Design and Evaluation of New Flue Gas Cleanup Processes to Meet New EPA Regulations

IPRO 496-304a

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Overview

- Introduction
- Project Validity
- Problem Definition
- Base Case Scenario
- Operation Descriptions
- Economic Analysis
- Process Selection
- Conclusions/Suggestions

Objectives

- Design the most cost efficient cleaning process for flue gas that removes SO_X, NO_X, Particulate Matter:
  - that meets current and future EPA standards
  - that is viable in the long run
  - based on existing and new technologies
  - which study its effects on cost of electricity by comparing and analyzing costs of burning IL vs. WY coal

Introduction – Pollution Control

- Clean Air Act (1990) – The EPA institutes new, more vigorous environmental regulations on power plant emissions
- By 2010
  - 6,400 fewer premature deaths
  - $40B health benefits reduction
- By 2020
  - 12,000 fewer premature deaths
  - $93B health benefits reduction

Clean Air Act (1990)

[lb/mmBtu]

OLD PLANTS

	SOX	NOX	HG	P.M.
1980	1.2	0.7	N/A	0.1
2000	0.6	0.4	N/A	0.05
2020	-70%	-70%	-80%	-70%

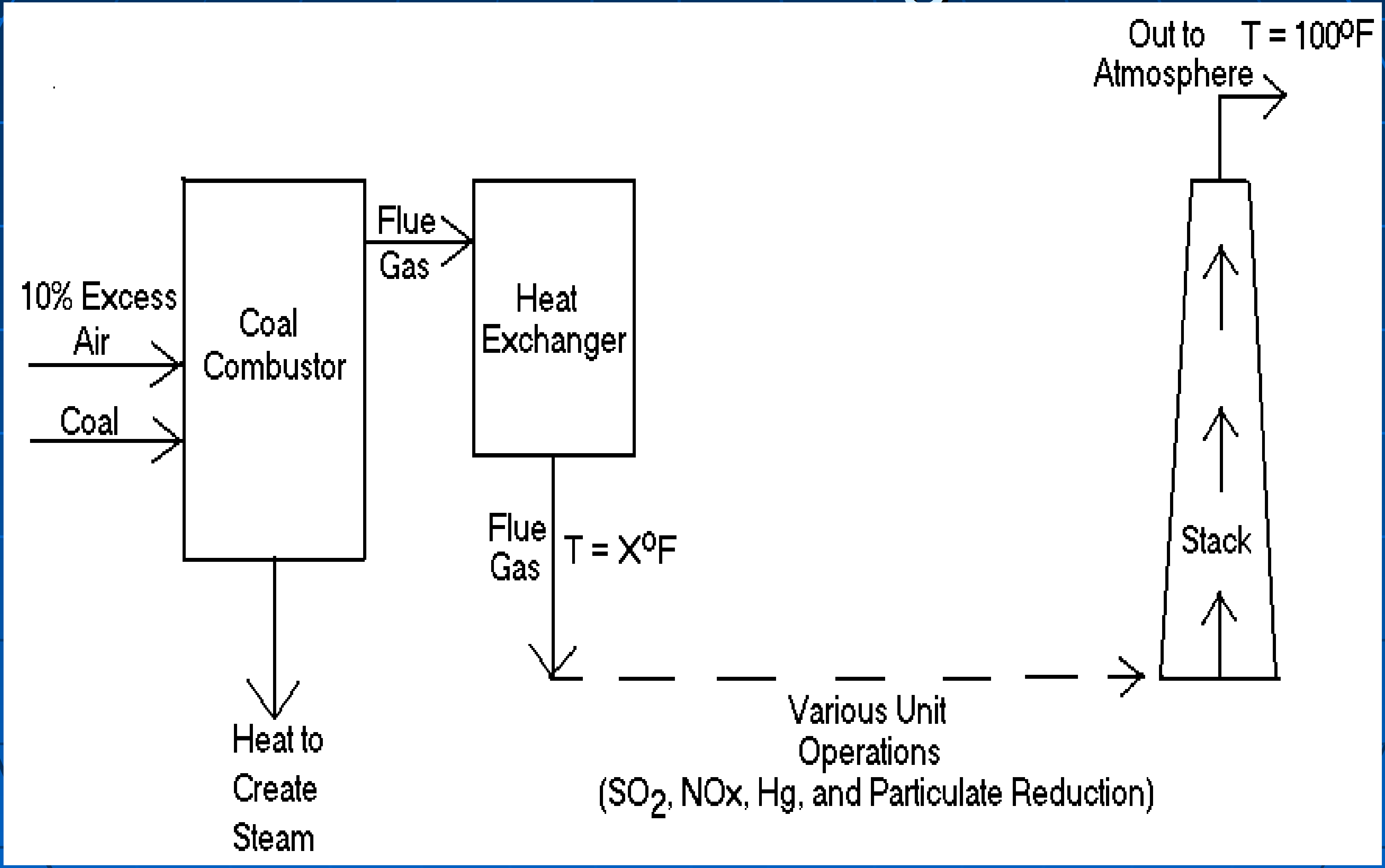
NEW PLANTS

	SOX	NOX	HG	P.M.
1980	X	X	X	X
2000	0.3	0.1	-80%	0.02
2020	-70%	-70%	-80%	-70%

Base Plant

- Mid-sized coal burning power plant (400MWe)
- Burning Illinois No. 6 coal
- Particulate matter removal only current unit operation (Electrostatic Precipitator (ESP) or Baghouse)
- Unit operations to remove SO_X and NO_X later.

Base Plant Diagram



Coal Statistics

- Illinois No. 6 (wt%)
  - C: 67.37
  - H_2: 4.20
  - N_2: 1.16
  - S: 3.25
  - O_2: 6.02
  - Ash: 10.00
  - Moisture: 8.00
- Wyoming PRB (wt %)
  - C: 49.88
  - H_2: 3.40
  - N_2: 1.62
  - S: 0.48
  - O_2: 9.82
  - Ash: 6.40
  - Moisture: 28.40

