DEVELOPMENT OF THE
INTEGRATED ENVIRONMENTAL CONTROL MODEL

Quarterly Progress Report

to

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from

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INTRODUCTION

The purpose of this contract is to develop and refine the Integrated Environmental Control Model (IECM) created and enhanced by Carnegie Mellon University (CMU) for the U.S. Department of Energy's Pittsburgh Energy Technology Center (DOE/PETC) under contract Numbers DE-FG22-83PC60271 and DE-AC22-87PC79864.

In its current configuration, the IECM provides a capability to model various conventional and advanced processes for controlling air pollutant emissions from coal-fired power plants before, during, or after combustion. The principal purpose of the model is to calculate the performance, emissions, and cost of power plant configurations employing alternative environmental control methods. The model consists of various control technology modules, which may be integrated into a complete utility plant in any desired combination. In contrast to conventional deterministic models, the IECM offers the unique capability to assign probabilistic values to all model input parameters, and to obtain probabilistic outputs in the form of cumulative distribution functions indicating the likelihood of different costs and performance results.

The most recent version of the IECM, implemented on a Macintosh II computer, was delivered to DOE/PETC at the end of the last contract in May 1991. The current contract will continue the model development effort to provide DOE/PETC with improved model capabilities, including new software developments to facilitate model use and new technical capabilities for analysis of environmental control technologies. Integrated environmental control systems involving pre-combustion, combustion, and post-combustion control methods will be considered.

The work in this contract is divided into two phases. Phase I deals with further developing the existing version of the IECM and training PETC personnel on the effective use of the model. Phase II deals with creating new technology modules, linking the IECM with PETC databases, and training PETC personnel on the effective use of the updated model.

The present report summarizes recent progress on the Phase I effort during the period April 1, 1995 through June 30, 1995. This report presents additional revisions to the new cost models of flue gas desulfurization (FGD) technology initially reported in our fourth quarterly report (Oct. 1993). For convenience, the complete description of the revised FGD models are presented here. Also included in this report is a technical paper with illustrative case studies that employ these FGD models. This paper was prepared during the last quarter for presentation at the 1995 DOE/PETC Contractors review meeting.

1.0 Background to FGD Models

In this report we describe the use of systematic sensitivity analysis and multivariate regression for the development of analytical models for the performance and cost of high-performance wet lime/limestone FGD systems and dry lime sprayer systems. Special attention has been paid to FGD systems whose performance with respect to sulfur removal efficiency lies in the 90-98% range. The cost of using additives such as dibasic acid (DBA) as a design option for achieving high performance is also examined. The cost models developed relates the capital costs and the operating and maintenance costs to input variables describing performance parameters and the costs of labor and materials. Systematic sensitivity analysis is used to select and rank the set of input variables and multivariate regression is used for the development of functional relations between the input variables and costs (outputs). This systematic approach along with engineering judgment is used to develop aggregate models for costing high performance FGD systems. These aggregate models are appropriate in size and form for conducting uncertainty analysis using Monte Carlo methods in the IECM.

The report is organized as follows. The next section describes the development of new FGD performance models. Based on a review of the literature some approximate functional relations to describe FGD performance are presented. Section 3 provides an overview of the methodological approach used to derive capital cost models. Four FGD systems are analyzed: (1) wet limestone with forced oxidation (LSFO), (2) dibasic acid enhanced wet limestone (LS/DBA), (3) a magnesium-enhanced wet lime system, and (4) a spray dryer with lime. The relations for direct process capital cost models are derived for each process area. The effect of different sparing philosophies on the capital cost are examined. Section 5 develops cost models for the fixed operating and maintenance costs associated with operating a FGD system. Section 6 develops models for the variable costs of reagent use, power use, waste disposal, energy consumption etc. Finally, Section 7 provides a numerical example to illustrate the new models.

2.0 FGD Performance Models

In this section we describe the performance models used to provide key parameter inputs to the cost models described later. We begin with a brief survey of FGD performance literature. Based on the literature, approximate functional relations between performance parameters are developed.

The analysis in this report is geared towards developing updated performance and cost models for four commercial FGD processes:

1) <u>Limestone with Forced Oxidation (LSFO)</u>: A limestone slurry is used in an open spray tower with in-situ oxidation to remove SO_2 and form a gypsum sludge. The main advantages as compared to conventional systems is easier dewatering, more economical disposal of scrubber products, and decreased scaling on tower walls.

2) <u>Limestone with Dibasic Acid Additive (LS/DBA)</u>: A modification to LSFO where dibasic acid (DBA) is added to act as a buffer/catalyst in the open spray tower. The main advantages are increased SO_2 removal and decreased liquid to gas ratio.

3) <u>Magnesium Enhanced Lime System</u>: A magnesium sulfite and lime slurry (maglime) is used to remove SO_2 and form a precipitate high in calcium sulfite. The high alkalinity of the maglime slurry allows very high SO_2 removal. However, the reagent cost is also higher and solid waste is not easily disposed.

4) <u>Lime Spray Dryer</u>: An atomized spray of a mixture of lime slurry and recycled solids is brought into contact with the hot flue gas. The water in the slurry evaporates leaving dry reaction products and flyash which drops out of the scrubber. A particulate control device such as a baghouse is also used to remove the rest of the dry products from the flue gas before releasing it. The SO_2 removal efficiency is the total of SO_2 removed in the scrubber and the baghouse.

2.1 Wet Limestone FGD Systems

Advanced wet limestone FGD systems are now designed to achieve SO_2 removal efficiencies in excess of 95%. The single loop countercurrent spray tower is the most commonly used device for the removal of SO_2. The design of spray towers for high efficiency without additives is achieved by using high liquid-to-gas (L/G) ratios and improving gas/liquid contact by spray nozzle design (Bhat, et al., 1993; Rader & Bakke, 1991) On the other hand, organic acids such as dibasic acid or adipic acid are added as buffers to improve performance (Blythe, et al., 1993; Moser & Owens, 1990; Smolenski, et al., 1993; Stevens, et al., 1993) In this section, brief descriptions and approximate relations for high performance LSFO and LS/DBA systems are provided. The approximate relations are gleaned from the literature to reflect US experience with high performance wet limestone FGD systems (Benson, 1993; Dene, et al., 1991; Johnson, 1993; Klingspor, 1993; Laslow, 1993; Moser & Owens, 1990; Noblett Jr., et al., 1990; Noblett Jr., 1993; Rader, 1993; Rader & Bakke, 1991; Smolenski, et al., 1993; Stevens, et al., 1993; Stevens, et al., 1991; Weilert, 1993; Weilert & Ratliff, 1990). The paragraph below provides some background (Corbett, et al., 1977; Noblett Jr., et al., 1990) for the scrubbing process which is useful in understanding the bases for the relations provided later.

The removal of SO_2 from flue gas in a lime/limestone scrubber depends on a gas-liquid-solid mass transfer process. The sulfur dioxide is transferred from the flue gas to the slurry liquid in the scrubber and subsequently precipitated as calcium salts. In this section we provide a very

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brief discussion of the key factors that affect the SO_2 removal efficiency from a theoretical standpoint. Against this backdrop we examine empirical data which reflects the recent experience with high efficiency scrubbers and develop an approximate response surface parametrized on the key variables.

The basis for the analysis of vapor-liquid mass transfer phenomena is the two-film theory in which the total resistance to mass transfer is expressed as the sum of individual resistances in the vapor and liquid phases near the interface. Based on expressions for molar flux in the gas and liquid films and assuming that the liquid-vapor interface is at equilibrium (Corbett, et al., 1977; Mehta & Rochelle, 1983; Rochelle, 1981; Rochelle, 1981), the overall mass transfer coefficient is written as:

$$K_g = \left(\frac{1}{k_g} + \frac{H}{e \times k_l} \right)^{-1} \tag{1}$$

where k_g (mole/cm^2-sec-atm) and k_l (cm/sec) are individual gas and liquid phase mass transfer coefficients, H is a physical constant (atm/mol-liter) from Henry's Law and e is an enhancement factor to account for chemical reactions that permit SO_2 to diffuse through the liquid film as sulfite or bisulfite ions rather than as undissociated SO_2 (Chang and Rochelle 1980). The amount of SO_2 transferred from gas phase per unit time is the integral of the molar flux and the interfacial area for mass transfer. This leads to an expression for SO_2 removal efficiency as follows:

$$\eta_{SO2} = 1 - \exp\left(-\frac{K_g \times a \times P \times V}{G} \right) \tag{2}$$

where a is the interfacial mass transfer area per unit volume, V the scrubber volume, P the total pressure in scrubber, and G is the molar gas flow rate. The interfacial area is determined by the contacter design, gas distribution in the scrubber and the gas and liquid flow rates (or residence time in the scrubber). V/G is the residence time of flue gas in the scrubber and it depends on superficial velocity and size of the scrubber. The mass transfer coefficient, K_g is influenced by process variables. Any process variable which affects the physical or chemical properties of the two films may affect K_g. The individual mass transfer coefficients k_g and k_l describe the diffusion rates across two hypothetically stagnant films. In the following paragraphs we discuss the effect of various process parameters on the SO_2 removal efficiency and develop a response surface using the exponential form. All the relations developed in this section are based on a log-linear approximation (as suggested by Equation 1) and are developed as follows:

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$$RTU = -\ln(1 - \eta_{SO2})$$
$$RTU = a + \sum_i b_i \times x_i \qquad\qquad (3)$$

where a and b_i parameters which represent the linear slope of the effect of process parameters x_i.

L/G is a key variable since it affects SO_2 removal by increasing the available liquid phase alkalinity and the interfacial mass transfer area. Increasing the L/G ratio brings more alkaline materials into the scrubber per mole of SO_2 scrubbed thus decreasing the liquid film mass transfer resistance and improving the SO_2 removal. This effect is magnified by an associated increase in the interfacial mass transfer area which improves efficiency. Industry practice is based on a log-linear relation between η_{SO_2} and L/G ratio (Benson, 1993; Bhat, et al., 1993; Dene, et al., 1991; Klingspor, 1993; Rader, 1993). Typical values for η_{SO_2} and L/G are provided in the table below.

η_{SO_2}	L/G(gpm/Kacfm)
90%	90
95%	130

Based on the values in the table above, an approximate relation[1] between sulfur removal efficiency and L/G is:

$$\eta_{SO_2} = 1 - \exp\{-(0.725 + 0.0175 \times L/G)\} \qquad (4)$$

where L/G is measured in gpm/1000 acfm. The effect of lime/limestone scrubbing chemistry on SO_2 removal can be understood by considering the mass transfer resistance from the gas and liquid film separately.

Liquid Film Limited Mass Transfer

Limestone systems are generally at least partially liquid film mass transfer limited. The liquid film mass transfer resistance is a strong function of liquid phase alkalinity. When SO_2 is absorbed by an aqueous scrubbing liquor, sulfurous acid is formed. Increasing the liquid phase or solid phase concentrations of alkaline materials (such as $CaCO_3$, $CaSO_3$, Mg^{++}) increases the liquid phase alkalinity which in turn improves SO_2 removal efficiency. Increasing the liquid

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[1] All relations developed in this section are based on a wet limestone/lime FGD tower with four spray headers per tower. The default process parameters are as follows: pH=5.3, ϕ=1.03, L/G=90, inlet SO2=1750 ppm (2.6% S coal), Cl =25,000 ppm (in the slurry) and superficial velocity in tower=10 fps.

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phase alkalinity decreases the Henry's Law constant which in turn decreases the mass transfer resistance $H/(e\ k_l)$. The enhancement factor depends on the inlet SO_2 concentration and it decreases with increasing SO_2 concentrations thus increasing the mass transfer resistance. The k_l portion of the mass transfer resistance is a function of the hydraulics of the scrubber and depends on gas distribution and the geometry of scrubber.

Increasing the limestone stochiometry (ϕ) improves liquid phase alkalinity and SO_2 removal. However the effect saturates and little improvement in SO_2 removal is observed over 1.1. Limestone utilization varies inversely with the pH and is a critical factor for the operating costs of SO_2 scrubbing. Most modern scrubbers are designed for high utilization of about 95% or higher. Therefore stochiometry affects the performance in opposite ways. A detailed quantification of the effect of stochiometry on pH is not straightforward and needs the development of process simulators (Agrawal & Rochelle, 1993; Noblett Jr., et al., 1990). It is possible to get an approximate idea of how SO_2 removal is affected by pH and in turn by ϕ based on empirical data (Klingspor, 1993; Noblett Jr., et al., 1990; Rader, 1993; Stevens, et al., 1991) as shown below:

η_{SO_2}	pH	ϕ
90%	5.3	1.03
95%	6.0	1.1

Based on these numbers a linear approximation for the effect of stochiometry can be represented by an additional term in Equation 4 as follows:

$$\eta_{SO2} = 1 - \exp\{-[0.725 + 0.0175 \times L/G + (10.0 \times \phi - 10.3)]\} \qquad (5)$$

Notice that the effect of stochiometry is represented as an increase in SO_2 removal due to an increase in pH (caused by increasing ϕ) over the default value of 5.3.

Increases in the inlet SO_2 concentrations beyond 1000 ppm decreases the enhancement factor e which in turn increases the mass transfer resistance. The enhancement factor is a function of gas and solution composition (Chang & Rochelle, 1983) which affects the conversion of SO_2 to bisulfite. Typical values of SO_2 removal for different inlet SO_2 concentrations are provided below based on industry experience (Moser & Owens, 1990; Noblett Jr., et al., 1990; Stevens, et al., 1991).

η_{SO_2}	SO_2 ppm
90%	2000 (2.8% S)
84%	4000 (4% S)

This can be represented by an additional term in Equation 5 which accounts for the loss of removal efficiency as the inlet SO_2 concentration increases over 2000 ppm.

$$\eta_{so2} = 1 - \exp\left\{ \begin{array}{l} -[0.725 + 0.0175 \times L/G + (10.0 \times \phi - 10.3)] \\ -2.5 \times 10^{-4}(SO_2 - 2000)] \end{array} \right\} \qquad (6)$$

Similarly calcium chloride accumulation in the slurry leads to a decrease in SO_2 removal. Chloride accumulation suppresses the desirable effects of alkali salts by permitting their accumulation as chloride salts rather than sulfate salts. The effect of accumulated Cl concentrations in the scrubber slurry on the SO_2 removal based on industry experience (Klingspor, 1993; Moser & Owens, 1990; Noblett Jr., et al., 1990; Rader, 1993; Stevens, et al., 1991) is provided below:

η_{so_2}	Cl ppm
86%	10000
80%	80000

This is represented by a term which represents the loss in removal efficiency as the chloride concentration in slurry increases above 25,000 ppm.

$$\eta_{so2} = 1 - \exp\left\{ \begin{array}{l} -[0.725 + 0.0175 \times L/G + (10.0 \times \phi - 10.3) \\ -2.5 \times 10^{-4}(SO_2 - 2000) + 5.14 \times 10^{-6}(Cl - 25000)] \end{array} \right\} \qquad (7)$$

Addition of organic acids such as adipic, glutiric, and succinct acids to the scrubber slurry improves SO_2 removal efficiency. These acids are usually stronger than sulfurous acid and weaker than carbonic acid. This provides a buffering effect. First it assists limestone dissolution by lowering carbonate ion backpressure and hence more alkalinity in form of bicarbonate enters the scrubber in soluble form. Moreover, since sulfurous acid is a stronger acid, the organic acid ion acts as a base in SO_2 sorption. Dibasic acid (a mixture of) has been found to be the most effective organic acid for use as an additive in commercial scale scrubbers. This improves SO_2 removal and typically every 500 ppm addition of organic acids in the slurry improves SO_2 removal that is comparable to increasing the L/G by 30 gpm/Kacfm in a normal pH operating range of 5.3-5.8 (Blythe, et al., 1993; Rader & Bakke, 1991; Smolenski, et al., 1993; Stevens, et al., 1993). This simple approximation can be represented as follows:

$$\eta_{so2} = 1 - \exp\left\{ \begin{array}{l} -[0.725 + 0.0175 \times L/G + (10.0 \times \phi - 10.3) \\ -2.5 \times 10^{-4}(SO_2 - 2000) + 5.14 \times 10^{-6}(Cl - 25000) \\ + 0.00042 \times DBA] \end{array} \right\} \qquad (8)$$

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where DBA represents the concentration (in ppm) of dibasic acid in the slurry. Figure 1 plots the sensitivity of SO_2 removal efficiency (η) to the reagent stochiometry (ϕ) and the liquid to gas ratio (L/G) holding the SO_2, Cl and DBA concentration constant.

