Evaluation of Air Pollution Control Costs for the Pulp and Paper Industry

Submitted to

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Background

Stone & Webster Management Consultants, Inc. ("Stone & Webster") was retained by National Economic Research Associates ("NERA") to evaluate the capital and operating costs of various air pollution control options for coal and wood waste fired boilers at pulp and paper mills. NERA is supporting the American Forest and Paper Association ("AF&PA") in its evaluation of the cost to the pulp and paper industry of compliance with pending air emissions regulations and proposed multi-pollutant legislation such as the Clear Skies Initiative. NERA is using the results from Stone & Webster's air pollution control cost evaluation in its analysis for AF&PA.

Stone & Webster evaluated the capital and operating cost of the eight different equipment configuration scenarios shown in Table 1. Stack emissions controls for particulate matter ("PM"), sulfur dioxide ("SO2"), nitrous oxides ("NOx"), and mercury ("Hg") were investigated for a pulverized coal ("PC") fired boiler producing 300,000 lb/hr of steam. In addition, PM control only options were investigated for a stoker-fired waste wood boiler that produces 300,000 lb/hr of steam. Electrostatic precipitators ("ESPs"), fabric filter collectors (baghouses), sodium-based SO2 scrubbing, selective catalytic reduction ("SCR"), and activated carbon injection technologies were evaluated. Before and after pollutant emission amounts were provided by NERA as listed on Table 1.

Reference Power Plants

Two reference power plants were developed as the basis for the air pollution control cost estimates. The key characteristics of these reference plants are described in Tables 2 through 5. For purposes of our evaluation, the reference power plants were assumed to be located at a pulp and paper mill in southeastern United States.

A key assumption in our evaluation was the type and quality of the fuel fired in the reference boilers. The coal-fired boiler facility is assumed to burn a high quality eastern bituminous coal with 0.5 to 1.5% sulfur content, as described in Table 2. The wood-fired boiler facility fires a waste wood with 50% moisture content and a typical heating value of 4,500 Btu/lb (as fired, higher heating value), as described in Table 3.

The coal-fired boiler has a heat input of 350.0 mmBtu/hr, which corresponds to an 86% thermal efficiency. This boiler produces 129,500 acfm-wet of flue gas at 350 deg F at the entrance to the emissions control equipment. It was assumed that the existing plant has a small ESP for emissions control which provides only 98.68% PM collection efficiency, as listed on Table 4.

The waste wood-fired boiler (Table 5) has a heat input of 423.4 mmBtu/hr, which corresponds to 70% thermal efficiency. This boiler produces 196,060 acfm-wet of flue gas at 350 deg F at the entrance to the emissions control equipment. It is assumed that the existing plant has either a small ESP or a wet venturi scrubber for PM emissions control.

Emissions Control Scenarios

Tables 6 through 13 describe the eight emissions control scenarios under investigation, including the control equipment's design parameters, stack emissions, operating parameters (such as power consumption, reagent consumption, etc.), and a list of balance-of-plant considerations for each case.

The ESP retrofit scenarios (Cases A and D, covered on Tables 6 and 9 respectively) assume that the existing ESP or venturi scrubber will be demolished and a new enlarged ESP with associated fluework retrofitted on site while using the existing ID fan. The fabric filter retrofit scenarios (Cases B and H, Tables 7 and 13 respectively) assume that the existing ESP will be demolished and a new pulse-jet fabric filter retrofitted onsite. The pulse-jet collector will utilize felted Ryton (Torcon) filter bags. Because of the significant system pressure loss impact due to a fabric filter retrofit, determined to be 7.0 in WC for this scenario, the retrofit of a new ID fan becomes necessary.

The ESP upgrade scenarios (Cases C and E, Tables 8 and 10 respectively) assume that the existing low efficiency ESP will be gutted and rebuilt with new state-of-the-art collection internals. Concurrently, the height of the ESP's collecting plates would be increased and a new mechanical field retrofitted onto the back end of the ESP casing.

The SO2 scrubber retrofit (Case F) assumes the following:

- Retain the existing ESP for PM control
- Retrofit the scrubber downstream of the ESP
- Sodium hydroxide (NaOH) to be used as the scrubbing reagent
- A single 15 ft diameter by 45 ft high absorber vessel
- 316L stainless steel construction for all saturated gas components
- Retrofit of a new wet ID fan
- Retrofit of a new 200 ft tall wet stack.