Coal Combustion

- Reactions
  - $C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$ ΔH_{rxn} = -393.509 kJ/mol
  - $S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$ ΔH_{rxn} = -296.830 kJ/mol
  - $0.5H_{2(g)} + O_{2(g)} \rightarrow H_2O_{(g)}$ ΔH_{rxn} = -241.818 kJ/mol
  - $0.5N_{2(g)} + 0.5O_{2(g)} \rightarrow NO_{(g)}$ ΔH_{rxn} = 90.250 kJ/mol
  - $0.5N_{2(g)} + O_{2(g)} \rightarrow NO_{2(g)}$ ΔH_{rxn} = 33.180 kJ/mol
- 100% conversion of carbon, sulfur, and hydrogen assumed

Coal Combustion Calculations

Coal					
Compound	**Wt%**	**g**	**M.W.**	**moles**	**mole%**
$H_2O(g)$	8.00	7.61E+10	18	4.23E+09	4.77
C(s)	67.37	6.41E+11	12	5.34E+10	60.22
$H_2(g)$	4.20	4.00E+10	2	2.00E+10	22.52
$N_2(g)$	1.16	1.10E+10	28	3.94E+08	0.44
S(s)	3.25	3.09E+10	32	9.66E+08	1.09
$O_2(g)$	6.02	5.73E+10	32	1.79E+09	2.02
C(s,ash)	10.00	9.51E+10	12	7.93E+09	8.94
Sum:	**100.00**	**9.51E+11**	**X**	**8.87E+10**	**100.00**

Total Grams
9.51E+11
Total Pounds
2.10E+09
Heating Value (Btu/lb)
12277.88
lb Coal/Hour
317823.81
ton Coal/Hour
158.91
$/ton Coal
29.49
$/yr
3.09E+07
Gas Flow Rate (ft^3/min)
1.03E+06
Gas Flow Rate (cm^3/s)
4.84E+08

Flue Gas							Heating Value	Heating Value
Compound	**Wt%**	**g**	**M.W.**	**moles**	**mole%**	**lb/mmBtu**	**(Btu/mol)**	**(Btu)**
$CO_2(g)$	23.61	2.35E+12	44	5.34E+10	16.08	X	373.22	1.99E+13
$SO_2(g)$	0.62	6.18E+10	64	9.66E+08	0.29	5.29	281.53	2.72E+11
$H_2O(g)$	4.38	4.36E+11	18	2.42E+10	7.29	X	229.35	5.55E+12
NO(g)	0.01	9.19E+08	30	3.06E+07	0.01	0.08	-85.60	-2.62E+09
$NO_2(g)$	0.07	6.58E+09	46	1.43E+08	0.04	0.56	-31.47	-4.50E+09
$N_2(g)$	71.15	7.08E+12	28	2.53E+11	76.14	X	0.00	0.00E+00
$O_2(g)$	0.17	1.65E+10	32	5.16E+08	0.16	X	0.00	0.00E+00
Sum:	**100.00**	**9.96E+12**	**X**	**3.32E+11**	**100.00**	5.94	**767.04**	**2.58E+13**