Key	Reagent Stoichiometry (mol Ca/mol S removed)
——	1.02
— —·	1.03
········	1.05
-----	1.1

Figure 1: IECM performance model for Wet Limestone FGD (with Forced oxidation). Constant parameter value for this case are [SO2]=1260 ppm, [Cl]= 32360 ppm, and [DBA]=0 ppm.

Figure 2 plots sensitivity of SO_2 removal efficiency (η) to the DBA concentration and the liquid to gas ratio (L/G) holding the SO_2, Cl and ϕ constant.

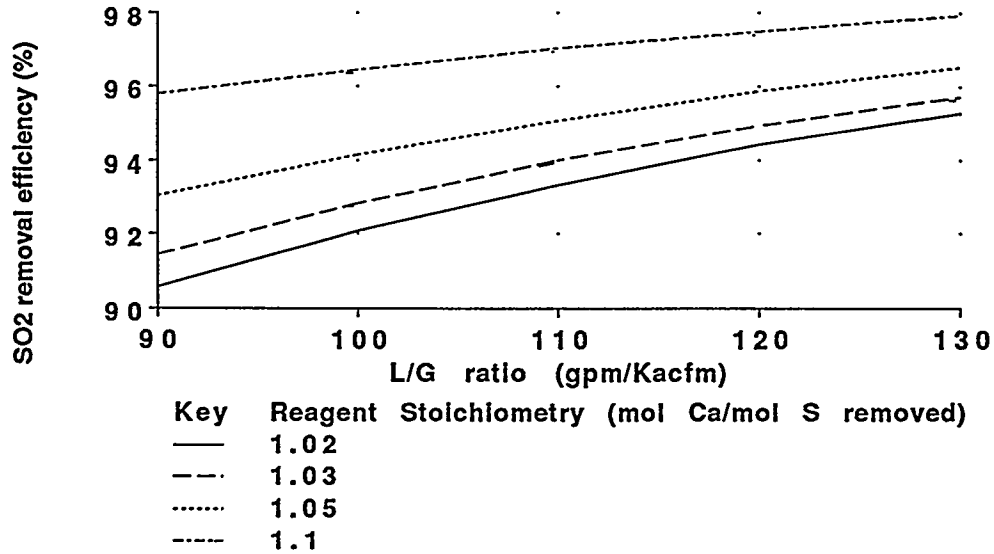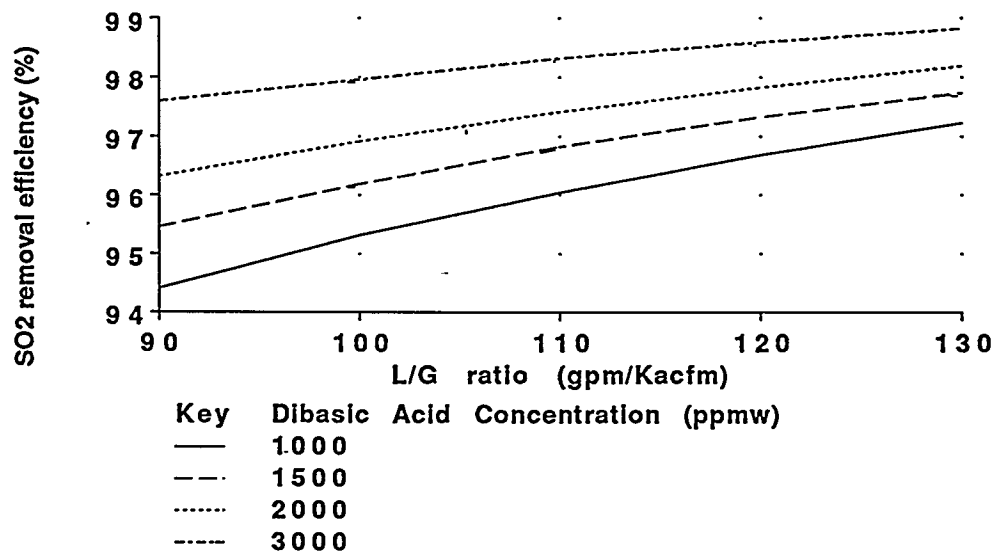| Key	Dibasic Acid Concentration (ppmw)
——	1000
— —·	1500
········	2000
-----	3000

Figure 2: IECM performance model for Wet Limestone FGD (with Forced oxidation). Constant parameter value for this case are [SO2]=1260 ppm, [Cl]= 32360 ppm, and ϕ =1.03.

Gas Film Limited

Systems with low inlet SO_2 concentrations are gas film limited, since the liquid phase alkalinity is sufficient to neutralize the dissolved SO_2. For gas film limited case the removal efficiency is largely determined by the contactor design and the L/G ratio and is not affected by the liquid phase alkalinity. The SO_2 concentration at which the liquid film resistance becomes large enough to be comparable to the gas film resistance depends on the liquid phase alkalinity and L/G ratio. For typical limestone systems with L/G in the 90-130 gpm/Kacfm interval and pH between 5.3-5.8 the transition is in the 500-1000 ppm range. Therefore for inlet SO_2 concentrations below 1000 ppm the SO_2 removal can be treated as gas film limited and a relation without the effects of liquid phase alkalinity as given in Equation 1 can be used for determining SO_2 removal.

2.2 Wet Lime FGD System

Magnesium lime systems are also gas film limited. Mag-lime systems have abundant liquid phase alkalinity since lime has a higher solubility than limestone and magnesium species (usually about 2-4% by weight) provides additional liquid phase alkalinity. Hence the availability of liquid phase alkalinity does not impose any resistance in the absorption of SO_2 and the mass transfer coefficient K_g is based solely on the gas film resistance for inlet SO_2 concentrations from 500-5000 ppm. Typical values for η_{SO_2} and L/G for mag-lime systems are provided in the table below (Benson, 1993; Benson, et al., 1991; Johnson, 1993).

η_{SO_2}	L/G(gpm/Kacfm)
95%	40
98%	56

Based on these values an approximate relation between sulfur removal efficiency and L/G is:

$$\eta_{SO_2} = 1 - \exp\{-(0.2 + 0.07 \times L / G)\} \tag{9}$$

where L/G is measured in gpm/1000 acfm. Figure 3 graphs the sensitivity of this model with the removal efficiency versus the L/G ratio for Mg-Lime systems.
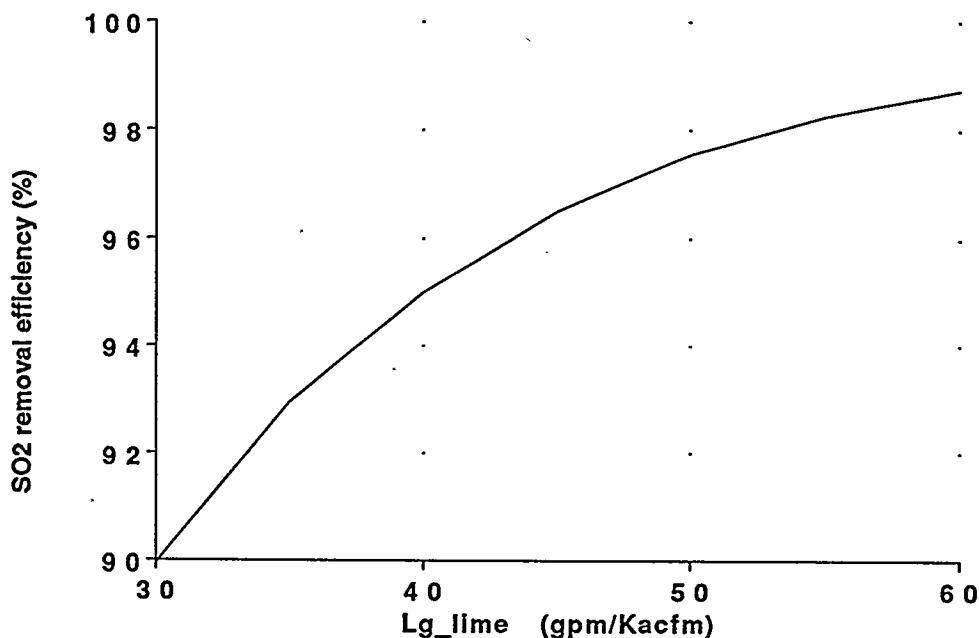
Figure 3: IECM performance model for Wet Mg-Lime FGD

2.3 Lime Spray Dryer System

Spray dryer scrubber are sometimes used as an alternative to wet scrubbing since it provides simpler waste disposal and can be installed with lower capital costs. In a typical system, hot flue gas is contacted with finely atomized aqueous solution in the spray dryer. Dry products leave the spray dryer and are removed from the gas in a baghouse. The liquid phase consists of an aqueous slurry of slaked lime. The sulfur dioxide in the flue gas is absorbed into the droplets which simultaneously evaporate on contact with the hot flue gas. Although some moisture still remains in the flue gas solids which later promotes further removal of SO_2 in the fabric filter. The total SO_2 removal is the sum of the removal in the dryer and the baghouse. In this subsection, we develop empirical relations to describe the total SO_2 removal (Blythe, et al., 1985; Blythe, et al., 1991; Brown & Felsvang, 1991).

The main process parameters which affect the SO_2 removal efficiency are: inlet SO_2 concentration, reagent ratio[2], (ϕ) calcium chloride concentrations in the liquid slurry (Cl), the inlet flue gas temperature (T_{in}), and the approach temperature to the adiabatic saturation temperature of the flue gas at outlet (ΔT) (Brown & Felsvang, 1991; Jozewicz & Rochelle, 1984). Increase in the reagent ratio increases the alkalinity in the liquid phase which improves

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[2] For spray dryers the reagent ratio is measured as moles of reagent supplied/mole of SO_2 *entering* the scrubber. Note that for wet FGD systems the reagent ratio is measured as moles of reagent/mole of SO_2 *removed.*

the SO_2 removal. Effects of inlet SO_2 concentrations are similar to those in wet FGD systems. Low inlet SO_2 concentrations (< 1000 ppm) lead to gas film limited mass transfer and medium to high inlet SO_2 concentration leads to comparable contributions from both gas and liquid film resistances. As a result, we develop different response surfaces to describe the removal efficiency for low and high inlet SO_2 concentrations. Increasing the inlet temperature allows more water to be added to the spray dryer to achieve the same approach temperature. This in turn leads to a higher recycle ratio and increased mass transfer area thus improving the removal efficiency.

In order to understand the effect of the other parameters one has to consider the heat transfer characteristics of the spray dryer. The evaporation time, t, for a given droplet is also the time available for a droplet to absorb SO_2. As the approach to saturation temperature increases, the evaporation time decreases thereby decreasing removal efficiency. The addition of chlorides in the slurry improves the SO_2 removal efficiency of the spray dryer. This is due to the deliquescent properties of chlorides which helps the droplet to retain water and hence increase the evaporation time. Hence chlorides are often used as additives to reduce the lime consumption. We now develop response surfaces to describe the overall SO_2 removal efficiency in spray dryers using data from pilot studies conducted by EPRI (1985, 1991) and Joy/Niro (Svend, et al. 1983). We use the log-linear form shown in Equation 3 to develop these response surfaces.

The reagent ratio is a key process variable and it affects the removal efficiency significantly. Typical value of SO_2 removal for different stochiometries are presented in the table below:

η_{SO_2}	ϕ
80%	0.9
90%	1.1

These values are representative of both low and high inlet SO_2 concentrations. Based on these numbers the log-linear approximation for the effect of reagent ratio is as follows:

$$\eta_{SO2} = 1 - \exp\{-(-1.495 + 3.45 \times \phi)\} \qquad (10)$$

This relation can be used for reagent ratios in the range of 0.9-1.8. Now we develop the response surface for low and high SO_2 concentrations separately.

Low Inlet SO_2 Concentrations ($\leq$ 1000 ppm)

The data presented in this section was collected against baseline conditions of 1000 ppm inlet SO_2, approach temperature of $20°F$, and inlet temperature of $280°F$. For low inlet SO_2

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concentrations, the inlet temperatures in the range of $280-325^\circ F$ has been observed to have no effect on the removal efficiency. However increasing the approach temperature to saturation from 20 to $40^\circ F$ results in the requirement of higher stochiometries for the same removal efficiencies as shown in the table below:

η_{SO_2}	ϕ
80%	1.1
85%	1.3

Averaging the effects of these values an additional term to describe this effect is added to Equation 6 as follows:

$$\eta_{SO2} = 1 - \exp\{-[-1.495 + 3.45 \times \phi - 0.05 \times (\Delta T - 20)]\} \qquad (11)$$

As discussed earlier the deliquescent properties of calcium chloride improves the removal efficiency. A presence in the slurry resulting in 0.6% calcium chloride by weight in solids collected in the fabric filter results in higher removal efficiencies for the same stochiometry as shown below:

η_{SO_2}	ϕ
90%	1.0
95%	1.2

Averaging the effects based on these values an additional term is added in Equation 7 to describe the effect of calcium chlorides as shown below:

$$\eta_{SO2} = 1 - \exp\{-[-1.495 + 3.45 \times \phi - 0.05 \times (\Delta T - 20) + 0.58 \times Cl]\} \qquad (12)$$

This is the final form of the response surface for low SO_2 inlet concentrations.

Medium to High SO_2 Concentrations (> 1000 ppm)
The data presented in this section was collected against baseline conditions of 2000 ppm inlet SO_2, approach temperature of $20^\circ F$, and inlet temperature of $325^\circ F$. For inlet SO_2 concentrations greater than 1000 ppm, the removal efficiency increases with increases in inlet temperatures from $280-325^\circ F$. Decreasing the inlet temperature to $280^\circ F$ decreases the removal efficiency to 80% for a given stochiometry of 1.1. This effect is represented by an additional term to Equations 10 as follows:

$$\eta_{SO2} = 1 - \exp\{-[-1.495 + 3.45 \times \phi + 0.015 \times (T - 325)]\} \qquad (13)$$

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The presence of 0.4% by weight of calcium chloride in the fabric filter solids provides an improved efficiency of 90% for a reagent ratio of 1.0. This is described in by an additional term as follows:

$$\eta_{SO2} = 1 - \exp\{-[-1.495 + 3.45 \times \phi + 0.015 \times (T - 325) + 0.86 \times Cl]\} \qquad (14)$$

Increasing the approach temperature to $30°F_{-}$ reduces the removal efficiency to 75% for a reagent ratio of 1.05. On the other hand increasing the inlet SO$_2$ concentration to 3000 ppm reduces removal efficiency to 80% at a reagent ratio of 1.1. These effects are included as shown below:

$$\eta_{SO2} = 1 - \exp\left\{ \begin{array}{l} -[-1.495 + 3.45 \times \phi + 0.015 \times (T - 325) + 0.86 \times Cl \\ -0.0007 \times (SO_2 - 2000) + 0.08475 \times (\Delta T - 20)] \end{array} \right\} \qquad (15)$$

This is the final form of the response surface for high SO$_2$ inlet concentrations. Figures 4 plots the removal efficiency as a function of the inlet flue gas temperature for different stochiometries. Figure 5 graphs the sensitivity of the removal efficiency as a function of the approach temperature for different stochiometries.

