicable.

The following factors and assumptions underlie calculations of the VOM:

- All of the VOM costs were tabulated on a per megawatt-hour (MWh) basis.
- The carbon usage is calculated from the unit size and heat rate.
- The carbon waste generation rate is equal to the carbon feed rate.
- When the carbon is captured in the same particulate collector as the fly ash, any fly ash produced may have to be landfilled. As a worst case cost estimate, the entire fly ash amount is included in the waste rate. Typical ash contents for each fuel are used to calculate a total fly ash production rate. The fly ash production is only added to the carbon waste when a new baghouse is not included. With the addition of a new baghouse, the existing particulate collector should remain in operation to capture the fly ash and maintain any beneficial uses.
- Bag and cage replacement every 3 and 9 years respectively for unit operations with 6.0 A/C.
- Bag and cage replacement every 5 and 10 years respectively for unit operations with 4.0 A/C.
- The additional power required includes air blowers for the injection system and power for the baghouse compressors as applicable.
- An allowance for wet FGD additives, to reduce re-emission of the mercury, is included for wet FGD systems with SCRs only.
- An additional allowance is included for PRB or lignite coals. The allowance is based on halogen coal additives to enhance ionic mercury formation with units that have both an FGD and an SCR.

Mercury Control Cost Development Methodology – Final

Input options are provided for the user to adjust the variable O&M costs per unit. Average default values are included in the base estimate. The variable O&M costs per unit options are:

- Carbon cost in $/ton;
- Waste disposal costs in $/ton;
- Auxiliary power cost in $/kWh;
- Bag and cage costs in $/item; and
- Operating labor rate (including all benefits) in $/hr.

The variables that contribute to the overall VOM are:

VOMR = Variable O&M costs for carbon
VOMW = Variable O&M costs for waste disposal
VOMB = Variable O&M costs for bags and cage replacement
VOMF = Variable O&M costs for a wet FGD additive, only applies when there is an SCR, wet FGD system, and less than 80% total mercury capture. In that case, no ACI system is required.
VOMA = Variable O&M costs for a coal additive, only applies when there is an SCR, FGD system, and less than 80% total mercury capture and either PRB or lignite fuel. In that case, no ACI system is required.

The total VOM is the sum of VOMR, VOMW, VOMB, and VOMF and/or VOMA as applicable. The additional auxiliary power requirement is reported as a percentage of the total gross power of the unit.

Table 1 contains an example of the complete capital and O&M cost estimate worksheet when using an existing ESP for the carbon and fly ash capture. Table 2 contains an example of the complete capital and O&M cost estimate worksheet when using an existing baghouse for the carbon and fly ash capture. Table 3 shows the same complete cost methodology except with the addition of a baghouse. Table 4, contains details of an existing SCR and wet FGD system burning PRB coal and requiring less than 80% total mercury removal.

Table 1. Example Complete Cost Estimate for an ACI System with an Existing ESP (Costs are all based on 2009 dollars)

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<--- User Input
Type of Coal	D		Bituminous ▼	<--- User Input
Existing FGD System	E		Wet FGD ▼	<--- User Input
Exisitng SCR	F		☑ TRUE	<--- User Input (Activated carbon may not be required. Co-benefit of SCR and FGD system should achieve 80% removal.)
Removal Less Than 80%?	G		☐ FALSE	<--- User Input
Existing PM Control	H		ESP ▼	<--- User Input
Baghouse Addition	J		Not Added ▼	<--- User Input for retrofit of an additional baghouse after the existing PM control.
Heat Input	K	(Btu/hr)	4.75E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	2,068,502	Downstream of an air preheater For Bituminous Coal = A*C*0.435 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.362
Carbon Feed Rate	M	(lb/hr)	621	= If Existing FGD, SCR, and removal is less than 80% then 0 else L*60*(if Baghouse then 2 else 5)/1000000 Based on 2 lb/MMacf for baghouse applications 5 lb/MMacf for ESP applications Flow determined downstream of an air preheater
Carbon Waste Rate	N	(lb/hr)	621	= M
Fly Ash Waste Rate	P	(ton/hr)	20.7	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7200
Total Waste Rate	Q	(ton/hr)	21.0	Based on no beneficial uses for fly ash with activated carbon without an additional baghouse if J = True or G = True then 0 else P + N/2000
Aux Power	R	**(%)**	**0.12**	if J = True then 0.6 else 0 + (0.1*M/A) **Should be used for model input.**
Carbon Cost	S	($/ton)	1500	
Waste Disposal Cost	T	($/ton)	50	
Aux Power Cost	U	($/kWh)	0.06	
Bag Cost	V	($/bag)	80	
Cage Cost	W	($/cage)	30	
Operating Labor Rate	X	($/hr)	60	Labor cost including all benefits