The SCR retrofit scenario (Case G and Table 12) assumes that the SCR will be installed downstream of the boiler's economizer, where flue gas temperature ranges from 675 to 750 deg F, and will be equipped with provisions for flue gas bypass and catalyst bed temperature modulation. SCRs use anhydrous ammonia as a reagent to reduce NOx to N2 and H2O; ammonia is injected in vapor phase into the flue gas stream upstream of the SCR catalyst, and NOx is destroyed as it passes through the multiple layers of catalyst. Concurrent with an SCR retrofit will be the change-out of air heater baskets to a basket design that is less prone to ammonium sulfate plugging, and also the retrofit of a new ID fan.

The activated carbon injection system (Case H and Table 13) for Hg emissions control encompasses the retrofit of both an activated carbon storage/delivery system as well as a pulse-jet fabric filter collector. Activated carbon is stored onsite in a 90 day silo, and injected dry into the flue situated between the air heater outlet and the fabric filter collector inlet.

It was assumed that both the reference coal and wood-fired boilers had either no continuous emissions monitoring ("CEM") equipment or CEMs that will not be in compliance with the new air quality regulations. Consequently, new CEM equipment was assumed for all the cases. The basic CEM configuration consists of NOx, SO2, CO2, O2 analyzers, a flow meter, and an electronic data reporting system.

Capital and Operating Costs

Presented in Table 14 are the economic factors used in the capital and operating cost analyses described below.

Capital cost estimates were developed for each case, and all capital cost components are listed on Table 15. The base capital cost for each case assumes that the owner will act as the construction manager for the retrofit. The alternate capital cost is based on a single engineering, procurement and construction ("EPC") contractor being retained by the owner to perform the retrofit. The alternate case includes additional costs associated with the EPC contractor's margin.

In developing the retrofit capital costs, it was assumed that the pulp mill site is congested and that a moderate to difficult retrofit factor is most appropriate when developing equipment installation costs. At the bottom of Table 15 are capital cost estimates in units $ per kW (electric equivalent) and $ per kLbs/hr of steam, assuming that the reference plant is generating 35 MWe. These cost factors range from a low of $90/kW for Cases C and E, the ESP upgrade cases, to a high of $224/kW for Case F, the sodium-based scrubber retrofit.

The development of annual O&M cost estimates is shown on Table 16. These estimates are representative of a first year O&M cost. However, when a consumable such as SCR catalyst is to be changed out after each four years of equipment operation, this cost was averaged on a per year basis and shown as an annual amount. Footnotes to the table identify where this cost-averaging technique was used. Annual O&M costs ranged from a low of $65,010 for Case C (the coal-fired boiler ESP upgrade) to a high of $1.99 million for Case F (the sodium-based scrubber retrofit).

The estimated capital and operating costs are listed below and presented in detail in Tables 15 and 16.

	Base Case Capital Cost ($000)	**Annual Operating Cost ($000/year)**
Case A: Coal boiler, 300,000 lb/hr steam, new ESP	$4,725	$72
Case B: Coal boiler, 300,000 lb/hr steam, new baghouse	$5,877	$194
Case C: Coal boiler, 300,000 lb/hr steam, upgraded ESP	$3,162	$65
Case D: Wood boiler, 300,000 lb/hr steam, new ESP	$5,080	$77
Case E: Wood boiler, 300,000 lb/hr steam, upgraded ESP	$3,162	$67
Case F: Coal boiler, 300,000 lb/hr steam, scrubber for 90% SO2 removal	$7,844	$1,993
Case G: Coal boiler, 300,000 lb/hr steam, SCR for NOX	$6,440	$301
Case H: Coal boiler, 300,000 lb/hr steam, carbon injection/fabric filter	$6,295	$222

Finally, Table 17 shows the results of a parameterization study of SO2 emissions versus annual O&M cost for the sodium-based scrubber (Case F). This study was conducted for three SO2 collection efficiencies, 90%, 80% and 70%, which are in addition to the scrubber's base efficiency of 94.55% as covered on Table 16.