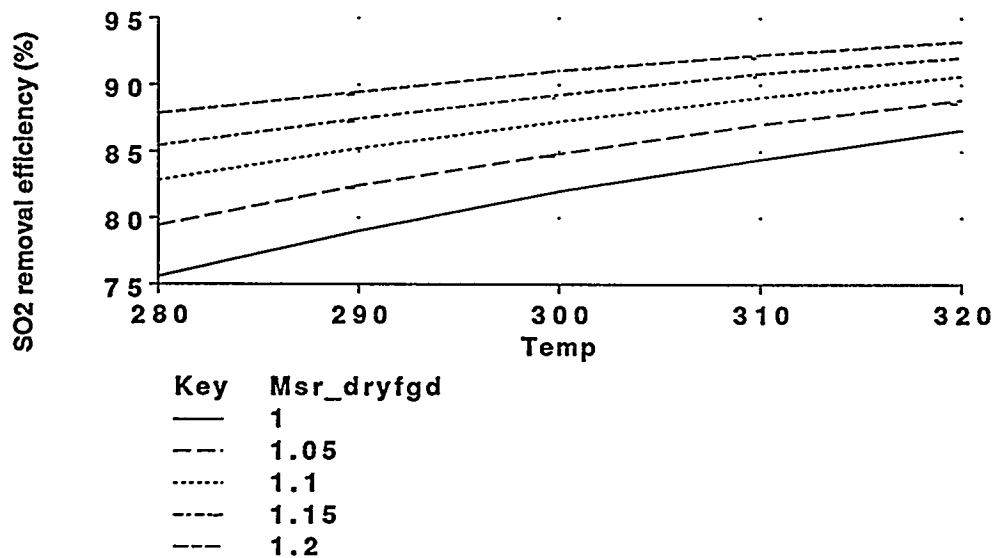| Key	Msr_dryfgd
——	1
— —·	1.05
········	1.1
----	1.15
---	1.2

Figure 4: IECM performance model for Lime Spray Dryer. Constant parameter value for this case are [Cl]=0.4% wt., [ΔT]=28 F, and [SO$_2$]= 1260 ppm
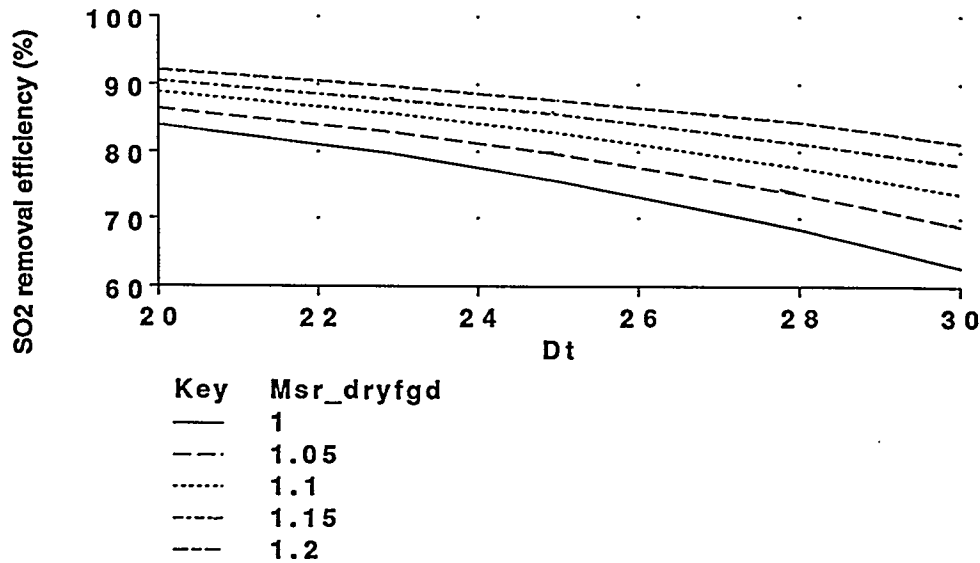
Figure 5: IECM performance model for Lime Spray Dryer. Constant parameter value for this case are [Cl]=0.4% wt., [T]=300 F, and [SO$_2$]= 1260 ppm

3.0 FGD Cost Models

The cost models that we developed were based on results from FGDCOST -- a spreadsheet program model developed for EPRI which provides the most up-to-date cost models for fifteen FGD processes (Keeth, et al., 1991). The cost development and breakdown follow the EPRI economic premises. We have augmented FGDCOST to allow for systematic sensitivity analysis with large numbers of input variables. In order to allow the simultaneous variation of many input parameters, the values of the input parameters are read from a lookup table. The values for input variables are generated from sampling probability distributions. These values are imported into the tables. On each execution, the values of all the inputs are read from each row of the table, the corresponding performance parameters are calculated and finally the capital and O&M costs are written along the same row. The output columns can be now exported to other programs for sensitivity analysis and regression modeling. In the following paragraphs we provide a brief outline of the criteria used for designing costs estimates.

Cost is broken down in terms of capital and operating and maintenance costs. We describe in some detail the breakdown of the capital costs estimates. The process parameters which affect operating costs are also outlined.

3.1 Capital Costs

Process Facilities Cost: The bases and items included for each component of the capital estimate is provided in Table 1. The process capital estimate is broken down on an area basis for each

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process area. The costs areas along with the equipment used in each area are provided in Table 2. The equipment size is based on a mass balance for various flue gas species such as SO_2, NO_x, HC_1, CO_2, N_2, and other species. The sulfur content of the flue gas flowstream is key in costing various aspects of the FGD process. Based on the mass balance the size of the various equipment required for the process areas is determined, which is then used to determine costs. The capital costs are also affected by the sparing philosophy for the absorber towers. The sum of the capital cost for all process areas provides the total process facilities cost (ctot).

General Facilities: The general facilities costs include roads, office buildings, shops, laboratories etc. A cost factor (f_{gf}) of 5 - 20% of the process capital cost is used to evaluate this cost. A cost factor of $f_{gf}=10\%$ is used as default value in the FGDCOST models.

Engineering & Home Office Fees: An estimate of engineering, home office overhead and fees is included in capital costs estimates. A cost factor (f_{eho}) of about 10 -15% is used to estimate this expense. FGDCOST uses a value of $f_{eho}=10\%$ of the process facilities cost.

Table 1. Nomenclature for EPRI Cost Estimates

ITEMS INCLUDED IN PROCESS CAPITAL COST ESTIMATE

Earthwork
Concrete
Buildings and Structures
Process Equipment
Piping
Electrical
Painting
Instruments and Controls
Insulation
Direct Field Labor
Indirect Field Costs
  Payroll Taxes
  Insurance, Bonds
  Construction Supplies
  Temporary Facilities
  Construction Equipment
  Vendor Fees

FGD SYSTEM CAPITAL COST ESTIMATE COMPONENTS

Capital Investment	$/kW
Process Capital (includes sales tax)	A
General Facilities	B
Engineering and Home Office Fees	C
Project Contingency	D
Process Contingency	E
Total Plant Cost, TPC	= A+B+C+D+E
Total Cash Expended, TCE	TPC x Adjust factor*
AFDC (Allowance for Funds During Construction)	F
Total Plant Investment, TPI	= TCE + F
Royalty Allowance	G
Preproduction Costs	H
Inventory Capital	I
Initial Catalyst and Chemicals	J
Land	K

Total Capital Requirement, TCR
  (Capital Investment Jan., 1990,
  Startup Jan., 1990)
	TPI+G+H+I+J+K

*Adjustment Factor for TCE per table 3-4 of EPRI TAG (P6587-L)

Table 2. Cost Areas for Process Capital Breakdown (Source: EPRI)

Area	Description
10	Reagent Feed System
20	SO_2 Removal System
30	Flue Gas System
40	Regeneration System
50	By-product System
60	Solids Handling System
70	General Support Area
80	Miscellaneous Equipment

10: Reagent Feed System-- all equipment required for storage, handling and preparation of raw materials, reagents, and additives used in each process.

20: SO_2 Removal System - equipment required for SO_2 scrubbing, such as the absorption tower, recirculation pumps and other associated equipment.

30: Flue Gas System - duct work and fans required for flue gas distribution to the SO_2 scrubbing system, plus gas reheat as required.

40: Regeneration System - specific to regenerable reagent systems, equipment used to regenerate spent absorbent for return to the process, plus any preconditioning system for SO_2 or H_2S off gas.

50: By-product System - production equipment for salable process by-products and storage facilities for the final products.

60: Solids Handling System - equipment required for fixation, treatment, and transportation of all sludge/dry solids materials produced by each scrubbing process.

70: General Support Area - additional equipment required to support FGD system operation such as makeup water and instrument air.

80: Miscellaneous Equipment - This area will include plant modifications necessitated by the addition of the FGD system. Also included are costs for electrical equipment tie-ins and other associated systems.

Project Contingency: Project contingency costs covers additional equipment and other costs that would arise from a more detailed design. Project contingency factors (f_{cproj}) range from 10 - 20% of process capital costs. An average value of about 15% is used in FGDCOST.

Process Contingency: A process contingency is applied to a new technology in an attempt to quantify the design uncertainty and the cost of a commercial scale system. The contingency factor (f_{cproc}) can range from 2-50% of the process capital costs. For FGD processes a contingency factor of 2% is used.

Total Plant Cost: The total plant cost (tpc) is the sum of process capital, general facilities, engineering and home office fees, and contingencies.

Total Cash Expended: The total cash expended is an estimate of the cash expected to be spend during the construction duration of the FGD system. This estimate accounts only for the escalation of costs up to the date of expenditure.

Allowance for Funds During Construction (AFUDC): The schedule for engineering procurement and construction is assumed to be two years for installation. For example, for an escalation of 5% a year, the total plant costs is multiplied by 0.0548 to calculate the allowance for interest expenses during a two year construction period. The IECM has general function which calculates the escalation costs given the escalation rate and the time for installation.

Total Plant Investment: The total plant investment is the sum of the total cash expended and the allowance for interest during construction.

Royalty Allowance: Royalties paid are 0.5% of the process capital.

Preproduction Costs: Preproduction costs are intended to cover operator training, equipment checkout, major changes in plant equipment, extra maintenance, and inefficient use of materials during plant startup. It is a sum of one-month fixed operating costs, one-month variable operating costs at full capacity and 2% of the total plant investment.

Inventory Capital: The inventory costs includes the expense of raw materials and other consumables based on a 100% capacity operation for 60 days.

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Table 3: Criteria for Calculating Operating Costs

Fixed Operating Costs	Unit	Rate
Operating Labor	Man-hrs	$20.00 (Jan. 1990)
Maintenance Labor - Slurry Handling	$/yr	3.2% of Process Capital
- Liquid Handling	$/yr	1.2% of Process Capital
Maintenance Material - Slurry Handling	$/yr	4.8% of Process Capital
- Liquid Handling	$/yr	1.8% of Process Capital
Administrative & Support Labor	$/yr	30% of Operating and Maintenance Labor

Variable Operating Costs	Unit	Jan. 1990 Cost/Unit	Additional Freight $/t	30-Yr Level Factor	30-Yr Levelized Cost/Unit
Fuel Oil (No. 6)	gal	$ 0.41	Incl	1.613	$ 0.66
Raw water	1000 gal	$ 0.60	Incl	1.613	$ 0.97
Cooling Water	1000 gal	$ 0.16	Incl	1.613	$ 0.26
Power	kwh	50 mills	Incl	1.668	83 mills
Methane	1000 ft^3	$ 3.00	Incl	1.668	$ 5.00
Lime	ton	$ 55.00	Incl	1.613	$ 88.72
Limestone	ton	$ 15.00	Incl	1.613	$ 24.20
Soda Ash	ton	$ 93.00	$ 43.00	1.613	$ 219.37
Magnesia	ton	$ 232.00	$135.00	1.613	$ 591.97
Ammonia	ton	$ 145.00	$ 5.50	1.613	$ 242.76
Sulfur Emulsion	ton	$ 220.00	Incl	1.613	$ 354.86
Dibasic Acid	ton	$ 360.00	Incl	1.613	$ 580.68
Formic Acid	ton	$ 800.00	$20 (est.)	1.613	$1322.66
Allied Catalyst	ton	$2500.00	$45.00	1.613	$4105.09
Claus Catalyst	ton	$1000.00	Incl	1.613	$1613.00
Disposal Charges,					
Dry Solids (lined)	ton (dry)	$ 9.29	Incl	1.613	$ 14.98
Fly ash (unlined)	ton (dry)	$ 8.00	Incl	1.613	$ 12.90
Fly ash with Nahcolite	ton (dry)	$ 11.14	Incl	1.613	$ 17.97
Sludge (trucked to lined landfill)	ton (dry)	$ 9.25	Incl	1.613	$ 14.92
Sludge (trucked to unlined landfill)	ton (dry)	$ 8.15	Incl	1.613	$ 13.15
Sludge (ponded)	ton (dry)	$ 6.00	Incl	1.613	$ 9.68
Gypsum (pumped & stacked)	ton (dry)	$ 4.75	Incl	1.613	$ 7.66
Condensate	1000 lb.	$ 0.77	Incl	1.613	$ 1.24
Steam					
0-70 psia	1000 lb.	$ 2.85	Incl	1.668	$ 4.75
70-250 psia	1000 lb.	$ 3.50	Incl	1.668	$ 5.84
250-400 psia	1000 lb.	$ 5.30	Incl	1.668	$ 8.84
By-product Credit					
Sulfur	Long ton	$ 90.00	Incl	1.613	$ 145.17
Sulfuric Acid	ton	$ 50.00	Incl	1.613	$ 80.65
Liquid Sulfur Dioxide	ton	$ 230.00	Incl	1.613	$ 371.00
Gypsum	ton	$ 2.00	Incl	1.613	$ 3.23

Note: 1000 gal = 3.785 m^3, t (short) = 0.9072 t (SI),
1000 ft^3 = 28.32 m^3, 1000 lb = 453.6 Kg
Assumed 100 mile shipping distance for all chemical reagents except where noted.

Table 4: Description of Default Criteria used in the Model

Variable name	Units	Description	Default Value
gas	Kacfm	flue gas flow rate	971
MW	10^6 MW	Net plant capacity	300
L/G	gpm/Kacfm	liquid to gas ratio	90/55/30[a]
%S	%	% sulfur in coal by weight	2.6% 1750 ppm
stochiometry (ϕ)		moles of Ca per mole of SO_2 removed	1.03/1.02/ 1.1[b]
labor	$/hr	FGD operating labor rate	20
reag	$/ton	reagent ($CaCO_3$/CaO) cost	15/55[d]
solid	$/ton	sludge disposal cost	8.15
stack	$/ton	sludge disposal - stacking cost	4.75
power	mills/kWh	power cost	50
steam	$/1000 lbs	steam cost	3.5
waterf	$/1000 gallons	fresh water cost	0.6
waterc	$/1000 gallons	cooling water cost	0.16
DBA_{ppm}*	ppm	scrubber slurry DBA concentration	1500
DBA_{feed}*	lbs DBA/ton SO_2 removed	DBA feed rate	20
DBA_{cost}[c]	$/ton	DBA additive cost	360
ΔP	inches of H_2O	total system pressure drop	10
ΔT	°F	temperature increase of scrubbed flue gas due to reheat	25

[a] the default values are: 90 gpm/Kacfm for LSFO and 55 gpm/Kacfm for LSDBA and 30 for Mg-lime System for a 90% removal efficiency.