Capital Cost Calculation	**Example**		**Comments**
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BMC ($) = 1,350,000*B*(M^0.15)	$	3,542,000	Base ACI module includes all equipment from unloading to injection
BMB ($) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 422, J = 4.0 Air-to-Cloth then 476)*B*L^(	$	-	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMF ($) = if there is a wet FGD, SCR, and capture is less than 80% then $500,000 else 0	$	-	Base module for wet FGD additive addition (as applicable)
BMA ($) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then $1,000,000 else 0	$	-	Base module for coal additive addition (as applicable)
BM ($) = BMC + BMB + BMF + BMA	$	3,542,000	Total Base module cost including retrofit factor
BM ($/KW) =		7	Base module cost per kW
Total Project Cost			
A1 = if baghouse addition then 10% else 5% of BM	$	177,000	Engineering and Construction Management costs
A2 = 5% of BM	$	177,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 5% of BM	$	177,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3	**$**	**4,073,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =		**8**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$	204,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = if baghouse addition then 6% else 0% of CECC + B1	$	-	AFUDC For ACI system only: 0% for less than 1 year engineering and construction cycle For additional baghouse: 6% for a 2 year engineering and construction cycle
C2 = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 2500*A else 0	$	-	One time coal additive royalty fee (as applicable)
TPC ($) = CECC + B1 + B2 + C2	**$**	**4,277,000**	Total project cost
TPC ($/kW) =		**9**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW-yr) = (0 additional operators)*2080*X/(A*1000)	$	-	Fixed O&M additional operating labor costs
FOMM ($/kW-yr) = BM*0.005/(B*A*1000)	$	0.04	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW-yr) = 0.03*(FOMO+0.4*FOMM)	$	0.00	Fixed O&M additional administrative labor costs
FOM ($/kW-yr) = FOMO + FOMM + FOMA	**$**	**0.04**	Total Fixed O&M costs
Variable O&M Cost			
VOMR ($/MWh) = M*S/(2000*A)	$	0.93	Variable O&M costs for carbon sorbent
VOMW ($/MWh) = Q*T/A	$	2.10	Variable O&M costs for waste disposal that includes the carbon and the fly ash waste as applicable
VOMB ($/MWh) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 0.004, J = 4.0 Air-to-Cloth then 0.005) *(V/3+W/9)	$	-	Variable O&M costs for bags and cages.
VOMF ($/MWh) = if there is a wet FGD, SCR, and capture is less than 80% then 115/A else 0	$	-	Variable O&M costs for wet FGD additive addition
VOMA ($/MWh) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 290/A else 0	$	-	Variable O&M costs for coal additive addition
VOM ($/MWh) = VOMR + VOMW + VOMB + VOMF + VOMC	**$**	**3.04**	

Mercury Control Cost Development Methodology – Final

Table 2. Example Complete Cost Estimate for an ACI System with an Existing Baghouse (Costs are all based on 2009 dollars)

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<--- User Input
Type of Coal	D		Bituminous	<--- User Input
Existing FGD System	E		Wet FGD	<--- User Input
Exisitng SCR	F		☑ TRUE	<--- User Input (Activated carbon may not be required. Co-benefit of SCR and FGD system should achieve 80% removal.)
Removal Less Than 80%?	G		☐ FALSE	<--- User Input
Existing PM Control	H		Baghouse	<--- User Input
Baghouse Addition	J		Not Added	<--- User Input for retrofit of an additional baghouse after the existing PM control.
Heat Input	K	(Btu/hr)	4.75E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	2,068,502	Downstream of an air preheater For Bituminous Coal = A*C*0.435 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.362
Carbon Feed Rate	M	(lb/hr)	248	= If Existing FGD, SCR, and removal is less than 80% then 0 else L*60*(if Baghouse then 2 else 5)/1000000 Based on 2 lb/MMacf for baghouse applications 5 lb/MMacf for ESP applications Flow determined downstream of an air preheater
Carbon Waste Rate	N	(lb/hr)	248	= M
Fly Ash Waste Rate	P	(ton/hr)	20.7	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7200
Total Waste Rate	Q	(ton/hr)	20.9	Based on no beneficial uses for fly ash with activated carbon without an additional baghouse if J = True or G = True then 0 else P + N/2000
Aux Power	R	**(%)**	**0.05**	if J = True then 0.6 else 0 + (0.1*M/A) **Should be used for model input.**
Carbon Cost	S	($/ton)	1500	
Waste Disposal Cost	T	($/ton)	50	
Aux Power Cost	U	($/kWh)	0.06	
Bag Cost	V	($/bag)	80	
Cage Cost	W	($/cage)	30	
Operating Labor Rate	X	($/hr)	60	Labor cost including all benefits