Heat Value Calculations

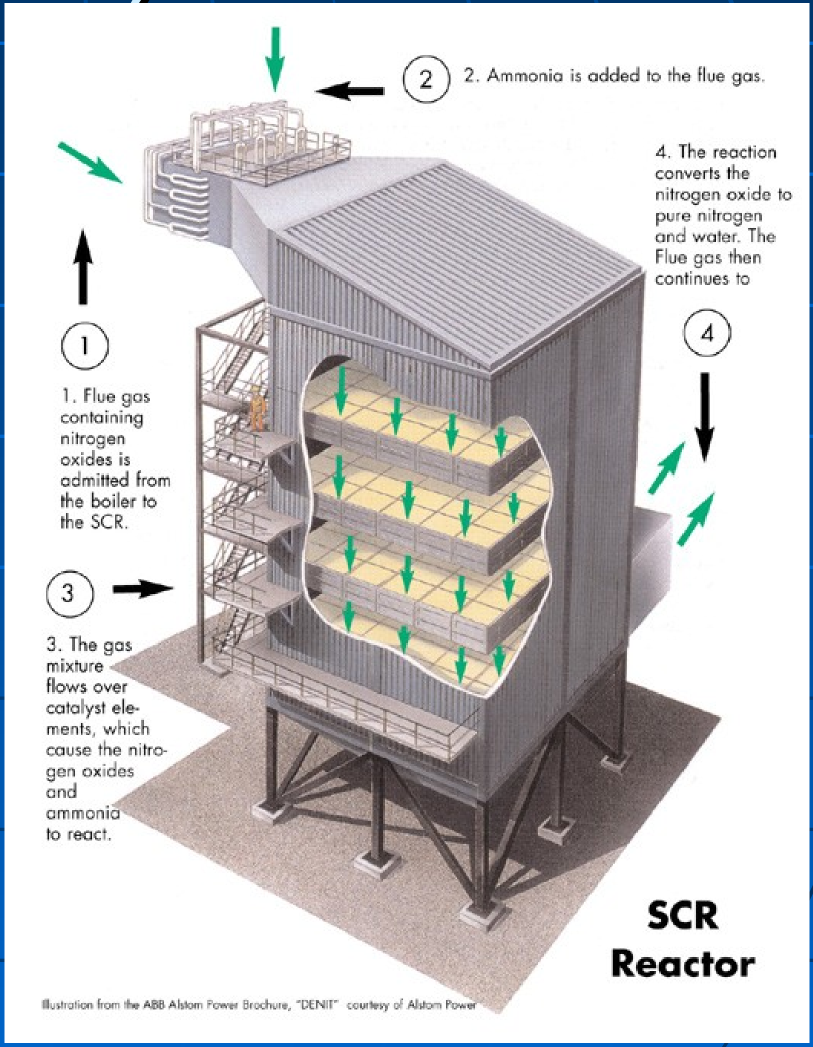
- 400MWe/0.35 = $2.7*10^{10}$MJ/yr
- $2.7*10^{10}$MJ/yr*(1Btu/.001054MJ) = $2.58*10^{13}$Btu/yr
- $2.58*10^{13}$Btu/yr*1lb coal/12,280Btu = $2.1*10^{9}$lb coal/yr
- $2.1*10^{9}$lb coal/yr = 158.9ton coal/hr

Coal Selection Dilemma

- Due to the higher sulfur content, flue gas from Illinois coal must be desulfurized before being released to the atmosphere.
- Under current regulations, Wyoming PRB coal must only undergo a particulate removal process, thereby making it more economical to use.
- New regulations, in addition to the Clean Air Act, would require the same cleaning operations (SO_X, NO_X, P.M.) for both forms of coal in an attempt to make Illinois coal more competitive.