Table 1 - Units and Control Equipment to be Evaluated

Case	Boiler	Fuel	lb/hr Steam	Pollutant	Control Scheme	Emissions (lb/mmBtu) Before	After
A	p-c	Coal	300,000	PM	Retrofit ESP	0.25	0.065
B	p-c	Coal	300,000	PM	Retrofit Fabric Filter	0.25	0.020
C	p-c	Coal	300,000	PM	Upgrade ESP	0.10	0.065
D	Stoker	Wood	300,000	PM	Retrofit ESP	0.25	0.065
E	Stoker	Wood	300,000	PM	Upgrade ESP	0.10	0.065
F	p-c	Coal	300,000	SO2	Sodium Scrubber	2.2(Max)	<0.12
G	p-c	Coal	300,000	NOx	SCR	0.85	0.17
H	p-c	Coal	300,000	Hg	Carbon Injection + FF	8.76 lb/trillionBtu	3.50 lb/trillionBtu

Table 2 - Eastern Bituminous Coal Analysis

Ultimate Fuel Analysis (%)

Parameter	Typical	Range
Carbon	72.7	68.0 to 81.0
Moisture	6.0	4.0 to 15.0
Hydrogen	4.9	3.4 to 5.8
Oxygen	6.0	3.4 to 10.0
Nitrogen	1.2	1.0 to 2.0
Chlorine	0.1	0.1 to 0.3
Sulfur	1.2	0.5 to 1.5
Ash	8.0	6.0 to 12.0
HHV (Btu/lb)	13,200	12,900 to 13,635

Ash Analysis (%)

Parameter	Typical	Range
SiO2	44.0	30.0 to 58.0
Fe2O3	7.0	2.9 to 45.0
Al2O3	28.0	18.0 to 36.0
TiO2	1.0	0.3 to 3.0
CaO	7.0	0.9 to 9.0
MgO	2.0	0.2 to 2.0
SiO3	6.0	0.1 to 7.0
K2O	1.5	0.4 to 4.0
Na2O	0.5	0.2 to 2.0
P2O5	0.5	0.04 to 3.0
Undetermined	2.5	

Note: Mercury content in whole coal is 0.113 ppmw, of which 60% is oxidized and 40% is elemental.

Table 3 - Wastewood Analysis

Ultimate Fuel Analysis (%)

Parameter	Typical	Range
Carbon	26.7	24.8 to 26.7
Moisture	50.0	45.0 to 55.0
Hydrogen	2.8	2.5 to 2.9
Oxygen	18.8	18.8 to 21.2
Nitrogen	0.1	0.05 to 0.1
Chlorine	100 ppmv	Trace to 100 ppmv
Sulfur	0.1	0.05 to 0.1
Ash	1.5	0.2 to 2.7
HHV (Btu/lb)	4,500	4,185 to 4,515

Ash Analysis (%)

Parameter	Typical	Range
SiO_2	39.0	11.1 to 39.0
Fe_2O_3	3.0	3.0 to 6.4
Al_2O_3	14.0	0.1 to 14.0
TiO_2	0.2	0.1 to 0.8
CaO	25.5	6.0 to 64.5
MgO	6.5	1.2 to 6.6
SiO_3	0.3	0.3 to 7.4
K_2O	6.0	0.2 to 10.6
Na_2O	1.3	1.3 to 18.0
Mn_3O_4	Trace	
Cl	Trace	
Undetermined	4.2	

Source: Steam/40th Edition, Babcock & Wilcox, (c)1992, Chapter 8 - Sources of Chemical Energy

Table 4 - Existing Coal-fired Boiler/ESP Facility

Parameter	Units	Value
Steam Generator:		
Steam Flow	lb/hr	300,000
Boiler Type		p-c
Fuel		Eastern Bit
Fuel Heat Input	mmBtu/hr	350.0
Thermal Efficiency	%	86.0
Heat Recovery?		Yes
Fly Ash Carryover	%	90.0
ESP Inlet Conditions:		
Flue Gas Flow Rate	acfm-wet	129,500
Flue Gas Flow Rate	lb/hr - wet	386,300
Gas Temperature	deg F	350
Gas Pressure	in Hg	29.85
Gas O2 - dry	%	5.75
Max. Fly Ash Loading	gn/acf	2.65
Max. Fly Ash Loading	lb/mmBtu	8.37
ESP Design (Used for ESP Rebuild Case Only):		
No. Chambers		1
Plate Size (H x L)	ft x ft	30 x 9
No. Gas Passages		24
Plate Spacing	inches	9
No. Mechanical Fields		3
No. Electrical Fields		3
Type Electrode		Weighted Wire
Total Plate Area	sq ft	38,880
Aspect Ratio	ft/ft	0.90
ESP Performance:		
SCA	sq ft/kacfm	297
Chamber Gas Velocity	fps	4.0
Collection Efficiency	%	98.68
Emissions	lb/mmBtu	0.10
Operating Power	kW	85