[b] the stochiometry for limestone systems is 1.03, for lime systems is 1.02, and for lime spray dryer is 1.1(note that for lime spray dryer the reported stochiometry is moles of Ca per mole of inlet SO_2).

[c] these input variables for LS/DBA only

[d] limestone cost is 15 and lime cost is 55 $/ton

Land: FGD system land requirements include the plant site area and disposal area. Land has not been included as a line item.

Total Capital Requirement: The total capital requirement is calculated as the total of all the costs enumerated above.

3.2 Operating & Maintenance Costs

Operating costs for FGD systems are separated into fixed and variable operating costs. Fixed costs include operating and maintenance labor, maintenance materials and administrative/support labor. Various factors based on EPRI premises are used to estimate these costs many of which are based on capital cost estimates. Variable operating costs include consumables such as fuel, water, power, chemicals, and solids disposal. Table 3 provides the operating cost criteria used. The fixed and variable O&M costs depend on the feed rate of reagent, sludge disposal costs, power for pumping, labor and other operations. Table 4 provides the default process design criteria used in our models.

3.3 The Methodological Approach

Response surface construction is the central objective of the sensitivity analysis techniques presented in this section. Sensitivity analysis seeks to identify the set of input variables that have significant effect on the model output and to rank order them according to the magnitude of their effects. Once the relevant variables are identified regression methods can be used to develop adequate response surface replacements for the models. Subsequently probability distributions on the input variables can be used in conjunction with the response surface to derive the probability distributions of the model outputs. In this section, we briefly describe the use of Latin hypercube sampling (LHS) (Iman, et al., 1980) along with partial rank correlation coefficients (PRCC) to examine the influence of individual variables on the model output (Iman, et al., 1981a; Iman, et al., 1981b). Finally the use of regression analysis with log-linear transformations for developing response surfaces is described (Ang & Tang, 1975; Draper & Smith, 1966; Neter, et al., 1983).

3.3.1 Sampling and Ranking Methods

In order to perform sensitivity analysis it is necessary to obtain model output for various values of input variables. Latin hypercube sampling is used to select values for input variables. The LHS technique to select n different values from k different input variables operates in the following manner. For each variable, the range is divided into n nonoverlapping intervals of equal probability. One value from each interval is selected at random with respect to the

probability density in the interval. The n values for variable x_1 are paired at random with the n values of x_2 and these n pairs are paired at random with n values of x_3 and so on to generate n k-tuples. This is the Latin hypercube sample used as input to the model. The model is then exercised at each of these n input values to generate n l-tuples for l output variables of interest. This data set of n k-tuples of input values and n l-tuple of output values forms the basis for the rest of the analysis.

The importance of an input variable is derived by assessing its influence on the output variable. For linear relationships this can be assessed by the use of partial correlation coefficients (PCC) which measure the correlation between an input and output variable when the effects of all the other variables is removed. For nonlinear relations it becomes more difficult to assess the importance of individual variables. However, if the model output is a monotonic function of the input then it is possible to linearize the relationship by using rank transformations on the input and output values. A rank transformation involves replacing each value of a variable by its rank. Now the partial correlation coefficient on the rank transformed variables (PRCC) can be used to assess the importance of the input variables.

3.3.2 Regression Analysis

Once the important input variables are chosen, multivariate linear regression approaches can be used with the data set to construct response surfaces. If k input variables are chosen as relevant, a linear regression model is written as:

$$y_i = a + b_1 x_1 + b_2 x_2 + ... + b_k x_k + \varepsilon \tag{17}$$

where ε is an error term which represents the variance in y_i unexplained by the model. The linear fit is obtained by selecting a, b_i so as to minimize the sum of squares between the model predictions and the data for y_i. Often the relationships between input and output variables is nonlinear. In this case it is often possible to use some data transformation to linearize the relationship. A commonly used transformation for exponential nonlinearities is the logarithm transform. Therefore an exponential relationship such as:

$$y_i = a \times x_1^{b_1} \times x_2^{b_2} ... \times x_k^{b_k} \tag{18}$$

is transformed to:

$$\ln(y_i) = \ln(a) + b_1 \ln(x_1) + ... + b_k \ln(x_k) \tag{19}$$

which has a linear relationship.

Common statistical tests are used to determine the adequacy of the regression model. The most common measure is the coefficient of multiple correlation (R^2) which is a ratio of the variation explained by the regression to the total variation in y_i. Values of R^2 near 1 represent good fits. R^2 however is not a sufficient measure of the goodness of fit of a model. The t-statistic is used to test if the partial regression coefficients a, b_i are significantly different from zero. Moreover an F-statistic can be used to check if any of the partial correlation coefficients are different from zero. This statistic provides an idea of the lack of fit of a regression model as a whole. However, for large R^2 values this test is not informative. Standard error of a regression model provide an estimate of the variance in the residual errors for y_i. This can be used to compare across regression models (in terms of functional forms) and to conduct the Kolmogorov-Smirnov test to evaluate if the errors ε are normally distributed. The normality assumption underlies the most of the statistical tests used. Most statistical packages provide utilities for regression analysis and the statistical tests outlined in this section. The regression analysis for this work was done using *Splus* on the Andrew network (Becker, et al., 1988).

3.3.3 Analysis & Results

In the following sections we present the sensitivity analysis conducted with the FGDCOST model and provide response surface algorithms for capital costs and O&M costs based on results from FGD cost. A set of input variables is chosen and Latin hypecube sampling is used to generate a sample of 100 values for each variable using a uniform distribution for the given range. A Fortran77 package was used to generate the samples (Iman 81a). These samples are then imported into the sensitivity analysis module in FGDCOST and the model exercised to generate corresponding output values for capital and O&M costs. The data set consisting of the input samples and the corresponding output samples is used for response surface generation. PRCC, a Fortran77 package, is used to compute the partial rank correlation coefficients between the input and output variables. Note that linear relations are monotonic, hence a rank transformation does not affect the order of importance of the input variables. Using these coefficients the relevant variables for regression modeling are gleaned. *Splus* is used to generate regression models for capital and O&M costs.

4.0 FGD Capital Cost Models

In this section we present the response surface models for capital cost derived from applying the method outlined section 3 to FGDCOST . The results are very robust and provide excellent reduced form models for capital costs parametrized on a few operating parameters (no more than four to five). The accuracy is within 5% of FGDCOST which is well within the 20% uncertainty

associated with FGDCOST. The standard error of the regression models are explicitly included in the IECM as an additional uncertainty in the costs (they are usually very small, about 1%).

In the following subsection we present the capital cost models by process areas for each of the four technologies outlined in the introduction. The format used for presenting the results are as follows. For each technology, the results of the PRCC analysis are presented in tabular form. Based on the results of this analysis, the most important variables for explaining the variation in the capital costs are identified. Usually the first four or five variables are chosen. Subsequently, regression models for each process area parametrized on these few important variables are presented.

Usually, the main variables which effect the process capital costs are flue gas flow rate (Kacfm), SO_2 the inlet SO_2 concentration in flue gas (ppm), L/G ratio (gpm/Kacfm), and stochiometry. The capital costs are calculated in millions of dollars It is known from prior engineering experience that the relation between the capital costs and the input variables is exponential, hence we use logarithmic transformations on the variables and conduct a linear regression of the transformed variables. The general form of the regression model is the same for all process areas and is presented below.

$$\log(C_i) = a_i + b_i \times \log(gas) + c_i \times \log(SO_2) + d_i \times \log(L/G) + e_i \times \log(\phi)$$
$$i \in (10, 20, 30, 60, 70, 80) \tag{20}$$

where C_i is the process facilities cost of each area (denoted by the numbers 10,20,30,60,70,80) in millions of 1990 dollars. The coefficients and the significance of explanatory variables differ by process area. In the following sections we present the coefficients for each of the process areas based on a regression analysis using *Splus* (the highlights are provided in Appendix A).

4.1 Wet Limestone with Forced Oxidation

A PRCC analysis of the data set for LSFO was performed. Based on this analysis the input variables are ranked in order of importance in Table 5 below.

Table 5: PRCC Analysis for Limestone Forced Oxidation

Variables	Range	Process PRCC	Capital Rank
flue gas(Kacfm) (MW equivalent)	625-3350 (300-1000)	-0.992	1
L/G(gal/Kacfm)	90-130	0.336	4
SO_2(inlet SO_2 ppm)	0.5-5.0	0.806	3
stochiometry	1.01-1.15	0.856	2
labor rate($/hr)	15-25	0.018	10
reagent cost($/ton)	10-20	-0.066	7
solid disposal	5-10	-0.161	5
powercost(mills/kwh)	40-60	-0.03	9
steam cost($/Klbs)	3-4	0.10	6
water ($/Klbs)	0.5-0.75	-0.059	8

Now we present the development of regression models using the variables identified from the PRCC analysis. The main variables which affect the process capital costs are flue gas flow rate (Kacfm), SO_2 the inlet SO_2 concentration in flue gas (ppm), L/G ratio (gpm/Kacfm), and stochiometry (ϕ). The capital costs are expressed in millions of dollars(1990 M$) for all process areas. The coefficients for the regression model (Equation 20) are provided in Table 6 below. Recall that the models estimates $\log(C_i)$. Figure 6 graphs the sensitivity of the cost models for different coals and sizes. The y-axis plot the normalized cost ($/kW) as a function of size (MW gross) for different coals.

Table 6: Regression Coefficients for LSFO

Wet Limestone with Forced Oxidation						
Variables	Area 10	Area 20	Area 30	Area 60	Area 70	Area 80
intercept (a_i)	5.532139	5.199094	4.967549	3.728971	5.29923	5.118347
$\log$(gas) - b_i	0.2047287	0.5526016	0.5968993	0.3751297	0.0963776	0.2987416
$\log(SO_2)$ - c_i	0.1998244	0.0171820	-	0.3600074	. -	-0.0070039
$\log$(L/G) - d_i	0.064419	0.1531021	-	0.0984928	0.01744453	-
$\log(\phi)$ - e_i	0.297487	-	-	0.2896275	0.0639004	-0.4110633
R^2	0.96	0.998	0.997	0.96	0.97	0.999

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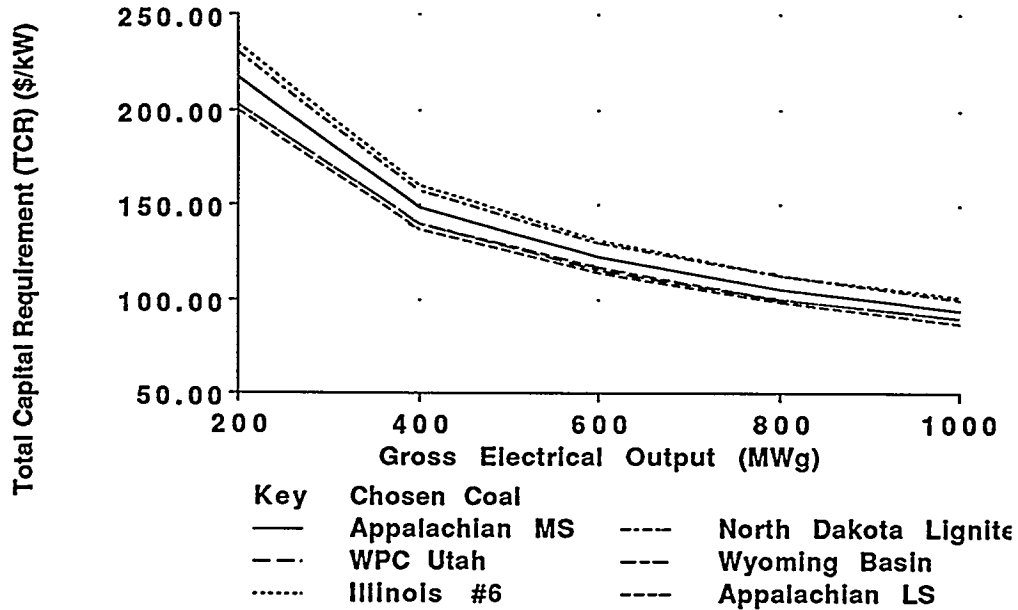
Figure 6: IECM cost model for LSFO with $\phi = 1.03$

4.2 Wet Limestone with Additives

The PRCC analysis for the LS/DBA system was performed. Based on this analysis the input variables are rank ordered in terms of the magnitude of their influence on the costs in Table 7 below:

Table 7. PRCC analysis for Wet Limestone with Dibasic Acid

Variables	Range	Capital Costs	
		PRCC	Rank
flue gas(Kacfm) size (MW)	625-3350 (300-1000)	-0.991	1
L/G(gpm/Kacfm)	50-90	0.293	4
%S(weight)	0.5-5.0	0.803	3
stochiometry	1.01-1.15	0.852	2
labor rate($/hr)	15-25	0.071	9
reagent cost($/ton)	10-20	-0.031	11
solid disposal	5-10	-0.173	6
powercost(mills/kwh)	40-60	0.056	10
steam cost($/Klbs)	3-4	0.192	5
water fresh($/Klbs)	0.5-0.75	-0.073	8
DBA ppm	1-2K	0	12
DBA feed (lbs/ton of SO_2)	15-25	-0.147	7
DBA cost($/ton)	300-400	0	12

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Now we present the development of regression models using the variables identified by the PRCC analysis. The regression analysis is parallel to the one presented for LSFO with a data set that is different, i.e. generated using a cost model for LS/DBA. The main variables which affect the process capital costs (expressed in 1990 M$) are flue gas flow rate (Kacfm), SO_2 in inlet flue gas, L/G ratio (gpm/Kacfm), and stochiometry (ϕ). Note that the range of L/G for LS/DBA is between 60-90. Once again using logarithmic transformations, linear regressions (Equation 20) for each process area are presented in Appendix A. We provide highlights for each process area in Table 8 below. Figure 7 graphs the sensitivity of the normalized cost ($/kW) for different coals and sizes (MW gross).