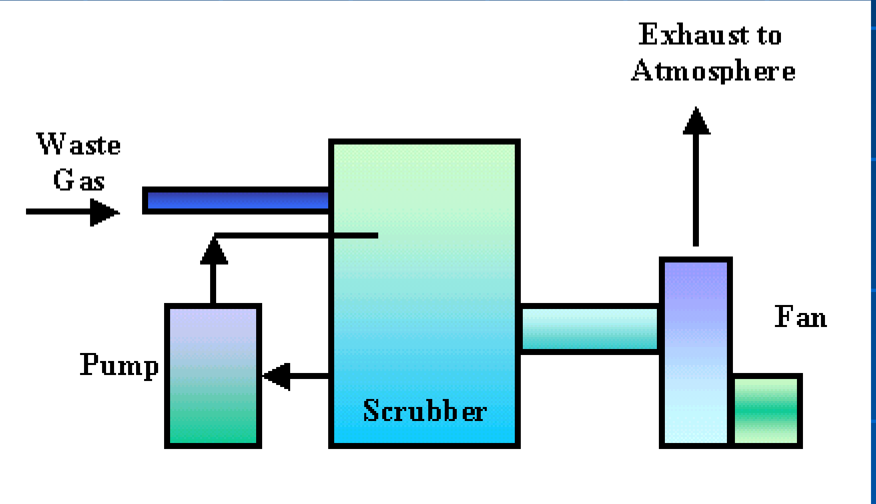
Selective Catalytic Reduction (SCR)

- Selective Catalytic Reduction
  - $2NH_{3(l)} + 3NO_{(g)} \rightarrow 2.5N_{2(g)} + 3H_2O_{(g)}$
  - $4NH_{3(g)} + 3NO_{2(g)} \rightarrow 3.5N_{2(g)} + 6H_2O_{(g)}$
- Ammonia injected into flue gas before passing through a honeycomb catalyst vessel at 700°F
- Reaction is pushed to completion to prevent ammonia slip.



Wet Scrubbing

- A limestone slurry reacts with sulfur dioxide at 300°F to create calcium sulfate, which is trapped in the slurry stream and removed