Capital Cost Calculation	**Example**		**Comments**
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BMC ($) = 1,350,000*B*(M^0.15)	$	3,087,000	Base ACI module includes all equipment from unloading to injection
BMB ($) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 422, J = 4.0 Air-to-Cloth then 476)*B*L^0	$	-	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMF ($) = if there is a wet FGD, SCR, and capture is less than 80% then $500,000 else 0	$	-	Base module for wet FGD additive addition (as applicable)
BMA ($) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then $1,000,000 else 0	$	-	Base module for coal additive addition (as applicable)
BM ($) = BMC + BMB + BMF + BMA	$	3,087,000	Total Base module cost including retrofit factor
BM ($/KW) =		6	Base module cost per kW
Total Project Cost			
A1 = if baghouse addition then 10% else 5% of BM	$	154,000	Engineering and Construction Management costs
A2 = 5% of BM	$	154,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 5% of BM	$	154,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3	**$**	**3,549,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =		**7**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$	177,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = if baghouse addition then 6% else 0% of CECC + B1	$	-	AFUDC For ACI system only: 0% for less than 1 year engineering and construction cycle For additional baghouse: 6% for a 2 year engineering and construction cycle
C2 = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 2500*A else 0	$	-	One time coal additive royalty fee (as applicable)
TPC ($) = CECC + B1 + B2 + C2	**$**	**3,726,000**	Total project cost
TPC ($/kW) =		**7**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW-yr) = (0 additional operators)*2080*X/(A*1000)	$	-	Fixed O&M additional operating labor costs
FOMM ($/kW-yr) = BM*0.005/(B*A*1000)	$	0.03	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW-yr) = 0.03*(FOMO+0.4*FOMM)	$	0.00	Fixed O&M additional administrative labor costs
FOM ($/kW-yr) = FOMO + FOMM + FOMA	**$**	**0.03**	Total Fixed O&M costs
Variable O&M Cost			
VOMR ($/MWh) = M*S/(2000*A)	$	0.37	Variable O&M costs for carbon sorbent
VOMW ($/MWh) = Q*T/A	$	2.09	Variable O&M costs for waste disposal that includes the carbon and the fly ash waste as applicable
VOMB ($/MWh) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 0.004, J = 4.0 Air-to-Cloth then 0.005) *(V/3+W/9)	$	-	Variable O&M costs for bags and cages.
VOMF ($/MWh) = if there is a wet FGD, SCR, and capture is less than 80% then 115/A else 0	$	-	Variable O&M costs for wet FGD additive addition
VOMA ($/MWh) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 290/A else 0	$	-	Variable O&M costs for coal additive addition
VOM ($/MWh) = VOMR + VOMW + VOMB + VOMF + VOMC	**$**	**2.46**	

Table 3. Example Complete Cost Estimate for an ACI System with an Additional Baghouse (Costs are all based on 2009 dollars)

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<--- User Input
Type of Coal	D		Bituminous	<--- User Input
Existing FGD System	E		Wet FGD	<--- User Input
Exisitng SCR	F		☑ TRUE	<--- User Input (Activated carbon may not be required. Co-benefit of SCR and FGD system should achieve 80% removal.)
Removal Less Than 80%?	G		☐ FALSE	<--- User Input
Existing PM Control	H		ESP	<--- User Input
Baghouse Addition	J		6.0 Air-to-Cloth	<--- User Input for retrofit of an additional baghouse after the existing PM control.
Heat Input	K	(Btu/hr)	4.75E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	2,068,502	Downstream of an air preheater For Bituminous Coal = A*C*0.435 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.362
Carbon Feed Rate	M	(lb/hr)	248	= If Existing FGD, SCR, and removal is less than 80% then 0 else L*60*(if Baghouse then 2 else 5)/1000000 Based on 2 lb/MMacf for baghouse applications 5 lb/MMacf for ESP applications Flow determined downstream of an air preheater
Carbon Waste Rate	N	(lb/hr)	248	= M
Fly Ash Waste Rate	P	(ton/hr)	20.7	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7200
Total Waste Rate	Q	(ton/hr)	0.1	Based on no beneficial uses for fly ash with activated carbon without an additional baghouse if J = True or G = True then 0 else P + N/2000
Aux Power	R	**(%)**	**0.65**	if J = True then 0.6 else 0 + (0.1*M/A) **Should be used for model input.**
Carbon Cost	S	($/ton)	1500	
Waste Disposal Cost	T	($/ton)	50	
Aux Power Cost	U	($/kWh)	0.06	
Bag Cost	V	($/bag)	80	
Cage Cost	W	($/cage)	30	
Operating Labor Rate	X	($/hr)	60	Labor cost including all benefits