Table 8: Regression Coefficients for Wet Limestone with DBA

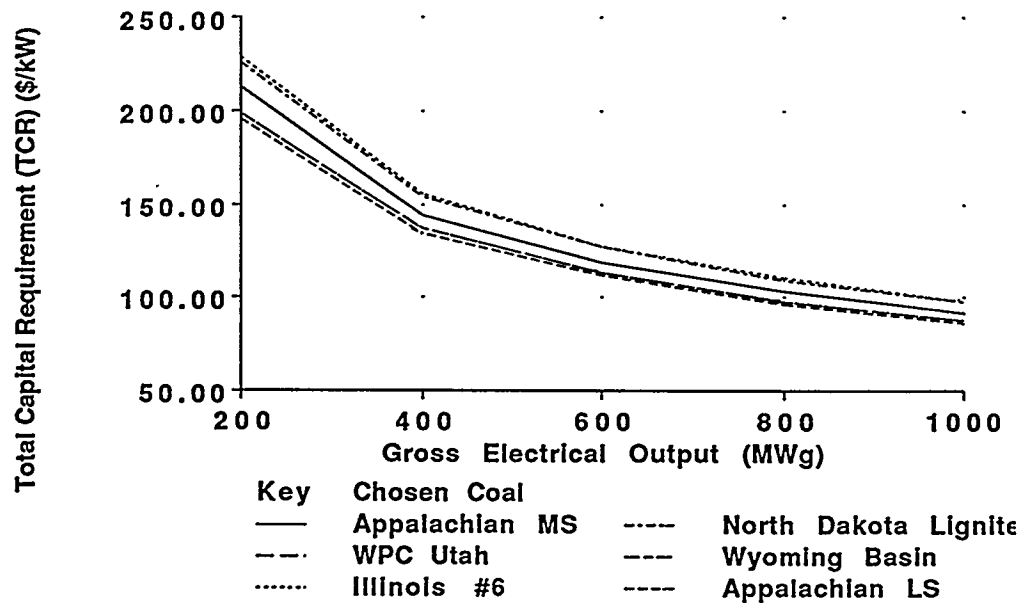| Wet Limestone with DBA						
Model Parameter	Area 10	Area 20	Area 30	Area 60	Area 70	Area 80
intercept (a_i)	5.656823	5.283843	4.967474	3.914778	5.33193	5.118347
log(gas) - b_i	0.2116698	0.5487767	0.5969214	0.3830471	0.0932564	0.2987416
log(SO_2) - c_i	0.1965567	0.0182601	-	0.3528121	0.0033284	-0.0070039
log(L/G) - d_i	-	0.1124185	-	-	-	-
log(ϕ) - e_i	0.3971839	-	-	0.6173974	0.0825347	-0.4110633
R^2	0.96	0.998	0.997	0.95	0.98	0.999

Figure 7: IECM cost model for Wet Limestone FGD with 1500 ppm of DBA as additive.

4.3 Magnesium-Enhanced Lime System

A PRCC analysis of the data set for Mg-Lime system was performed. Based on this analysis the input variables are ranked in order of importance in Table 9 below.

Table 9: PRCC Analysis for Mg-Lime

Variables	Range	Process PRCC	Capital Rank
flue gas(Kacfm) (MW equivalent)	625-3350 (300-1000)	-0.986	1
L/G(gal/Kacfm)	30-56	0.149	4
SO$_2$(inlet SO$_2$ ppm)	0.5-5.0	0.890	2
stochiometry	1.01-1.15	0.801	3
labor rate($/hr)	15-25	0.13	6
reagent cost($/ton)	50-60	-0.069	8
solid disposal	5-10	-0.133	5
powercost(mills/kwh)	40-60	-0.051	10
steam cost($/Klbs)	3-4	0.064	9
water ($/Klbs)	0.5-0.75	-0.097	7

Now we present the development of regression models using the variables identified from the PRCC analysis. The main variables which affect the process capital costs are flue gas flow rate (Kacfm), SO$_2$ the inlet SO$_2$ concentration in flue gas (ppm), L/G ratio (gpm/Kacfm), and stochiometry. The results of a regression analysis based on Equation 20 using *Splus* is provided in Appendix A. The highlights are presented in Table 10. Figure 8 graphs the sensitivity of the normalized cost ($/kW) for different coals and sizes (MW gross).

Table 10: Regression Coefficients for

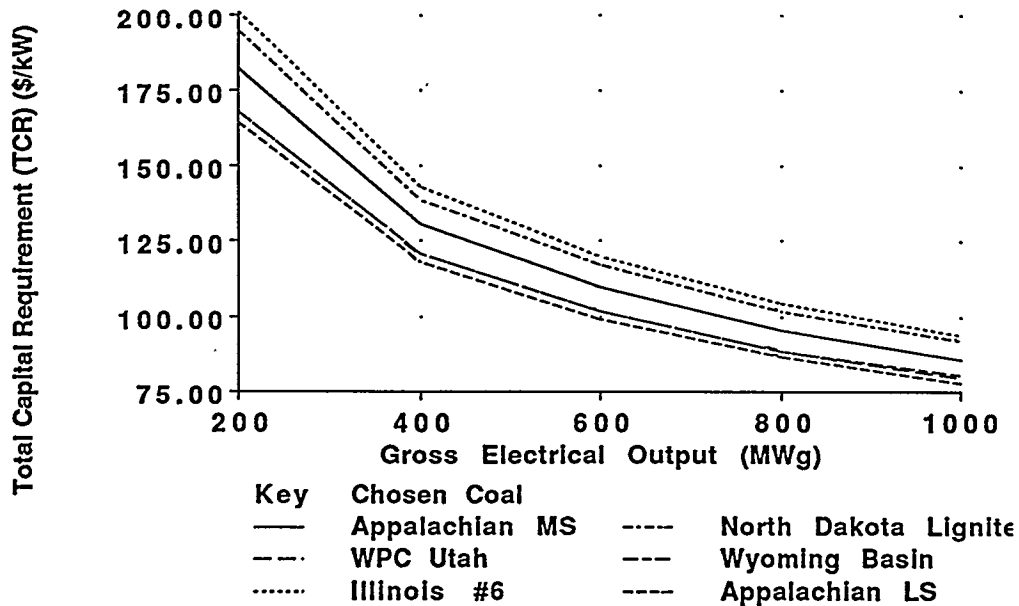| Wet Limestone with Mg-Lime						
	Area 10	Area 20	Area 30	Area 60	Area 70	Area 80
intercept (a$_i$)	4.18205	5.343637	4.985706	3.805031	5.406733	5.118347
log(gas) - b$_i$	0.4287465	0.5571364	0.5965417	0.4408358	0.0859990	0.2987416
log(SO$_2$) - c$_i$	0.3973585	-0.0031376	-0.0057330	0.4067988	-0.0042571	-0.0070039
log(L/G) - d$_i$	-	0.0865696	-	-	-	-
log(ϕ) - e$_i$	-	-	-	-	0.0711735	-0.4110633
R^2	0.96	0.999	0.999	0.97	0.98	0.999

Figure 8: IECM cost model for Mg-enhanced Lime FGD with φ = 1.02

4.4 Lime Spray Dryer

A PRCC analysis of the data set for the Lime Spray Dryer was performed. Based on this analysis the input variables are ranked in order of importance in the table below. Note however, that some of the key operating parameters are different for the Lime Spray Dryer. The water entering with the slurry spray vaporizes and the dried reaction products are carried by the flue gas (along with the fly ash). These particles are then removed in the baghouse (downstream of the FGD) and a portion of the collected solids are recycled back to the absorber. The amount of recycle (lb of dry solids recycled/lb of lime added) is based on the sulfur content of the flue gas. The total slurry that is recycled to the absorber (gpm) depends on the recycle ratio (rr), stochiometric ratio (φ) and the flue gas flow rate (gas). In order to determine the gpm we need to solve the process flowsheet of the LSD iteratively. In order to avoid this computational burden for the IECM we have developed a regression equation for the slurry flow rate as a function the recycle ratio, stochiometry and the flue gas flow rate as shown below.

$$
\begin{aligned}
\log(\text{gpm}) = \ & -0.9312959 + 0.9959784 \times \log(\text{gas}) \\
& -0.03043575 \times \log(\text{rr}) + 0.09146684 \times \log(\phi)
\end{aligned}
\tag{21}
$$

with R^2=0.994. The operating parameter gpm is used in the PRCC analysis (Table 11) and the regression analysis (instead of the equivalent L/G used for other technologies). The coefficients of the regression analysis is in Table 12.

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Table 11: PRCC Analysis for Lime Spray Dryer

Variables	Range	Process PRCC	Capital Rank
flue gas(Kacfm) (MW equivalent)	625-3350 (300-1000)	-0.602	2
stochiometry(φ	1.1-1.8	0.325	3
SO_2(inlet SO_2 ppm)	500-3500	0.827	1
gpm	70-400	0.151	5
labor rate($/hr)	15-25	0.061	9
reagent cost($/ton)	50-60	0.121	6
solid disposal	5-10	0.043	10
powercost(mills/kwh)	40-60	-0.165	4
steam cost($/Klbs)	3-4	0.084	8
water ($/Klbs)	0.5-0.75	0.106	7

Now we present the development of regression models using the variables identified from the PRCC analysis. The main variables which effect the process capital costs are flue gas flow rate (Kacfm), SO_2 the inlet SO_2 concentration in flue gas (ppm), L/G ratio (gpm/Kacfm), and stochiometry. The results of a regression analysis based on Equation 20 using *Splus* is provided in Appendix A. The highlights are presented in Table 12. Figure 9 graphs the sensitivity of the normalized cost ($/kW) for the lime spray dryer for different sizes (MW gross) and coals.

Table 12: Regression Coefficients for Lime Spray Dryer

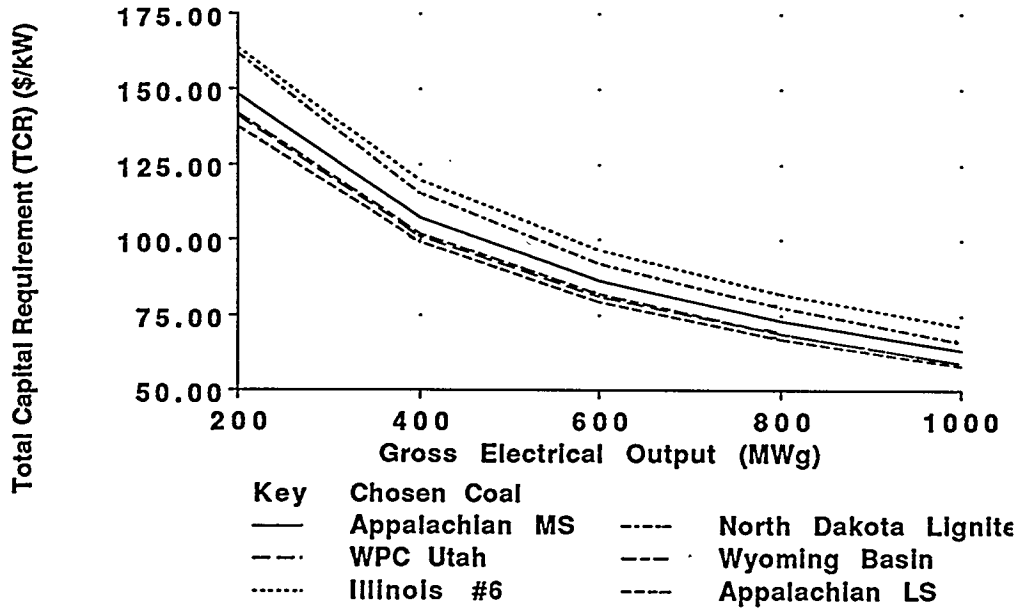| Lime Spray Dryer						
Model Parameters	Area 10	Area 20	Area 30	Area 60	Area 70	Area 80
intercept (a_i)	-1.187585	-1.391273	-1.154033	-1.742325	-0.3249075	-0.9106584
log(gas) - b_i	-0.3133721	0.8549951	0.6044183	-	-	0.300299
log(SO_2) - c_i	0.386108	-	-	0.4840697	-0.0089210	-0.0052555
gpm - d_i	0.7677725	-0.0009575	-	0.00161753	0.00016397	-
log(ϕ) - e_i	0.3871053	-	-	-	-0.0177219	-
R^2	0.97	0.97	0.998	0.95	0.98	0.9999

Figure 9: IECM cost model for Lime Spray Dryer for $\phi = 1.1$

4.5 Sparing Philosophy

The models developed in the previous subsections are based on the assumption of two operating absorber towers (each rated at 50% of the plant capacity, with a maximum of 650MW) and one spare absorber tower. With the recent development of advanced absorber towers of near 100% reliability it is possible to eliminate the spare tower and reduce capital costs significantly (no significant changes in variable costs). Another approach to reducing capital cost exploits the economy of scale by using single absorber towers of large capacity. In this subsection we develop scaling factors to estimate the reduction in capital costs for different FGD systems by changing the sparing philosophy. Note that in all the factors developed below, the scaling factors are derived by regressing the capital cost of various sparing philosophies against the capital cost of the default system, i.e. an FGD with two operating towers and one spare absorber.

In order to estimate the reduction in capital costs from eliminating the spare tower, we set the number of spare towers in FGDCOST to zero and exercise the model for various values of input for the relevant variables such as flue gas flow rate (*gas*), SO_2 in flue gas, L/G, and stochiometry (ϕ). The capital costs for system with no spares (C') is then regressed against the capital cost for the system with one spare tower (C) and correlation coefficient (s_i) of this regression provides us with the scaling factor we desire:

$$C_i' = s_i \times C_i, \quad i \in (20, 30) \tag{22}$$

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where C_i is the process area (denoted by 20, 30) cost. The capital cost of the SO_2 removal system (includes absorber towers) and the flue gas system (includes piping to absorber towers) is affected by the sparing philosophy. We present results for those process areas whose capital cost is affected in Table 13 below. The columns under "Zero Sparing" characterize the reduction in capital cost by dropping the spare absorber. The columns under "One Absorber" characterize the reduction in capital cost by reducing the number of absorbers from two (rated @50% each) to one (rated @100% of capacity).

Table 13: Regression Coefficients for Different Sparing Philosophies

System	Zero Sparing		One Absorber	
	Area 20	Area 30	Area 20	Area 30
LSFO	0.7306793	0.943658	0.5818281	0.9449641
LSFO with DBA	0.7213572	0.9436423	0.5692575	0.9316498
Mg-Lime	0.6926448	0.9437713	0.525391	0.9316498
Lime Spray Dryer	0.7114379	0.8002883	0.5126236	0.64543523

5.0 Fixed O&M Costs

The O&M costs for FGD consists of fixed costs and variable costs. The fixed operating cost consists of labor, maintenance labor, material, and administrative labor. A mathematical model for the fixed cost is provided below.

$$FOM = FOM_{labor} + FOM_{maint} + FOM_{admin}$$

$$FOM_{labor} = labor \times N_{labor} \times 40 \ (hrs/week) \times 52 \ (weeks/yr)$$

$$FOM_{maint} = \sum_i (f_{maint})_i \times TPC_i \quad where \ i = process \ area \qquad (23)$$

$$FOM_{admin} = f_{admin} \times (FOM_{labor} + f_{maintlab} \times FOM_{maint})$$

where

FOM = fixed operating and maintenance cost, M$/yr

FOM_{labor} = operating labor, M$/yr

FOM_{maint} = maintenance material costs, M$/yr, (coefficients based on EPRI TAG, the fraction $f_{maintlab}$ of these costs are allocated to maintenance labor and rest to maintenance material).