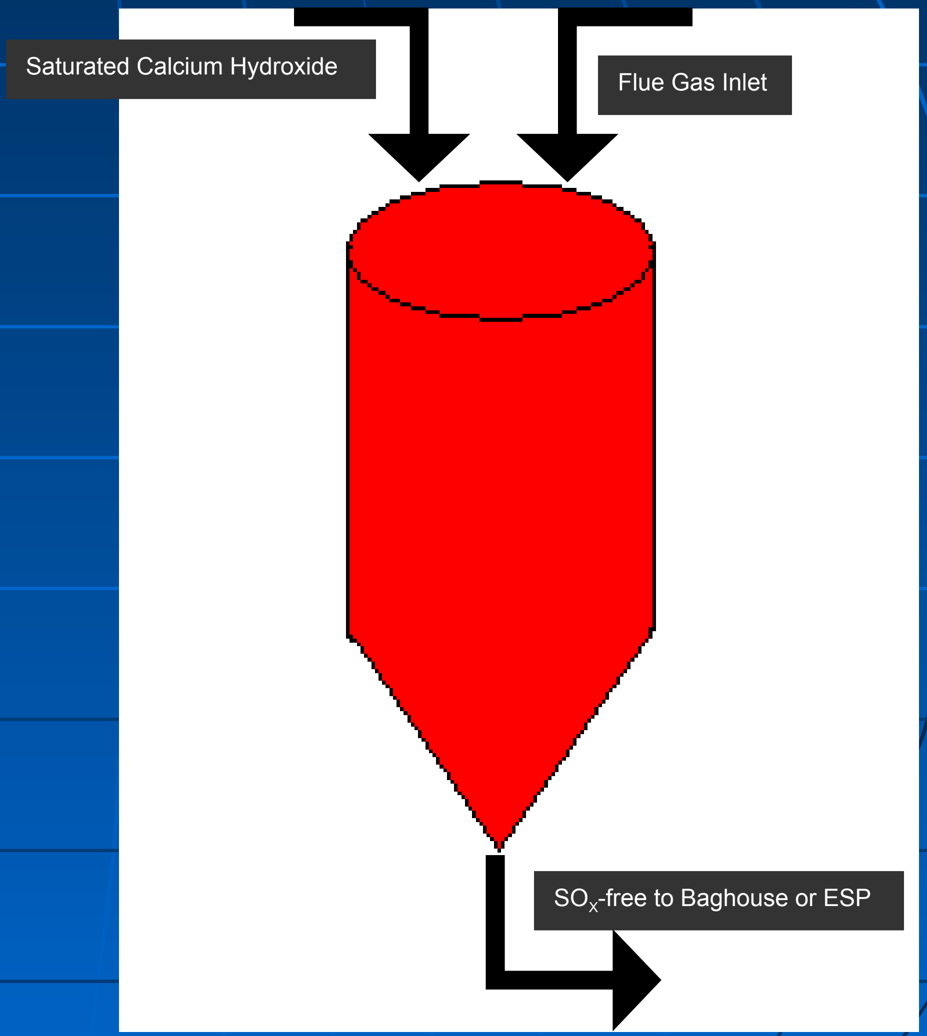


Scrubbing the Gas

- $CaCO_{3(aq)} + SO_{2(g)} + 0.5O_{2(g)} \rightarrow CaSO_{4(aq)} + CO_{2(g)}$

Dry Scrubbing

- A saturated calcium hydroxide solution is passed through atomizers so that the droplets evaporate into the flue gas. The calcium hydroxide reacts with the sulfur dioxide and creates calcium sulfate again.
- $Ca(OH)_{2(aq)} + SO_{2(g)} + 0.5O_{2(g)} \rightarrow CaSO_{4(aq)} + H_2O_{2(g)}$
- The solid particles are caught in the P.M. removal system as opposed to in the slurry.



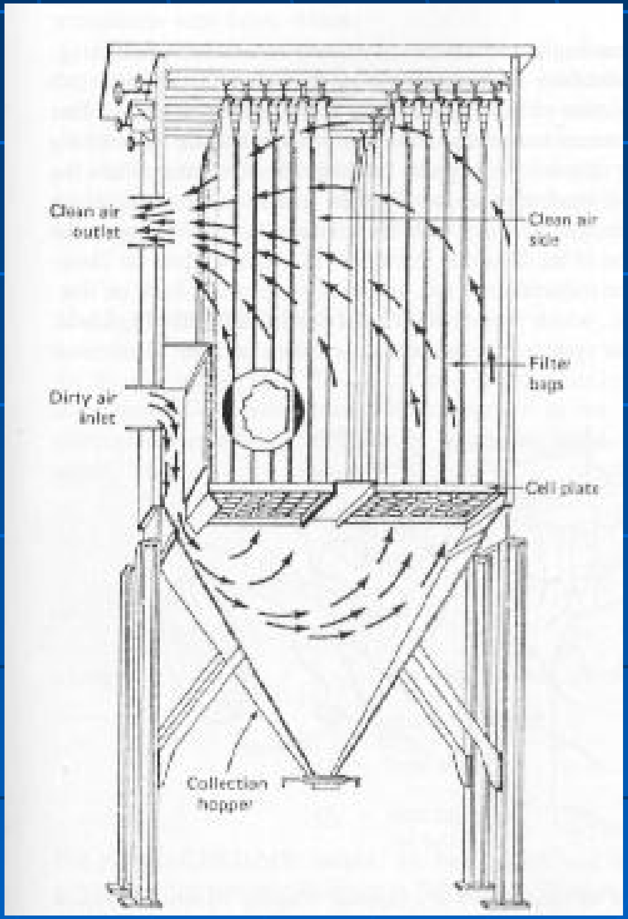
Vessel Design

- V = Reaction Vessel = [m^3]
- Q = Flue Gas Flow Rate = [m^3/s]
- θ = Residence Time = [s]

$$V = Q \cdot \theta$$

Baghouse Filter

- Gas passed through fabric bag network
- Particulates collect on fabric surface
- Periodically, particles knocked off bags into hoppers to maintain efficiency and low pressure drop