Table 5 - Existing Wastewood Boiler/ESP Facility

Parameter	Units	Value
Steam Generator:		
Steam Flow	lb/hr	300,000
Boiler Type		Stoker
Fuel		Wastewood
Fuel Heat Input	mmBtu/hr	423.4
Thermal Efficiency	%	70.2
Heat Recovery?		Yes
Mechanical Collector?		Yes
ESP Inlet Conditions:		
Flue Gas Flow Rate	acfm-wet	196,080
Flue Gas Flow Rate	lb/hr - wet	554,720
Gas Temperature	deg F	350
Gas Pressure	in Hg	30.01
Gas O2 - dry	%	6.02
Fly Ash Loading	gn/acf	0.38
Fly Ash Loading	lb/mmBtu	1.52
ESP Design (Used for ESP Rebuild Case Only):		
No. Chambers		1
Plate Size (H x L)	ft x ft	30 x 9+6
No. Gas Passages		42
Plate Spacing	inches	9
No. Mechanical Fields		2
No. Electrical Fields		3
Type Electrode		Weighted Wire
Total Plate Area	sq ft	37,800
Aspect Ratio	ft/ft	0.50
ESP Performance:		
SCA	sq ft/kacfm	193
Chamber Gas Velocity	fps	3.5
Collection Efficiency	%	93.42
Emissions	lb/mmBtu	0.10
Operating Power	kW	95

Table 6 - Coal-fired Boiler ESP Retrofit (Case A)

Parameter	Units	Value
ESP Design:		
No. Chambers		1
Plate Size (H x L)	ft x ft	34 x 9
No. Gas Passages		18
Plate Spacing	inches	12
No. Mechanical Fields		4
No. Electrical Fields		4
Type Electrode		RDE
Total Plate Area	sq ft	44,064
Aspect Ratio	ft/ft	1.059
ESP Performance:		
SCA	sq ft/kacfm	340
Chamber Gas Velocity	fps	3.5
Max. Collection Eff.	%	99.22
Emissions	lb/mmBtu	0.065
Pressure Loss Impact	in WC	plus 1
Operating Power	kW	110

Balance of Plant:

1. Demolish existing ESP
2. 100 ft of new ductwork
3. New foundations for ESP and new ductwork
4. New ash handling system to existing ash storage silo
5. Assume existing ID fan is adequate
6. Assume existing electrical supply is adequate.

Note: For coal combustion at typical air heater outlet temperatures and typical fly ash LOI contents, Hg removal in a conventional cold-side ESP varies from 5 to 30%. (Source: Encyclopedia of Environmental Analysis and Remediation, Air Toxic Control Strategies for Utilities, Gary J. Grieco & Chis Wedig, John Wiley & Sons, Inc., 1998). Considering the high flue gas temperature (350 deg F) and low fly ash LOI (typically 1 to 3% for p-c firing with conventional burners) it is estimated that the above described ESP would only remove about 5% of the Hg present in the flue gas.

Table 7 - Coal-fired Boiler Fabric Filter Retrofit (Case B)

Parameter	Units	Value
Fabric Filter Design:		
Type Fabric Filter		Pulse-Jet
No. Collectors		1
No. Modules		8
Module Size (LxWxH)	ft x ft x ft	14x11x36
Collector Size (LxWxH)	ft x ft x ft	56x32x36
Filter Bag Size (DiaxL)	inch x ft	5.1 x 19.17
No. Bags per Module		216
Filter Area per Module	sq ft	5530
Gross Filter Area	sq ft	44,240
Filter Media		Ryton Felt
Fabric Filter Performance:		
Gross Air-to-Cloth	fpm	2.93
Net Air-to-Cloth	fpm	3.35
Pressure Loss Impact	in WC	plus 7
Collection Efficiency	%	99.735
Emissions	lb/mmBtu	0.020
Operating Power	kW	75
Est. Hg Removal Eff.	%	10

Balance of Plant:

1. Demolish existing ESP
2. 100 ft of new ductwork
3. Reinforce existing ductwork for new design pressure.
4. New foundations for FF and new ductwork
5. New ash handling system to existing ash storage silo
6. New ID fan
7. New air compressor building
8. Assume boiler design adequate for new pressure
9. Assume existing electrical supply is adequate.