		Example	Comments
Capital Cost Calculation			
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BMC ($) = 1,350,000*B*(M^0.15)	$	3,087,000	Base ACI module includes all equipment from unloading to injection
BMB ($) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 422, J = 4.0 Air-to-Cloth then 476)*B*L^C	$	55,080,000	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMF ($) = if there is a wet FGD, SCR, and capture is less than 80% then $500,000 else 0	$	-	Base module for wet FGD additive addition (as applicable)
BMA ($) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then $1,000,000 else 0	$	-	Base module for coal additive addition (as applicable)
BM ($) = BMC + BMB + BMF + BMA	$	58,167,000	Total Base module cost including retrofit factor
BM ($/KW) =		116	Base module cost per kW
Total Project Cost			
A1 = if baghouse addition then 10% else 5% of BM	$	5,817,000	Engineering and Construction Management costs
A2 = 5% of BM	$	2,908,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 5% of BM	$	2,908,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3	**$**	**69,800,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =		**140**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$	3,490,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = if baghouse addition then 6% else 0% of CECC + B1	$	4,397,000	AFUDC For ACI system only: 0% for less than 1 year engineering and construction cycle For additional baghouse: 6% for a 2 year engineering and construction cycle
C2 = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 2500*A else 0	$	-	One time coal additive royalty fee (as applicable)
TPC ($) = CECC + B1 + B2 + C2	**$**	**77,687,000**	Total project cost
TPC ($/kW) =		**155**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW-yr) = (0 additional operators)*2080*X/(A*1000)	$	-	Fixed O&M additional operating labor costs
FOMM ($/kW-yr) = BM*0.005/(B*A*1000)	$	0.58	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW-yr) = 0.03*(FOMO+0.4*FOMM)	$	0.01	Fixed O&M additional administrative labor costs
FOM ($/kW-yr) = FOMO + FOMM + FOMA	**$**	**0.59**	Total Fixed O&M costs
Variable O&M Cost			
VOMR ($/MWh) = M*S/(2000*A)	$	0.37	Variable O&M costs for carbon sorbent
VOMW ($/MWh) = Q*T/A	$	0.01	Variable O&M costs for waste disposal that includes the carbon and the fly ash waste as applicable
VOMB ($/MWh) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 0.004, J = 4.0 Air-to-Cloth then 0.005) *(V/3+W/9)	$	0.12	Variable O&M costs for bags and cages.
VOMF ($/MWh) = if there is a wet FGD, SCR, and capture is less than 80% then 115/A else 0	$	-	Variable O&M costs for wet FGD additive addition
VOMA ($/MWh) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 290/A else 0	$	-	Variable O&M costs for coal additive addition
VOM ($/MWh) = VOMR + VOMW + VOMB + VOMF + VOMC	**$**	**0.50**	

Table 4. Example Complete Cost Estimate for both Additives Systems without ACI (Costs are all based on 2009 dollars)