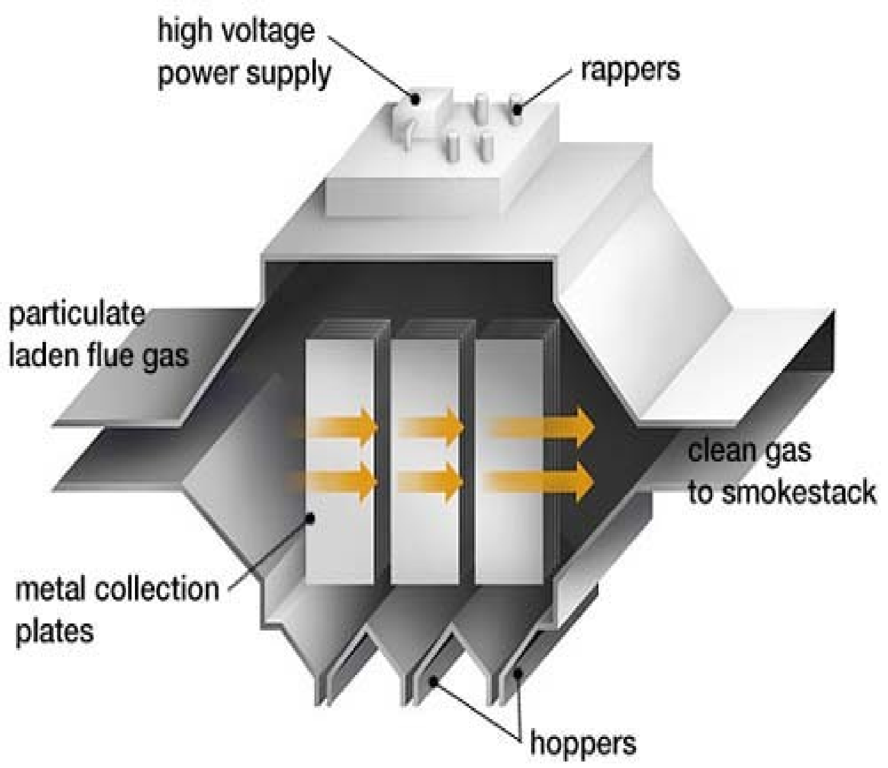
Baghouse Design

- A = total Baghouse area [ft^2]
- Q = flue gas flow rate [ft^3/min]
- F_M = filtration velocity [ft/min] = 2.2

$$A = \frac{Q}{V_F}$$

Electrostatic Precipitator (ESP)

- Uses electric forces to remove particulates
- Ionized particles are attracted to oppositely charged collection plates.
- Particles are dislodged from plates using the rapper



ESP Design

Design Equation :

$$[\ln(1-\eta)]^{1/k} = -\frac{Aw}{Q}$$

- *A* = total plate area
- *w* = precipitation rate parameter
- *Q* = flow rate
- η = efficiency
- k = efficiency constant

Project values:

A= $1.2*10^{6}$ ft^{2}

w = 0.33 ft/sec

Q = $1.03*10^{6}$ ft^{3}/min

η = 0.999

k = 0.6

Vessel Costing

- Total volume found from previous equations
- Maximum volume from cost correlation graph used to find theoretical number of vessels, each of which has an individual cost
- Summing the individual costs gives total cost for the total volume
- Costs then inflated to 2003 values

Vessel Costing Continued

- Baghouse and ESP costs dependent on total area and found through empirical equations
- In addition, total cost has associated costs based on percentages of the bare module cost
- All values inflated to 2003 values

Cost Comparison One

Calculated Values

Illinois No. 6	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
CAPITAL	2.43E+07	5.41E+07	4.41E+07	2.68E+07	1.81E+07
OPERATING	3.41E+06	9.74E+06	9.70E+06	2.47E+06	1.99E+06
ANNUALIZED	6.11E+06	1.57E+07	1.46E+07	5.44E+06	4.00E+06

Cents/kW-h	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
ANNUALIZED	0.232	0.599	0.555	0.207	0.152

IECM Values

Illinois No. 6	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
CAPITAL	2.27E+07	6.23E+07	4.86E+07	2.46E+07	1.87E+07
OPERATING	3.18E+06	1.11E+07	1.06E+07	2.27E+06	2.08E+06
ANNUALIZED	5.52E+06	1.85E+07	1.56E+07	4.45E+06	3.86E+06

Cents/kW-h	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
ANNUALIZED	0.210	0.702	0.592	0.169	0.147

System of Choice: SCR, Dry Scrubbing, ESP

Average Difference (Calculations vs. IECM): 9%

Cost Comparison Two

Illinois No. 6

Illinois No. 6	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
ANNUALIZED	5.52E+06	1.85E+07	1.56E+07	4.45E+06	3.86E+06
Cents/kW-h	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
ANNUALIZED	0.210	0.702	0.592	0.169	0.147

Wyoming PRB

Wyoming PRB	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
ANNUALIZED	6.47E+06	1.39E+07	9.03E+06	4.24E+06	3.26E+06
Cents/kW-h	S.C.R.	W.S.	D.S.	B.F.	E.S.P.
ANNUALIZED	0.246	0.527	0.343	0.161	0.124

System of Choice: SCR, Dry Scrubbing, ESP

Final Analysis

- Illinois Current Cost (SO_X, P.M.): 0.739cents/kW-h
- Wyoming Current Cost(P.M.): 0.124cents/kW-h Diff.:0.615
- Illinois New Cost (NO_X, SO_X, P.M.): 0.949cents/kW-h
- Wyoming New Cost(NO_X, SO_X, P.M.): 0.713cents/kW-h Diff.:0.236
- IL: $326.48/ton SO_X removed

WY: $180.16/ton SO_X removed