FOM_{admin} = administrative costs, M$/yr (calculated as the fraction f_{admin} of total labor-costs)

TPC_i = total process capital for each process area, (10,20,30,40, 50,60)

N = total number of laborers (per week)

labor = labor rate ($/hr)

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Figure 10 provides the levelized fixed costs (mills/kWh) as a function of size (MW gross) for different coals for wet limestone FGD systems. Similar sensitivity analysis can be conducted for other technologies.
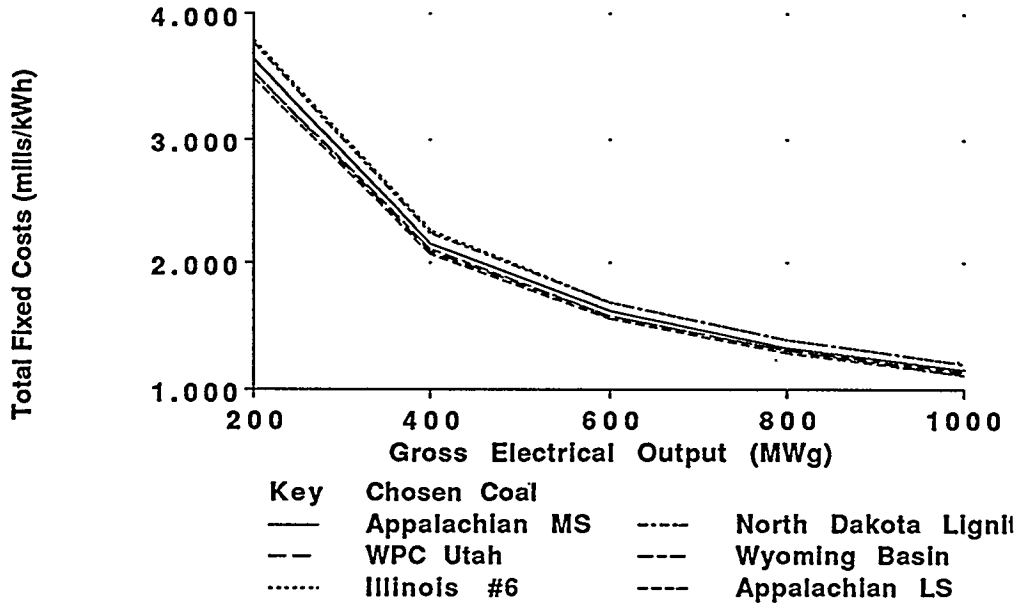
Figure 10: Fixed costs for all Wet Limestone FGD systems for 90% SO_2 removal, and default stochiometry ϕ =1.03.

6.0 Variable O&M Costs

Variable operating costs include consumables such as reagents, additives, water, power, steam for reheat and the continuous costs related to solid disposal. The variable operating costs can be usually calculated directly based on engineering principles. In this section we outline the formulations based on basic engineering principles for the calculation of variables costs. We then characterize the parameters that are specific to the different FGD technologies. The total variable cost (in M$) is given as:

varcost = rcost + scost + dbacost + pcost + stcost + wcost

where

rcost $\equiv$ reagent consumption, M$ / yr

scost $\equiv$ solid disposal cost, M$ / yr

dbacost $\equiv$ cost of Dibasic Acid feed, M$ / yr $\hspace{2cm}$ (24)

pcost $\equiv$ power consumption, M$ / yr

stcost $\equiv$ steam consumption, M$ / yr

wcost $\equiv$ makeup water cost, M$ / yr

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6.1 Reagent Cost

The total amount of reagent usage cost (rcost, M$/yr) depends on the total amount of reagent used and the cost of the reagent (reag, $/ton). The amount of reagent used (M_{reag} tons/yr) depends on the reactive species in flue gas (gas_i lbmole/yr), sulfur removal efficiency (η_{SO2}), the plant capacity factor, and the stochiometric ratio (ϕ). Therefore the model to calculate the total cost of reagent (rcost) used is:

$$rcost = reag \times T_{reag}$$

$$M_{reag} = \frac{1}{2000}\left(\sum_i (\eta_i \times \phi_i \times gas_i \times r_i) \times MW_{CaCO_3} \times cf \times 8766\right)/R_{purity} \qquad (25)$$

where $i \in (SO_2, SO_3, HCl)$

$r_i \equiv$ moles of reagent required per mole of species i

$r_i \in (1,1,\frac{1}{2})$

$MW_{CaCO_3} \equiv$ molecular weight of $CaCO_3$

$R_{purity} \equiv$ reagent purity (weight fraction of $CaCO)_3$

6.2 Solid Waste Disposal Costs

The solid waste disposal cost (scost, M$/yr) depends on the amount of solid waste and the unit cost of disposal (disposal, in $/ton). The amount of solid waste produced depends on the amount of reactive species scrubbed from the flue gas ($M_{disposal}$ tons/yr), the total amount of inerts in the slurry (M_{inerts}, tons/yr) and the amount of unused reagent in the slurry ($M_{unused\ reagent}$, tons/yr). Therefore the model to calculate the total cost of waste disposal (scost) is:

$$scost = disposal \times \left(M_{disposal} + M_{inerts} + M_{unused\ reagent}\right)$$

$$M_{disposal} = \frac{1}{2000} \times \sum_i (\eta_i \times \phi_i \times gas_i \times r_i) \times MW_i \times cf \times 8766$$

$$M_{inerts} = M_{reag} \times (1 - R_{purity}) \times cf \times 8766/2000 \qquad (26)$$

$$M_{unused\ reagent} = \frac{1}{2000} \times \sum_i \eta_i \times gas_i \times r_i \times (\phi_i - 1) \times M_{CaCO_3} \times cf \times 8766/R_{purity}$$

where $i \in (SO_2, SO_3, HCl)$

$r_i \equiv$ moles of reagent required per mole of species i

hoursannual $\equiv$ total operating hours

$r_i \in (1,1,\frac{1}{2})$

$$MW_i = \begin{cases} (MW_{CaSO_4 \bullet 2H_2O}, MW_{CaSO_4 \bullet 2H_2O}, MW_{CaCl_2}) & \text{Limestone Systems} \\ (MW_{CaSO_3 \bullet 5H_2O}, MW_{CaSO_3 \bullet 5H_2O}, MW_{CaCl_2}) & \text{Lime Systems} \end{cases}$$

6.3 Power Costs

The power costs (pcost, M$/yr) depends on the unit cost of power (power, $/MWh), and power consumption in the reagent handling (P_{20}, MW) and flue gas handling systems (P_{30}, MW). Slurry is injected into the absorber towers at four levels to remove SO_2 and each level is served by a pump. The power consumption for these pumps is proportional to the amount of slurry being pumped (Q, gallons/hr) and the total dynamic head required. Similarly the power consumption for the I.D. fans to overcome the flow resistance (or equivalent pressure drop) of the absorber towers and ducts to the chimney is proportional to the total flue gas flow rate and the pressure drop. The total power consumption (P_{total}, MW) is given by:

$$pcost = power \times P_{total} \times cf \times 8766$$
$$P_{total} = P_{20} + P_{30}$$
$$P_{20} = \rho \times Q \times H / \eta_{pump} \tag{27}$$
$$P_{30} = 0.12 \times 10^{-6} \times gas \times \Delta p / \eta_{fan}$$

where

$\rho \equiv$ density of slurry (lb/gallon)

$H \equiv$ total dynamic head, (ft)

$gas \equiv$ flue gas flow rate, (acfm)

$\Delta p \equiv$ total pressure drop, (inches of water)

$Q \equiv$ flow rate (gallons/hr = $\dfrac{L}{G} \times gas \times 60$, or $gpm \times 60$)

$\eta_{fans} \equiv$ pumping efficiency (fraction)

$\eta_{pumps} \equiv$ pumping efficiency (fraction)

The power consumption due to I.D. fans (P_{30}) is easily calculated by assuming an efficiency for the centrifugal fans (usually 60-70%). The constant factor (0.12×10^6) is a conversion factor which provides power required in MW. The total dynamic head (H) and slurry density (ρ) are not easily available in the specification of FGD systems. In order to minimize the data requirements of the model we have developed a regression model which provides a proportionality constant for the slurry pumps by aggregating the head and density as a fraction of the slurry flow rate as follows:

$$P_{30} = k_t \times Q + c, \quad t \in (LSFO, LS/DBA, Mg-Lime, LSD) \tag{28}$$

The units for k_t are in lb-ft/gallons and value reported in the table below includes the conversion factor for changing to MW. The constant c is in MW. The regression coefficients for the different technologies is provided in Table 14 below.

Table 14: Regression Coefficients for Power

Technology	LSFO	LS/DBA	Mg-Lime	LSD
k_t	3.6165×10^{-5}	3.8234×10^{-5}	3.2456×10^{-5}	9.99×10^{-5}
c	-	-	0.21	-
R2	0.99	0.98	0.99	0.9

6.4 Steam Costs

The saturated gas exiting the absorbers at approximately $127°F$ is reheated to $152°F$ using steam heat. The steam cost (stcost, M$/yr) of reheating depends on the cost of electricity, heat rate, and the energy required (E_{reqd}, Btu/hr) to reheat the flue gas. The energy required is calculated as the change in enthalpy of the flue gas (ΔH_{127}^{152}) and the heat of vaporization for the water removed (ΔH_{vapor}). IECM calculates all the necessary thermodynamic relationships and properties.

$$E_{reqd} = \Delta H_{127}^{152} + \Delta H_{vapor} \tag{29}$$

The cost of reheating is calculated by estimating the cost of the equivalent electricity that could have been generated if the steam had not been used for reheating:

$$stcost = E_{reqd} / hr \times power \times cf \times 8766 \tag{30}$$

where hr is the steam cycle heat rate (Btu/kWh) and *power* is the cost of electricity ($/kWh).

6.5 DBA Costs

For systems that use organic acid additives (LS/DBA), the cost of replacing DBA which degrades on a yearly basis (dbacost, M$/yr) depends on the replacement cost of Dibasic Acid (C_{DBA}, $/ton), and the amount of DBA degradation (F_{DBA}, tons/yr), which depends on the amount of SO_2 removed (M_{SO2}, tons/yr) and the degradation of DBA per ton of SO_2 removed (D_{DBA}, lb of DBA/ton of SO_2 removed). This is characterized as follows:

$$dbacost = C_{DBA} \times F_{DBA}$$

$$M_{SO_2} = \frac{1}{2000} \times (\eta_{SO_2} \times gas_{SO_2} \times M_{SO_2}) \times cf \times 8766 \tag{31}$$

$$F_{DBA} = \frac{1}{2000} \times D_{DBA} \times T_{SO_2} \times cf \times 8766$$

6.6 Water Costs

Water from the scrubbing slurry is lost due to evaporation in the scrubber. The water costs pertain to the supply needed to replenish this loss. The water cost (wcost, M$/yr) depends on the

cost of fresh water (waterf, $/Kgallons), and the total amount of water used (Wtotal, Kgallons). The water costs are characterized as:

$$wcost = waterf / 1000 \times W_{total}$$

$$W_{total} = W_{MW} \times 60 \times MW_{gross} \times hoursannual \qquad (32)$$

where W_{MW} is the water consumed (gallons/min) per MW gross. This consumption differs for different technologies. Nominal values used for model development are shown in Table 15 below.

Table 15: Water Consumption for FGD Systems

Technology	LSFO	LS/DBA	Mg-Lime	LSD
W_{MW} (gpm/MW)	0.098	0.098	1.08	-

Figure 11 graphs the total levelized variable O&M costs (mills/kWh) as a function of size (MW gross) and coal type for Wet Limestone FGD. Similar analysis can be conducted for different technologies.
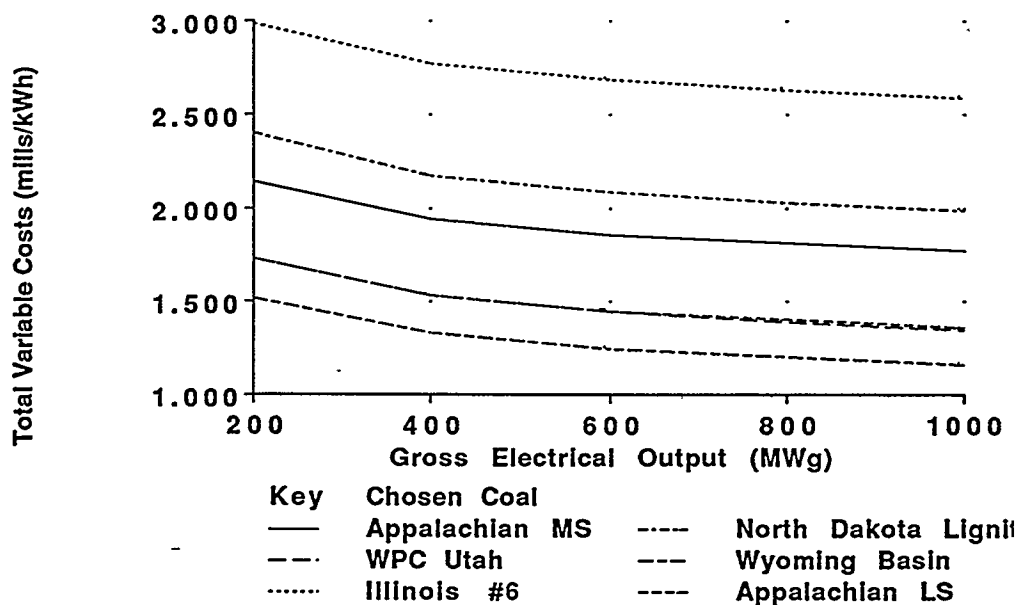

Figure 11: Variable costs for all Wet Limestone FGD systems for 90% SO2 removal, and default stochiometry ϕ = 1.03.

7.0 A Numerical Example

In this section we provide an illustrative example which uses the models developed above to calculate the capital and O&M costs for a given set of inputs. We compute costs for the limestone forced oxidation (LSFO) FGD system. A plant of gross capacity of 330 MW (300 net) which uses a medium sulfur Appalachian coal (2.13% sulfur and 0.07% chlorine) and operates at 65% capacity factor, yielding 5698 hours/yr of operation. We design the FGD system for a SO_2 removal efficiency of 95% with a stochiometric ratio of 1.03. The base case assumes 2 absorber towers and 1 spare tower. We use Equation 8 to evaluate the L/G ratio as shown.

$$0.95 = 1 - \exp\left\{ \begin{array}{l} -(0.725 + 0.0175 \times L/G + (10.0 \times 1.03 - 10.3) \\ -2.5 \times 10^{-4}(1260 - 2000) + 5.14 \times 10^{-6}(27900 - 25000)) \end{array} \right\}$$

$$\Rightarrow L/G = 120 \text{ gpm} / \text{Kacfm}$$

The operating parameters of the power plant are calculated using IECM and are provided below

Operating parameters	Variable name	Value
flue gas flow rate, Kacfm	gas	1064 Kacfm
SO_2 inlet concentration, SO_2, ppm	SO_2	1260 ppm
Chloride conc. in slurry stream, Cl, ppm	Cl	27900 ppm
L/G ratio, gpm/Kacfm	L/G	120 gpm/Kacfm

7.1 Capital Cost

The calculation of process facilities capital is based on Equation 20 and the regression coefficients in Table 11. The template for such calculations is provided in Table 16 below.

Table 16: Example Calculation of Process Capital Costs (1990 $)

Wet Limestone with Forced Oxidation						
Variables	Area 10	Area 20	Area 30	Area 60	Area 70	Area 80
(a_i)	5.532139	5.199094	4.967549	3.728971	5.29923	5.11835
$b_i \times \log(gas)$	0.6197	1.673	1.807	1.136	0.2918	0.9043
$c_i \times \log(SO_2)$	0.6185	0.05318	-	1.114	-	-0.0217
$d_i \times \log(L/G)$	0.134	0.3184	-	0.2048	0.03627	-
$e_i \times \log(\phi)$	3.819m	-	-	3.718m	820.3u	-5.277m
sum(variables)	6.908	7.243	6.774	6.187	5.628	5.996
C_i (M$)	8.094	17.52	5.949	1.54	0.425	0.99

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The total process facilities cost is the sum over all process areas.

$$\text{PFC} = \sum_i C_i = 34.52 \text{ M\$ (1990)}$$

$$= 34.86 \text{ M\$ (1993)}$$

The IECM uses chemical engineering cost indices to provide the cost indexed by other years. The typical default year that is used in IECM is 1993, hence we scale the costs to this year and conduct all subsequent calculations in 1993 dollars. Note that a cost index of 1.01 has been used to provide all numbers in 1993 dollars. The indirect costs are calculated as fractions of the process capital based on Table 2. The calculations based on this are shown below in Table 17.