Table 8 - Coal-fired Boiler ESP Upgrade (Case C)

Parameter	Units	Value
ESP Design:		
No. Chambers		1
Plate Size (H x L)	ft x ft	34 x 9
No. Gas Passages		18
Plate Spacing	inches	12
No. Mechanical Fields		4
No. Electrical Fields		4
Type Electrode		RDE
Total Plate Area	sq ft	44,064
Aspect Ratio	ft/ft	1.059
ESP Performance:		
SCA	sq ft/kacfm	340
Chamber Gas Velocity	fps	3.5
Max. Collection Eff.	%	99.22
Emissions	lb/mmBtu	0.065
Pressure Loss Impact	in WC	Nil
Operating Power	kW	110

Balance of Plant:

1. Remove roof, internals and T/R sets from existing ESP
2. Foundations for new ESP field
3. Ash handling system extension for new ESP field
4. Assume existing ID fan is adequate
5. Assume existing electrical supply is adequate.

Note: For coal combustion at typical air heater outlet temperatures and typical fly ash LOI contents, Hg removal in a conventional cold-side ESP varies from 5 to 30%. (Source: Encyclopedia of Environmental Analysis and Remediation, Air Toxic Control Strategies for Utilities, Gary J. Grieco & Chis Wedig, John Wiley & Sons, Inc., 1998). Considering the high flue gas temperature (350 deg F) and low fly ash LOI (typically 1 to 3% for p-c firing with conventional burners) it is estimated that the above described ESP would only remove about 5% of the Hg present in the flue gas.

Table 9 - Wastewood Boiler ESP Retrofit (Case D)

Parameter	Units	Value
ESP Design:		
No. Chambers		1
Plate Size (H x L)	ft x ft	33 x 9+6+6
No. Gas Passages		32
Plate Spacing	inches	12
No. Mechanical Fields		3
No. Electrical Fields		4
Type Electrode		RDE
Total Plate Area	sq ft	44,352
Aspect Ratio	ft/ft	0.636
ESP Performance:		
SCA	sq ft/kacfm	226.2
Chamber Gas Velocity	fps	3.09
Collection Efficiency	%	95.72
Emissions	lb/mmBtu	0.065
Pressure Loss Impact	in WC	plus 1
Operating Power	kW	125

Balance of Plant:

1. Demolish existing Venturi Scrubber
2. 100 ft of new ductwork
3. New foundations for ESP and new ductwork
4. New ash handling system to existing ash storage silo
5. Assume existing ID fan is adequate
6. Assume existing electrical supply is adequate.

Table 10 - Wastewood Boiler ESP Upgrade (Case E)

Parameter	Units	Value
ESP Design:		
No. Chambers		1
Plate Size (H x L)	ft x ft	33 x 9+6+6
No. Gas Passages		32
Plate Spacing	inches	12
No. Mechanical Fields		3
No. Electrical Fields		4
Type Electrode		RDE
Total Plate Area	sq ft	44,352
Aspect Ratio	ft/ft	0.636
ESP Performance:		
SCA	sq ft/kacfm	226.2
Chamber Gas Velocity	fps	3.09
Collection Efficiency	%	95.72
Emissions	lb/mmBtu	0.065
Pressure Loss Impact	in WC	Nil
Operating Power	kW	125

Balance of Plant:

1. Remove roof, internals and T/R sets from existing ESP
2. Foundations for new ESP field
3. Ash handling system extension for new ESP field
4. Assume existing ID fan is adequate
5. Assume existing electrical supply is adequate.

Table 11 - Coal-fired Boiler Sodium-based Wet Scrubber Retrofit (Case F)

Parameter	Units	Value
Scrubber Design:		
Reagent		Sodium Hydroxide
Vessel Size (Dia. X H)	ft x ft	15 x 45
Plan Area Envelope	ft x ft	20 x 30
No. Recycle Pumps		1 + 1 spare
Scrubber Performance:		
NaOH Usage	lb/hr	910
Makeup Water Usage	gpm	60
Blowdown Rate	gpm	25
SO2 Emissions	lb/mmBtu	<0.12
Pressure Loss Impact	in WC	plus 7
Operating Power	kW	70
Max. SO2 Removal Eff.	%	94.55
Est. Hg Removal Eff.	%	36
Est. HCl Removal Eff.	%	98

Balance of Plant:

1. Re-use existing ESP upstream of Scrubber
2. 75 ft of new stainless steel ductwork
3. Reinforce existing ductwork for new design pressure
4. New foundations for Scrubber and new ductwork
5. New ID fan
6. New 200 ft high stainless steel wet stack
7. New pump building
8. Blowdown treatment/transfer facility
9. Assume site has adequate NaOH supply
10. Assume site has adequate water supply
11. Assume boiler design adequate for new pressure
12. Assume existing electrical supply is adequate.