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	10500	<--- User Input
Type of Coal	D		PRB	<--- User Input
Existing FGD System	E		Wet FGD	<--- User Input
Exisitng SCR	F		☑ TRUE	<--- User Input (Activated carbon may not be required. Co-benefit of SCR and FGD system should achieve 80% removal.)
Removal Less Than 80%?	G		☑ TRUE	<--- User Input (Activated carbon is not required for caputre less than 80%.)
Existing PM Control	H		ESP	<--- User Input
Baghouse Addition	J		Not Added	<--- User Input for retrofit of an additional baghouse after the existing PM control.
Heat Input	K	(Btu/hr)	5.25E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	2,099,251	Downstream of an air preheater For Bituminous Coal = A*C*0.435 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.362
Carbon Feed Rate	M	(lb/hr)	0	= If Existing FGD, SCR, and removal is less than 80% then 0 else L*60*(if Baghouse then 2 else 5)/1000000 Based on 2 lb/MMacf for baghouse applications 5 lb/MMacf for ESP applications Flow determined downstream of an air preheater
Carbon Waste Rate	N	(lb/hr)	0	= M
Fly Ash Waste Rate	P	(ton/hr)	15.0	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7200
Total Waste Rate	Q	(ton/hr)	0.0	Based on no beneficial uses for fly ash with activated carbon without an additional baghouse if J = True or G = True then 0 else P + N/2000
Aux Power	R	**(%)**	**0.00**	if J = True then 0.6 else 0 + (0.1*M/A) **Should be used for model input.**
Carbon Cost	S	($/ton)	1500	
Waste Disposal Cost	T	($/ton)	50	
Aux Power Cost	U	($/kWh)	0.06	
Bag Cost	V	($/bag)	80	
Cage Cost	W	($/cage)	30	
Operating Labor Rate	X	($/hr)	60	Labor cost including all benefits

Capital Cost Calculation		**Example**		**Comments**
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty				
BMC ($) =	1,350,000*B*(M^0.15)	$	-	Base ACI module includes all equipment from unloading to injection
BMB ($) =	if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 422, J = 4.0 Air-to-Cloth then 476)*B*L^C	$	-	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMF ($) =	if there is a wet FGD, SCR, and capture is less than 80% then $500,000 else 0	$	500,000	Base module for wet FGD additive addition (as applicable)
BMA ($) =	if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then $1,000,000 else 0	$	1,000,000	Base module for coal additive addition (as applicable)
BM ($) =	BMC + BMB + BMF + BMA	$	1,500,000	Total Base module cost including retrofit factor
BM ($/KW) =			3	Base module cost per kW
Total Project Cost				
A1 = if baghouse addition then 10% else 5% of BM		$	75,000	Engineering and Construction Management costs
A2 = 5% of BM		$	75,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 5% of BM		$	75,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3		**$**	**1,725,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =			**3**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC		$	86,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = if baghouse addition then 6% else 0% of CECC + B1		$	-	AFUDC For ACI system only: 0% for less than 1 year engineering and construction cycle For additional baghouse: 6% for a 2 year engineering and construction cycle
C2 = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 2500*A else 0		$	1,250,000	One time coal additive royalty fee (as applicable)
TPC ($) = CECC + B1 + B2 + C2		**$**	**3,061,000**	Total project cost
TPC ($/kW) =			**6**	Total project cost per kW
Fixed O&M Cost				
FOMO ($/kW-yr) = (0 additional operators)*2080*X/(A*1000)		$	-	Fixed O&M additional operating labor costs
FOMM ($/kW-yr) = BM*0.005/(B*A*1000)		$	0.02	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW-yr) = 0.03*(FOMO+0.4*FOMM)		$	0.00	Fixed O&M additional administrative labor costs
FOM ($/kW-yr) = FOMO + FOMM + FOMA		**$**	**0.02**	Total Fixed O&M costs
Variable O&M Cost				
VOMR ($/MWh) = M*S/(2000*A)		$	-	Variable O&M costs for carbon sorbent
VOMW ($/MWh) = Q*T/A		$	-	Variable O&M costs for waste disposal that includes the carbon and the fly ash waste as applicable
VOMB ($/MWh) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 0.004, J = 4.0 Air-to-Cloth then 0.005) *(V/3+W/9)		$	-	Variable O&M costs for bags and cages.
VOMF ($/MWh) = if there is a wet FGD, SCR, and capture is less than 80% then 115/A else 0		$	0.23	Variable O&M costs for wet FGD additive addition
VOMA ($/MWh) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 290/A else 0		$	0.58	Variable O&M costs for coal additive addition
VOM ($/MWh) = VOMR + VOMW + VOMB + VOMF + VOMC		**$**	**0.81**	

Mercury Control Cost Development Methodology – Final

Table 5. Example Complete Cost Estimate for Coal Additives without ACI (Costs are all based on 2009 dollars)