Table 17: Capital Cost Summary (1993 $)

Capital Investment	M$	$/kW
Process Facilities Capital $\sum_i C_i$	34.86	116.6
General Facilities (10%)	3.486	11.66
Engg. & Home Office Fees(10%)	3.486	11.66
Project Contingency (15%)	5.229	17.49
Process Contingency (2%)	0.6972	2.333
Total Plant Cost	47.76	159.8
Total Cash Expended (Adjust Factor=1)	47.76	159.8
AFDUC (Adjust Factor=0.0548)	1.156	3.867
Total Plant Investment (TPI)	48.91	163.7
Royalty Allowance (0.5%)	0.1743	0.5831
Preproduction costs	1.621	5.416
Inventory Capital	0.1647	0.5509
Total Capital Requirement	50.87	169.9

7.2 Fixed O&M Costs

The calculations for fixed operating costs are provided using the following default values for model parameters:

N = 32 (total number of laborers, per week)

labor = 21.87 $/hr (labor rate)

f_{maint} = (0.04,0.06,0.02,0.04,0.015,0.015)

f_{admin} = 30%

$f_{maintlab}$ = 40%

These calculations are based on Equation 23

$$\text{FOM}_{\text{labor}} = 21.87 \times 32 \times 40 \ (\text{hrs}/\text{week}) \times 52 \ (\text{weeks}/\text{yr}) = 1.44 \ \text{M\$}/\text{yr}$$

$$\text{FOM}_{\text{maint}} = 0.04 \times \text{TPC}_{10} + 0.06 \times \text{TPC}_{20} + 0.02 \times \text{TPC}_{30}$$
$$+ 0.04 \times \text{TPC}_{60} + 0.015 \times \text{TPC}_{70} + 0.015 \times \text{TPC}_{80} = 2.182 \ \text{M\$}/\text{yr}$$

$$\text{FOM}_{\text{admin}} = 0.3 \times (\text{FOM}_{\text{labor}} + 0.4 \times \text{FOM}_{\text{maint}}) = 0.694 \ \text{M\$}/\text{yr}$$

$$\text{FOM} = \text{FOM}_{\text{labor}} + \text{FOM}_{\text{maint}} + \text{FOM}_{\text{admin}} = 4.32 \ \text{M\$}/\text{yr} \ (14.42 \ \text{\$}/\text{kW-yr})$$

7.3 Variable O&M Costs

The calculations for variable operating costs are providing using the following default values for model parameters:

η = 95% (SO_2 removal efficiency)

ϕ = 1.03 (reagent stochiometry)

gas_{SO2} = 140.8 (lb moles/hr, IECM calculation)

gas_{SO3} = 1.63 (lb moles/hr, IECM calculation)

gas_{HCl} = 8.67 (lb moles/hr, IECM calculation)

ΔH_{127}^{152} = 19.7 MBtu/hr (IECM calculation)

ΔH_{vapor} = 1.24 MBtu/hr (IECM calculation)

reag = 15 \$/ton (reagent cost)

cf = 65% (capacity factor)

R_{purity} = 94% (reagent purity, wt. fraction)

MW_{CaCO_3} = 100 (molecular weight)

$MW_{CaSO_4 \cdot 2H_2O}$ = 172 (molecular weight)

MW_{CaCl_2} = 112 (molecular weight)

<u>Reagent Cost</u>

This calculation is based on Equation 25

$$T_{\text{reag}} = \frac{1}{2000} \left(\sum_i \begin{Bmatrix} (0.95 \times 1.03 \times 140.8 \ (SO_2) \times 1) + \\ (0.95 \times 1.0 \times 1.63 \ (SO_3) \times 1) + \\ (0.95 \times 1.0 \times 8.67 \ (HCl) \times 0.5) \end{Bmatrix} \times 100 \times 5698 \right) / 0.94 = 44.26K$$

$$\text{rcost} = 15.15 \times T_{\text{reag}} = 0.671 \ \text{M\$}$$

Solid Waste Disposal Costs

This calculation is based on Equation 26

$$T_{disposal} = \frac{1}{2000} \times \left(\sum_i \left\{ \begin{array}{l} (0.9 \times 1.03 \times 140.8 \ (SO_2) \times 1 \times 172) + \\ (0.9 \times 1.0 \times 1.63 \ (SO_3) \times 1 \times 172) + \\ (0.9 \times 1.0 \times 8.67 \ (HCl) \times 0.5 \times 112) \end{array} \right\} \times 5698 \right) = 69.63K \ (tons/yr)$$

$$T_{inerts} = 44.26K \times (1 - 0.94) / 2000 = 3.365K \ (tons/yr)$$

$$T_{unused \ reagent} = \frac{1}{2000} \times \left(\sum_i \left\{ \begin{array}{l} (0.9 \times (1.03 - 1) \times 140.8 \ (SO_2) \times 1) + \\ (0.9 \times (1.0 - 1.0) \times 1.63 \ (SO_3) \times 1) + \\ (0.9 \times (1.0 - 1.0)1.0 \times 8.67 \ (HCl) \times 0.5) \end{array} \right\} \times 100 \times 5698 \right) / 0.94$$

$$= 1.238 \ K \ (tons/yr)$$

$$scost = 8.15 \times \left(T_{disposal} + T_{inerts} + T_{unused \ reagent} \right) = 0.605 \ M\$$$

Power Costs

This calculation is based on Equations 27 and 28

$$P_{20} = 3.62 \times 10^{-5} \times 120 \times 1064 + 0 = 3.34 \ MW$$

$$P_{30} = 0.12 \times 10^{-6} \times 1064 \times 10 / 0.5 = 2.56 \ MW$$

$$P_{total} = P_{20} + P_{30} = 5.73 \ MW$$

$$pcost = 43.45 \times P_{total} \times 5698 = 1.78 \ M\$$$

Steam Costs

This calculation is based on Equations 29 and 30

$$E_{reqd} = 19.7 \ (\Delta H_{127}^{152}, \ MBtu/hr) + 1.24 \ (\Delta H_{vapor}, \ MBtu/hr) = 20.94 \ (MBtu/hr)$$

$$stcost = 20.94 \times 1K / 7880 \times 43.45 \times 5698 = 0.665 \ M\$$$

Water Costs

This calculation is based on Equation 32

$$W_{total} = 0.098 \times 330 \times 60 \times 5698 = 11.06 \ Kgallons/year$$

$$wcost = 0.7 \ (\$/K \ gallons) \times W_{total} = 7721 \ \$/yr \ (4.53 \times 10^{-3} \ mills/kWh)$$

Total Variable Operating Costs

The total variable costs (mills/kWh) are derived as the sum of the reagent, solid waste disposal, power and steam costs as follows:

$$fixcost = 4.32 \ M\$$$

$$varcost = 0.671 + 0.605 + 1.78 + 0.665 + 0.0077 = 3.724 \ M\$$$

$$totalcost = 8.04 \ M\$ \ (4.735 \ mills/kWh)$$

7.4 Sparing Options

	Zero Sparing		One Absorber	
	Area 20	Area 30	Area 20	Area 30
LSFO	12.93 (17.69)	5.67 (6.01)	10.29 (17.69)	5.678 (6.01)

The numbers in (brackets) are capital costs for 2 towers and 1 spare (base case assumption) and are provided for comparison.

In the technical paper which is included in Appendix B, we exercise the IECM model to illustrate various sensitivities of the FGD performance and cost models. The paper also illustrates the use of uncertainty analysis.

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Appendix A: Regression Modeling of Capital Costs

```
=========================
LSFO w/o Additives
=========================


> mlc10<-log(c10*mw*1000*300/313,10)
> mcap10<-data.frame(mlc10,loggas,lognso2,logphi,loglg)
> mcap10.fit<-lm(mlc10~loggas+lognso2+logphi+loglg,mcap10)
> summary(mcap10.fit)


Call: lm(formula = mlc10 ~ loggas + lognso2 + logphi + loglg, data = mcap10)
Residuals:
       Min       1Q     Median       3Q      Max
  -0.02224 -0.008362 -0.002918 0.005144 0.05366

Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  5.5321   0.0707   78.2986   0.0000
     loggas  0.2047   0.0070   29.0497   0.0000
    lognso2  0.1998   0.0056   35.7683   0.0000
     logphi  0.2975   0.0820    3.6261   0.0005
      loglg  0.0644   0.0300    2.1463   0.0345


Residual standard error: 0.01314 on 93 degrees of freedom
Multiple R-Squared: 0.9574
F-statistic: 523 on 4 and 93 degrees of freedom, the p-value is 0


Correlation of Coefficients:
         (Intercept)  loggas lognso2  logphi
 loggas  -0.2848
lognso2  -0.4721       0.0439
 logphi  -0.0277      -0.0781  0.0002
  loglg  -0.9089      -0.0534  0.2357   0.0171
> coefficients(mcap10.fit)
  (Intercept)     loggas    lognso2    logphi       loglg
     5.532139 0.2047287 0.1998244 0.297487 0.06441896
---------------
> mlc20<-log(c20*mw/1000,10)
> mcap20<-data.frame(mlc20,loggas,lognso2,logphi,loglg)
> mcap20.fit<-lm(mlc20~loggas+lognso2+loglg,mcap20)
> summary(mcap20.fit)


Call: lm(formula = mlc20 ~ loggas + lognso2 + loglg, data = mcap20)
Residuals:
        Min       1Q     Median       3Q      Max
  -0.006228 -0.002519 -0.0003724 0.001683 0.03817

Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  5.1991   0.0273  190.1002   0.0000
     loggas  0.5526   0.0027  203.1090   0.0000
    lognso2  0.0172   0.0022    7.9424   0.0000
      loglg  0.1531   0.0116   13.1746   0.0000


Residual standard error: 0.005087 on 94 degrees of freedom
Multiple R-Squared: 0.9978
F-statistic: 13960 on 3 and 94 degrees of freedom, the p-value is 0


Correlation of Coefficients:
         (Intercept)  loggas lognso2
 loggas  -0.2880
lognso2  -0.4723       0.0441
  loglg  -0.9089      -0.0523  0.2357
> coefficients(mcap20.fit)
  (Intercept)     loggas    lognso2      loglg
     5.199094 0.5526016 0.01718195 0.1531021
```

```
--------------------------
> mlc30<-log(c30*mw*1000*300/313,10)
> mcap30<-data.frame(mlc30,loggas,lognso2,logphi,loglg)
> mcap30.fit<-lm(mlc30~loggas,mcap30)
> summary(mcap30.fit)

Call: lm(formula = mlc30 ~ loggas, data = mcap30)
Residuals:
      Min        1Q     Median        3Q       Max
 -0.01024 -0.004582 -0.001324  0.003668  0.03065

Coefficients:
              Value Std. Error  t value  Pr(>|t|)
(Intercept)  4.9675    0.0110  452.3771    0.0000
     loggas  0.5969    0.0034  176.2617    0.0000

Residual standard error: 0.006351 on 96 degrees of freedom
Multiple R-Squared: 0.9969
F-statistic: 31070 on 1 and 96 degrees of freedom, the p-value is 0

Correlation of Coefficients:
       (Intercept)
loggas -0.9983
> coefficients(mcap30.fit)
 (Intercept)    loggas
    4.967549 0.5968993
--------------
```

```
> mlc60<-log(c60*mw*1000*300/313,10)
> mcap60<-data.frame(mlc60,loggas,lognso2,logphi)
> mcap60.fit<-lm(mlc60~loggas+lognso2,mcap60)
> mcap60.fit<-lm(mlc60~loggas+lognso2,mcap60)
> summary(mcap60.fit)

Call: lm(formula = mlc60 ~ loggas + lognso2 + logphi + loglg, data = mcap60)
Residuals:
      Min       1Q    Median       3Q      Max
 -0.03372  -0.0176 -0.006184  0.01326  0.1023

Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  3.7290    0.1289  28.9272   0.0000
     loggas  0.3751    0.0129  29.1743   0.0000
    lognso2  0.3600    0.0102  35.3197   0.0000
     logphi  0.2896    0.1497   1.9349   0.0560
      loglg  0.0985    0.0548   1.7986   0.0753

Residual standard error: 0.02397 on 93 degrees of freedom
Multiple R-Squared: 0.9567
F-statistic: 513.4 on 4 and 93 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)  loggas lognso2  logphi
 loggas -0.2848
lognso2 -0.4721        0.0439
 logphi -0.0277       -0.0781  0.0002
  loglg -0.9089       -0.0534  0.2357   0.0171
>coefficients(mcap60.fit) coefficients(mcap60.fit)
 (Intercept)    loggas   lognso2    logphi      loglg
    3.728971 0.3751297 0.3600074 0.2896275 0.09849275
```

```
----------------------------
> mlc70<-log(c70*mw*1000*300/313,10)
> mcap70<-data.frame(mlc70,loggas,lognso2,logphi)
> mcap70.fit<-lm(mlc70~loggas+logphi+loglg,mcap70)
```

```
> summary(mcap70.fit)

Call: lm(formula = mlc70 ~ loggas + logphi + loglg, data = mcap70)
Residuals:
      Min       1Q     Median        3Q      Max
 -0.005065 -0.002174 -0.0008096 0.001201 0.008556

Coefficients:
              Value Std. Error  t value  Pr(>|t|)
(Intercept)  5.2992     0.0150 352.1608    0.0000
     loggas  0.0964     0.0017  56.6582    0.0000
     logphi  0.0639     0.0198   3.2239    0.0017
      loglg  0.0174     0.0070   2.4755    0.0151

Residual standard error: 0.003174 on 94 degrees of freedom
Multiple R-Squared: 0.9724
F-statistic: 1102 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)  loggas   logphi
loggas -0.2999
logphi -0.0313      -0.0782
 loglg -0.9310      -0.0657  0.0175
> coefficients(mcap70.fit)
  (Intercept)       loggas      logphi       loglg
      5.29923  0.09637758  0.06390039  0.01744526
----------------------


> mlc80<-log(c80*mw/1000,10)
> mcap80<-data.frame(mlc80,loggas,lognso2,logphi,loglg)
> mcap80.fit<-lm(mlc80~lognso2+logphi+loggas,mcap80)
> summary(mcap80.fit)

Call: lm(formula = mlc80 ~ lognso2 + logphi + loggas, data = mcap80)
Residuals:
      Min        1Q     Median        3Q      Max
 -0.002877 -0.0004898 -9.283e-05 0.0002998 0.01703

Coefficients:
              Value Std. Error   t value   Pr(>|t|)
(Intercept)  5.1183     0.0042 1207.8968     0.0000
    lognso2 -0.0070     0.0008   -8.9711     0.0000
     logphi -0.4111     0.0118  -34.8486     0.0000
     loggas  0.2987     0.0010  295.2050     0.0000

Residual standard error: 0.001889 on 94 degrees of freedom
Multiple R-Squared: 0.9989
F-statistic: 29330 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept) lognso2   logphi
lognso2 -0.6363
 logphi -0.0292     -0.0039
 loggas -0.8005      0.0582 -0.0773
> coefficients(mcap80.fit)
  (Intercept)       lognso2       logphi      loggas
     5.118347  -0.007003863  -0.4110633   0.2987416
------------------------


> summary(data.fit)

Call: lm(formula = mw ~ gas + sfrac, data = data.frame)
Residuals:
    Min     1Q  Median      3Q   Max
```

```
-68.27 -21.87 -0.4304 20.35 71.3
```

Coefficients:
```
               Value  Std. Error   t value   Pr(>|t|)
(Intercept)   39.3911   11.5421    3.4128     0.0009
       gas    0.3104     0.0043   71.4297     0.0000
     sfrac -842.6684   247.7371   -3.4015     0.0010
```