Notes: 1. Scrubber design and operating data provided by Croll-Reynolds Company, Inc., Westfield, NJ
2. Scrubber is assumed to remove 60% of ionic Hg species.

Table 12 - Coal-fired Boiler Selective Catalytic Reduction (SCR) Retrofit (Case G)

Parameter	Units	Value
SCR Design:		
Stand-alone or Integrated?		Integrated
Reactor Size (LxWxH)	ft x ft x ft	10 x 10 x 30
Catalyst Layers		3 + 1 Spare
Catalyst Weight	lb	60,000
Bypass Duct?		Yes
Temperature Modulating Duct?		Yes
SCR Performance:		
Ammonia Rate	lb/hr	75
NOx Efficiency	%	80
SCR Gas Temperature	deg F	675 - 750
Catalyst Life	years	4
Ammonia Slip	ppmv	2.0
Pressure Loss Impact	in WC	plus 9
Operating Power	kW	30

Balance of Plant:

1. Replace air heater baskets with enamel coated type
2. Install and permit anhydrous ammonia storage tank
3. Reinforce existing ductwork for new design pressure
4. New foundations for SCR and associated ductwork
5. Ash handling system extension to existing storage silo
6. New ID fan
7. Integrate SCR operation with existing boiler controls
8. Assume boiler design adequate for new pressure
9. Assume existing electrical supply is adequate
10. Assume Low NOx burners not installed.

Table 13 - Coal-fired Boiler Carbon Injection/Fabric Filter Retrofit (Case H)

Parameter	Units	Value
Activated Carbon Injection Design & Performance:		
Design Feed Rate	lb/hr	5.0
Silo Storage Capacity	days	90
Operating Feed Rate	lb/hr	3.0
Hg Removal Efficiency	%	60
Fabric Filter Design:		
Type Fabric Filter		Pulse-Jet
No. Collectors		1
No. Modules		8
Module Size (LxWxH)	ft x ft x ft	14x11x36
Collector Size (LxWxH)	ft x ft x ft	56x32x36
Filter Bag Size (DiaxL)	inch x ft	5.1 x 19.17
No. Bags per Module		216
Filter Area per Module	sq ft	5530
Gross Filter Area	sq ft	44,240
Filter Media		Ryton Felt
Fabric Filter Performance:		
Gross Air-to-Cloth	fpm	2.93
Net Air-to-Cloth	fpm	3.35
Pressure Loss Impact	in WC	plus 7
Collection Efficiency	%	99.735
Emissions	lb/mmBtu	0.020
Operating Power	kW	75

Balance of Plant:

1. Demolish existing ESP
2. 100 ft of new ductwork
3. Reinforce existing ductwork for new design pressure
4. New foundations for FF and new ductwork
5. New ash handling system to existing ash storage silo
6. New ID fan
7. New air compressor building
8. New activated carbon storage silo, 9 ft dia. by 18 ft high
9. Assume boiler design adequate for new pressure
10. Assume existing electrical supply is adequate.

Table 14 - Economic Factors

Factor	Units	Value	Comments
Energy Charge	$/kW-hr	0.05	
O&M Labor Rate	$/man-year	75,000	Includes benefits and overhead
Plant Capacity Factor	%	80	
ID Fan Fan/Motor Efficiency (ns)	fraction	75	ID Fan electric power consumption
NaOH Cost	$/lb	0.15	Scrubber reagent
Water Cost	$/gallon	0.00165	Scrubber make-up water
Wastewater Cost	$/gallon	0.00248	The waste is a feedstock to the process
Anhydrous Ammonia Cost	$/Ton	250	SCR
Catalyst Replacement Cost	$/cu.meter	6400	SCR
Activated Carbon Cost	$/lb	0.50	Hg Removal Reagent
Filter Bag Replacement Cost	$/bag	100	Fabric Filter
Bag Cage Replacement Cost	$/cage	30	Fabric Filter