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	10500	<--- User Input
Type of Coal	D		PRB	<--- User Input
Existing FGD System	E		Dry FGD	<--- User Input
Exisitng SCR	F		☑ TRUE	<--- User Input (Activated carbon may not be required. Co-benefit of SCR and FGD system should achieve 80% removal.)
Removal Less Than 80%?	G		☑ TRUE	<--- User Input (Activated carbon is not required for caputre less than 80%.)
Existing PM Control	H		ESP	<--- User Input
Baghouse Addition	J		Not Added	<--- User Input for retrofit of an additional baghouse after the existing PM control.
Heat Input	K	(Btu/hr)	5.25E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	2,099,251	Downstream of an air preheater For Bituminous Coal = A*C*0.435 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.362
Carbon Feed Rate	M	(lb/hr)	0	= If Existing FGD, SCR, and removal is less than 80% then 0 else L*60*(if Baghouse then 2 else 5)/1000000 Based on 2 lb/MMacf for baghouse applications 5 lb/MMacf for ESP applications Flow determined downstream of an air preheater
Carbon Waste Rate	N	(lb/hr)	0	= M
Fly Ash Waste Rate	P	(ton/hr)	15.0	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7200
Total Waste Rate	Q	(ton/hr)	0.0	Based on no beneficial uses for fly ash with activated carbon without an additional baghouse if J = True or G = True then 0 else P + N/2000
Aux Power	**R**	**(%)**	**0.00**	if J = True then 0.6 else 0 + (0.1*M/A) **Should be used for model input.**
Carbon Cost	S	($/ton)	1500	
Waste Disposal Cost	T	($/ton)	50	
Aux Power Cost	U	($/kWh)	0.06	
Bag Cost	V	($/bag)	80	
Cage Cost	W	($/cage)	30	
Operating Labor Rate	X	($/hr)	60	Labor cost including all benefits

Capital Cost Calculation	**Example**	**Comments**
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty		
BMC ($) = 1,350,000*B*(M^0.15)	$ -	Base ACI module includes all equipment from unloading to injection
BMB ($) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 422, J = 4.0 Air-to-Cloth then 476)*B*L^0	$ -	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMF ($) = if there is a wet FGD, SCR, and capture is less than 80% then $500,000 else 0	$ -	Base module for wet FGD additive addition (as applicable)
BMA ($) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then $1,000,000 else 0	$ 1,000,000	Base module for coal additive addition (as applicable)
BM ($) = BMC + BMB + BMF + BMA	$ 1,000,000	Total Base module cost including retrofit factor
BM ($/KW) =	2	Base module cost per kW
Total Project Cost		
A1 = if baghouse addition then 10% else 5% of BM	$ 50,000	Engineering and Construction Management costs
A2 = 5% of BM	$ 50,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 5% of BM	$ 50,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3	**$ 1,150,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =	**2**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$ 58,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = if baghouse addition then 6% else 0% of CECC + B1	$ -	AFUDC For ACI system only: 0% for less than 1 year engineering and construction cycle For additional baghouse: 6% for a 2 year engineering and construction cycle
C2 = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 2500*A else 0	$ 1,250,000	One time coal additive royalty fee (as applicable)
TPC ($) = CECC + B1 + B2 + C2	**$ 2,458,000**	Total project cost
TPC ($/kW) =	**5**	Total project cost per kW
Fixed O&M Cost		
FOMO ($/kW-yr) = (0 additional operators)*2080*X/(A*1000)	$ -	Fixed O&M additional operating labor costs
FOMM ($/kW-yr) = BM*0.005/(B*A*1000)	$ 0.01	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW-yr) = 0.03*(FOMO+0.4*FOMM)	$ 0.00	Fixed O&M additional administrative labor costs
FOM ($/kW-yr) = FOMO + FOMM + FOMA	**$ 0.01**	Total Fixed O&M costs
Variable O&M Cost		
VOMR ($/MWh) = M*S/(2000*A)	$ -	Variable O&M costs for carbon sorbent
VOMW ($/MWh) = Q*T/A	$ -	Variable O&M costs for waste disposal that includes the carbon and the fly ash waste as applicable
VOMB ($/MWh) = if(J = Not Added then 0, J = 6.0 Air-to-Cloth then 0.004, J = 4.0 Air-to-Cloth then 0.005) *(V/3+W/9)	$ -	Variable O&M costs for bags and cages.
VOMF ($/MWh) = if there is a wet FGD, SCR, and capture is less than 80% then 115/A else 0	$ -	Variable O&M costs for wet FGD additive addition
VOMA ($/MWh) = if there is an FGD, SCR, the coal is PRB or Lignite, and captures is less than 80% then 290/A else 0	$ 0.58	Variable O&M costs for coal additive addition
VOM ($/MWh) = VOMR + VOMW + VOMB + VOMF + VOMC	**$ 0.58**	