Table 15 - Capital Cost Estimates ($1000 US)

Cost Item	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
Emissions Equipment	830.0	930.0	435.0	840.0	435.0	830.0	1,075.0	1,030.0
Ductwork w/ Supports	100.0	100.0	-	100.0	-	195.0	-	100.0
ID Fan with Motor	-	75.0	-	75.0	-	100.0	75.0	75.0
Insulation & Lagging	74.4	88.4	34.8	81.2	34.8	90.0	92.0	96.4
Misc. Buildings	-	50.0	-	-	-	50.0	-	50.0
Ammonia Storage Tank	-	-	-	-	-	-	156.0	-
Foundations	100.4	124.3	47.0	109.6	47.0	172.5	139.8	135.1
Fly Ash Handling	40.0	80.0	20.0	40.0	20.0	-	20.0	80.0
Wastewater Treatment	-	-	-	-	-	60.0	-	-
Reinforce Exist Ducting	-	50.0	-	-	-	50.0	50.0	50.0
Air Heater Baskets	-	-	-	-	-	-	50.0	-
BOP Electrical and I&C	50.0	25.0	50.0	50.0	50.0	50.0	25.0	25.0
CEMS	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
New Wet Stack	-	-	-	-	-	460.0	-	-
Makeup Water Piping	-	-	-	-	-	25.0	-	-
Sub-Total Materials	1,344.8	1,672.7	736.8	1,445.8	736.8	2,232.5	1,832.8	1,791.5
Direct Construction	1,210.4	1,505.5	663.1	1,301.2	663.1	2,009.3	1,649.5	1,612.4
Retrofit Costs	726.2	903.3	795.7	780.7	795.7	1,205.6	989.7	967.4
Sub-Total	3,281.4	4,081.5	2,195.6	3,527.8	2,195.6	5,447.3	4,472.0	4,371.4
Indirect Construction	328.1	408.1	219.6	352.8	219.6	544.7	447.2	437.1
Engineering & Fee	328.1	408.1	219.6	352.8	219.6	544.7	447.2	437.1
Total Installed Cost	3,937.7	4,897.8	2,634.7	4,233.4	2,634.7	6,536.8	5,366.4	5,245.6
Contingency	787.5	979.6	526.9	846.7	526.9	1,307.4	1,073.3	1,049.1
Total Project Cost - Base Case	4,725.2	5,877.3	3,161.7	5,080.0	3,161.7	7,844.1	6,439.7	6,294.8
EPC Cost - Alternate Case	4,914.2	6,112.4	3,288.1	5,283.2	3,288.1	8,157.9	6,697.3	6,546.5
Cost in $ per kW for 35 MWe	135	168	90	145	90	224	184	180
Cost in $ per Klbs/Hr Steam	16	20	11	17	11	26	21	21

Table 16 - Annual O&M Cost Estimates ($1000 US)

	Retrofit ESP Coal Case A		Retrofit Fabric Filter Coal Case B		Upgrade ESP Coal Case C		Retrofit ESP Wood Fuel Case D	
Cost Item	**Quantity**	**$1,000**	**Quantity**	**$1,000**	**Quantity**	**$1,000**	**Quantity**	**$1,000**
Operating Power	25 kW	8.8	75 kW	26.3	25 kW	8.8	30 kW	10.5
Labor	0.5 man-yr	37.5	0.7 man-yr	52.5	0.5 man-yr	37.5	0.5 man-yr	37.5
Materials		18.8		26.3		18.8		18.8
Differential ID Fan Power	1 in WC	7.1	7 in WC	49.7		-	1 in WC	9.9
NaOH Consumption		-		-		-		-
Water Consumption		-		-		-		-
Wastewater Treatment		-		-		-		-
Ammonia Consumption		-		-		-		-
Activated Carbon Consumption		-		-		-		-
Filter Bag Changeouts		-	Every 5 yrs	34.6		-		-
Filter Cage Changeouts		-	Every 10 yrs	5.2		-		-
Catalyst Changeouts		-		-		-		-
Annual O&M Cost Totals		**72.1**		**194.5**		**65.0**		**76.7**

Notes:
1. Cases B & H - A total of 1,728 fabric filter bags are changed out every five (5) years, with a present worth cost of $100/bag including labor. In the table above this cost was evenly distributed over the five (5) year period to determine an annual cost.
2. Cases B & H - A total of 1,728 filter cages are changed out every ten (10) years, with a present worth cost of $30/cage including labor. In the table above this cost was evenly distributed over the ten (10) year period to determine an annual cost.
3. Case G - A total of 60,000 lbs of catalyst are changed out every four (4) years, with a present worth cost of $12.00/lb including labor. In the table above this cost was evenly distributed over the four (4) year period to determine an annual cost.
4. The Scrubber Major Maintenance costs are also annualized by evenly distributing the costs over each year.

Table 16 - Annual O&M Cost Estimates ($1000 US)

	Upgrade ESP		Sodium Scrubber		SCR		Carbon Injection + FF	
	Wood Fuel		Coal		Coal		Coal	
	Case E		Case F		Case G		Case H	
Cost Item	**Quantity**	**$1,000**	**Quantity**	**$1,000**	**Quantity**	**$1,000**	**Quantity**	**$1,000**
Operating Power	30 kW	10.5	70 kW	24.5	30 kW	10.5	75 kW	26.3
Labor	0.5 man-yr	37.5	6 man-yr	450.0	1 man-yr	75.0	0.75 man-yr	56.3
Materials		18.8		360.0		45.0		39.4
Differential ID Fan Power		-	7 in WC	49.7	9 in WC	63.9	7 in WC	49.7
NaOH Consumption		-	910 lb/hr	956.6		-		-
Water Consumption		-	90 gpm	62.5		-		-
Wastewater Treatment		-	40 gpm	41.7		-		-
Ammonia Consumption		-		-	75 lb/hr	65.7		-
Activated Carbon Consumption		-		-		-	3 lb/hr	10.5
Filter Bag Changeouts		-		-		-	Every 5 yrs	34.6
Filter Cage Changeouts		-		-		-	Every 10 yrs	5.2
Catalyst Changeouts		-		-	Every 4 yrs	41.3		-
Scrubber Major Maintenance			Every 6 yrs	27.7				
Scrubber BOP Major Maintenance			Every 10 yrs	20.2				
Annual O&M Cost Totals		**66.8**		**1,992.9**		**301.3**		**221.8**

Notes:

1. Cases B & H - A total of 1,728 fabric filter bags are changed out every five (5) years, with a present worth cost of $100/bag including labor. In the table above this cost was evenly distributed over the five (5) year period to determine an annual cost.
2. Cases B & H - A total of 1,728 filter cages are changed out every ten (10) years, with a present worth cost of $30/cage including labor. In the table above this cost was evenly distributed over the ten (10) year period to determine an annual cost.
3. Case G - A total of 60,000 lbs of catalyst are changed out every four (4) years, with a present worth cost of $12.00/lb including labor. In the table above this cost was evenly distributed over the four (4) year period to determine an annual cost.
4. The Scrubber Major Maintenance costs are also annualized by evenly distributing the costs over each year.

Table 17 - Sodium Scrubber (Case F) O&M Parameterization

SO2 Emissions:	0.22 lb/mmBtu		0.44 lb/mmBtu		0.66 lb/mmBtu	
SO2 Collection Efficiency:	90% Efficiency		80% Efficiency		70% Efficiency	
Cost Item	Quantity	$1,000	Quantity	$1,000	Quantity	$1,000
Operating Power	70 kW	24.5	70 kW	24.5	70 kW	24.5
Labor	6 man-yr	450.0	6 man-yr	450.0	6 man-yr	450.0
Materials		360.0		360.0		360.0
Differential ID Fan Power	7 in WC	49.7	7 in WC	49.7	7 in WC	49.7
NaOH Consumption	866 lb/hr	910.3	770 lb/hr	809.4	674 lb/hr	708.5
Water Consumption	85 gpm	59.0	76 gpm	52.7	66 gpm	45.8
Wastewater Treatment	38 gpm	39.6	34 gpm	35.5	29.5 gpm	30.8
Scrubber Major Maintenance	Every 6 yrs	27.7	Every 6 yrs	27.7	Every 6 yrs	27.7
Scrubber BOP Major Maintenance	Every 10 yrs	20.2	Every 10 yrs	20.2	Every 10 yrs	20.2
Annual O&M Cost Totals		**1,941.1**		**1,829.7**		**1,717.2**