Residual standard error: 31.33 on 95 degrees of freedom
Multiple R-Squared: 0.982
F-statistic: 2598 on 2 and 95 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
        (Intercept)        gas
  gas -0.7605
sfrac -0.6527         0.0873
```
```
> coefficients(data.fit)
  (Intercept)        gas       sfrac
     39.39107  0.3103845  -842.6684
```

```
==========================================
LSFO with DBA
==================================
```

```
> mdcap10<-data.frame(mldc10,loggas,lognso2,logphi,logdlg)
>  mdcap10.fit<-lm(mldc10~loggas+lognso2+logphi,mdcap10)
> summary(mdcap10.fit)
```

Call: lm(formula = mldc10 ~ loggas + lognso2 + logphi, data = mdcap10)
Residuals:
```
      Min         1Q     Median        3Q      Max
 -0.02362 -0.007943 -0.003366  0.005998  0.051
```

Coefficients:
```
              Value  Std. Error   t value  Pr(>|t|)
(Intercept)  5.6568    0.0302    187.2158   0.0000
     loggas  0.2117    0.0072     29.3330   0.0000
    lognso2  0.1966    0.0056     35.3073   0.0000
     logphi  0.3972    0.0841      4.7221   0.0000
```

Residual standard error: 0.01347 on 94 degrees of freedom
Multiple R-Squared: 0.956
F-statistic: 680.7 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
          (Intercept)   loggas  lognso2
  loggas -0.8005
 lognso2 -0.6363        0.0582
  logphi -0.0292       -0.0773  -0.0039
```
```
> coefficients(mdcap10.fit)
  (Intercept)      loggas    lognso2     logphi
     5.656823  0.2116698  0.1965567  0.3971839
```
```
-------------------
```

```
> mldc20<-log(dc20*mw*300/313*1000,10)
> mdcap20<-data.frame(mldc20,loggas,lognso2,logphi,loglg)
>  mdcap20.fit<-lm(mldc20~loggas+lognso2+logdlg,mdcap20)
> summary(mdcap20.fit)
```

Call: lm(formula = mldc20 ~ loggas + lognso2 + logdlg, data = mdcap20)
Residuals:
```
       Min         1Q     Median         3Q       Max
 -0.006319 -0.001789 -0.000441  0.0009615  0.03606
```

Coefficients:
```
              Value Std. Error  t value Pr(>|t|)
(Intercept)  5.2838    0.0199  265.3164   0.0000
    loggas   0.5488    0.0025  221.0866   0.0000
   lognso2   0.0183    0.0019    9.4345   0.0000
    logdlg   0.1124    0.0081   13.7953   0.0000
```

Residual standard error: 0.004631 on 94 degrees of freedom
Multiple R-Squared: 0.9981
F-statistic: 16310 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
        (Intercept)  loggas lognso2
 loggas  -0.4898
lognso2  -0.4552       0.0697
 logdlg  -0.8533       0.0835  0.1487
```
> coefficients(mdcap20.fit)
```
  (Intercept)     loggas      lognso2       logdlg
    5.283843  0.5487767   0.01826008   0.1124185
```

> mldc30<-log(dc30*mw*300/313*1000,10)
> mdcap30<-data.frame(mldc30,loggas,lognso2,logphi,logdlg)
>   mdcap30.fit<-lm(mldc30~loggas,mdcap30)
> summary(mdcap30.fit)

Call:. lm(formula = mldc30 ~ loggas, data = mdcap30)
Residuals:
```
     Min       1Q    Median       3Q      Max
 -0.01024 -0.004578 -0.001354 0.003609 0.03064
```

Coefficients:
```
              Value Std. Error  t value Pr(>|t|)
(Intercept)  4.9675    0.0110  453.0489   0.0000
    loggas   0.5969    0.0034  176.5327   0.0000
```

Residual standard error: 0.006342 on 96 degrees of freedom
Multiple R-Squared: 0.9969
F-statistic: 31160 on 1 and 96 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
        (Intercept)
loggas  -0.9983
```
> coefficients(mdcap30.fit)
```
  (Intercept)   ·loggas
    4.967474  0.5969214
```

> mldc60<-log(dc60*mw*300/313*1000,10)
> mdcap60<-data.frame(mldc60,loggas,lognso2,logphi,logdlg)
>   mdcap60.fit<-lm(mldc60~loggas+lognso2+logphi,mdcap60)
> summary(mdcap60.fit)

Call: lm(formula = mldc60 ~ loggas + lognso2 + logphi, data = mdcap60)
Residuals:
```
     Min       1Q    Median       3Q      Max
 -0.05077  -0.0166 -0.004444 0.01426  0.1004
```

Coefficients:
```
              Value Std. Error  t value Pr(>|t|)
(Intercept)  3.9148    0.0565   69.2848   0.0000
    loggas   0.3830    0.0135   28.3865   0.0000
   lognso2   0.3528    0.0104   33.8907   0.0000
    logphi   0.6174    0.1573    3.9253   0.0002
```

```
Residual standard error: 0.02519 on 94 degrees of freedom
Multiple R-Squared: 0.9525
F-statistic: 628.7 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
         (Intercept)   loggas  lognso2
 loggas  -0.8005
lognso2  -0.6363        0.0582
 logphi  -0.0292       -0.0773  -0.0039
> coefficients(mdcap60.fit)
  (Intercept)     loggas     lognso2      logphi
    3.914778   0.3830471   0.3528121   0.6173974
----------------------
```

```
> mldc70<-log(dc70*mw*300/313*1000,10)
> mdcap70<-data.frame(mldc70,loggas,lognso2,logphi,loglg)
> mdcap70.fit<-lm(mldc70~loggas+lognso2+logphi,mdcap70)
> summary(mdcap70.fit)

Call: lm(formula = mldc70 ~ loggas + lognso2 + logphi, data = mdcap70)
Residuals:
      Min        1Q      Median        3Q       Max
 -0.004295 -0.001974 -0.0007386  0.001419  0.007726

Coefficients:
              Value  Std. Error   t value   Pr(>|t|)
(Intercept)  5.3319     0.0063   841.5273     0.0000
     loggas  0.0933     0.0015    61.6298     0.0000
    lognso2  0.0033     0.0012     2.8511     0.0054
     logphi  0.0825     0.0176     4.6795     0.0000

Residual standard error: 0.002825 on 94 degrees of freedom
Multiple R-Squared: 0.9764
F-statistic: 1296 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
         (Intercept)   loggas  lognso2
 loggas  -0.8005
lognso2  -0.6363        0.0582
 logphi  -0.0292       -0.0773  -0.0039
> coefficients(mdcap70.fit)
  (Intercept)     loggas     lognso2      logphi
     5.33193  0.09325643  0.00332835  0.08253473
-----------------------------------
```

```
> mldc80<-log(dc80*mw*300/313*1000,10)
> mdcap80<-data.frame(mldc80,loggas,lognso2,logphi,loglg)
>  mdcap80.fit<-lm(mldc80~loggas+lognso2+logphi,mdcap80)
> summary(mdcap80.fit)

Call: lm(formula = mldc80 ~ loggas + lognso2 + logphi, data = mdcap80)
Residuals:
      Min        1Q       Median        3Q       Max
 -0.002877 -0.0004898 -9.283e-05  0.0002998  0.01703

Coefficients:
              Value  Std. Error    t value    Pr(>|t|)
(Intercept)  5.1183     0.0042   1207.8968     0.0000
     loggas  0.2987     0.0010    295.2050     0.0000
    lognso2 -0.0070     0.0008     -8.9711     0.0000
     logphi -0.4111     0.0118    -34.8486     0.0000

Residual standard error: 0.001889 on 94 degrees of freedom
Multiple R-Squared: 0.9989
```

F-statistic: 29330 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
        (Intercept)  loggas lognso2
 loggas -0.8005
lognso2 -0.6363       0.0582
 logphi -0.0292      -0.0773 -0.0039
> coefficients(mdcap80.fit)
Error: couldn't find function "coeffiicents"
> coefficients(mdcap80.fit)
 (Intercept)      loggas       lognso2       logphi
    5.118347 0.2987416 -0.007003863 -0.4110633
```

```
================================
```
Mg-Enhanced Lime FGD
```
================================
```

```
> mlmcap10<-data.frame(mlmc10,loggas,lognso2,logphi,loglmlg)
>  mlmcap10.fit<-lm(mlmc10~loggas+lognso2,mlmcap10)
summary(mlmcap10.fit)
>
Call: lm(formula = mlmc10 ~ loggas + lognso2, data = mlmcap10)
Residuals:
      Min       1Q    Median       3Q     Max
 -0.02996 -0.01643 -0.007135 0.004318 0.1307
```

Coefficients:

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	4.1820	0.0612	68.2805	0.0000
loggas	0.4287	0.0146	29.3867	0.0000
lognso2	0.3974	0.0113	35.1977	0.0000

Residual standard error: 0.02732 on 95 degrees of freedom
Multiple R-Squared: 0.9544
F-statistic: 994.5 on 2 and 95 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
        (Intercept)  loggas
 loggas -0.8055
lognso2 -0.6367       0.0581
> coefficients(mlmcap10.fit)
 (Intercept)      loggas    lognso2
    4.18205 0.4287465 0.3973585
```

```
> mlmcap20<-data.frame(mlmc20,loggas,lognso2,logphi,loglmlg)
>  mlmcap20.fit<-lm(mlmc20~loggas+lognso2+loglmlg,mlmcap20)
> summary(mlmcap20.fit)

Call: lm(formula = mlmc20 ~ loggas + lognso2 + loglmlg, data = mlmcap20)
Residuals:
       Min        1Q     Median       3Q      Max
 -0.004563 -0.001881 -0.0004001 0.001212 0.03311
```

Coefficients:

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	5.3436	0.0125	429.1404	0.0000
loggas	0.5571	0.0022	256.2420	0.0000
lognso2	-0.0031	0.0017	-1.8782	0.0635
loglmlg	0.0866	0.0049	17.8010	0.0000

Residual standard error: 0.004042 on 94 degrees of freedom
Multiple R-Squared: 0.9986
F-statistic: 22030 on 3 and 94 degrees of freedom, the p-value is 0

```
Correlation of Coefficients:
        (Intercept)  loggas lognso2
 loggas -0.6641
lognso2 -0.4526        0.0558
loglmlg -0.6858        0.1197 -0.0156
> coefficients(mlmcap20.fit)
  (Intercept)      loggas       lognso2      loglmlg
    5.343637 0.5571364 -0.003137549 0.08656957
```

```
> mlmcap30<-data.frame(mlmc30,loggas,lognso2,logphi,loglmlg)
>  mlmcap30.fit<-lm(mlmc30~loggas+lognso2,mlmcap30)
> summary(mlmcap30.fit)

Call: lm(formula = mlmc30 ~ loggas + lognso2, data = mlmcap30)
Residuals:
      Min       1Q    Median       3Q      Max
 -0.01184 -0.004222 -0.001109 0.003491 0.02848

Coefficients:
              Value Std. Error    t value  Pr(>|t|)
(Intercept)  4.9857     0.0143   349.0995    0.0000
    loggas   0.5965     0.0034   175.3502    0.0000
   lognso2  -0.0057     0.0026    -2.1778    0.0319

Residual standard error: 0.00637 on 95 degrees of freedom
Multiple R-Squared: 0.9969
F-statistic: 15450 on 2 and 95 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)  loggas
 loggas -0.8055
lognso2 -0.6367        0.0581
> coefficients(mlmcap30.fit)
  (Intercept)      loggas       lognso2
    4.985706 0.5965417 -0.005732976
```

```
> mlmcap60<-data.frame(mlmc60,loggas,lognso2,logphi,loglmlg)
>  mlmcap60.fit<-lm(mlmc60~loggas+lognso2,mlmcap60)
> summary(mlmcap60.fit)

Call: lm(formula = mlmc60 ~ loggas + lognso2, data = mlmcap60)
Residuals:
      Min       1Q    Median       3Q      Max
 -0.03638 -0.01481 -0.003966 0.0111 0.1097

Coefficients:
              Value Std. Error t value Pr(>|t|)
(Intercept)  3.8050     0.0498  76.3452   0.0000
    loggas   0.4408     0.0119  37.1316   0.0000
   lognso2   0.4068     0.0092  44.2820   0.0000

Residual standard error: 0.02223 on 95 degrees of freedom
Multiple R-Squared: 0.9708
F-statistic: 1580 on 2 and 95 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)  loggas
 loggas -0.8055
lognso2 -0.6367        0.0581
> coefficients(mlmcap60.fit)
  (Intercept)      loggas    lognso2
    3.805031 0.4408358 0.4067988
```

```
> mlmcap70<-data.frame(mlmc70,loggas,lognso2,logphi,loglmlg)
```

```
> mlmcap70.fit<-lm(mlmc70~loggas+lognso2+logphi,mlmcap70)
> summary(mlmcap70.fit)


Call: lm(formula = mlmc70 ~ loggas + lognso2 + logphi, data = mlmcap70)
Residuals:
      Min       1Q     Median      3Q       Max
 -0.00501 -0.002132 -0.0004851 0.00199 0.009311

Coefficients:
             Value Std. Error   t value   Pr(>|t|)
(Intercept)  5.4067    0.0069  781.0636    0.0000
    loggas   0.0860    0.0017   52.0203    0.0000
   lognso2  -0.0043    0.0013   -3.3379    0.0012
    logphi   0.0712    0.0193    3.6936    0.0004

Residual standard error: 0.003086 on 94 degrees of freedom
Multiple R-Squared: 0.9676
F-statistic: 935.6 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)  loggas lognso2
 loggas -0.8005
lognso2 -0.6363      0.0582
 logphi -0.0292     -0.0773 -0.0039
> coefficients(mlmcap70.fit)
 (Intercept)      loggas      lognso2      logphi
   5.406733 0.08599897 -0.004257059 0.07117349
----------------------
> mlmcap80<-data.frame(mlmc80,loggas,lognso2,logphi,loglmlg)
> mlmcap80.fit<-lm(mlmc80~loggas+lognso2+logphi,mlmcap80)
> summary(mlmcap80.fit)


Call: lm(formula = mlmc80 ~ loggas + lognso2 + logphi, data = mlmcap80)
Residuals:
       Min        1Q     Median       3Q      Max
 -0.002877 -0.0004898 -9.283e-05 0.0002998 0.01703

Coefficients:
             Value Std. Error    t value   Pr(>|t|)
(Intercept)  5.1183    0.0042 1207.8968    0.0000
    loggas   0.2987    0.0010  295.2050    0.0000
   lognso2  -0.0070    0.0008   -8.9711    0.0000
    logphi  -0.4111    0.0118  -34.8486    0.0000

Residual standard error: 0.001889 on 94 degrees of freedom
Multiple R-Squared: 0.9989
F-statistic: 29330 on 3 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)  loggas lognso2
 loggas -0.8005
lognso2 -0.6363      0.0582
 logphi -0.0292     -0.0773 -0.0039
> coefficients(mlmcap80.fit)
 (Intercept)      loggas      lognso2      logphi
   5.118347 0.2987416 -0.007003863 -0.4110633
----------------------
```

lime Spray Dryer
=================

```
> mlsdcap10<-data.frame(mlsdc10,loggas,logso2,logphi,loggpm)
> mlsdcap10.fit<-lm(mlsdc10~loggas+logso2+logphi+loggpm,mlsdcap10)
> summary(mlsdcap10.fit)


Call: lm(formula = mlsdc10 ~ loggas + logso2 + logphi + loggpm, data = mlsdcap10)
Residuals:
      Min       1Q    Median        3Q      Max
 -0.02892 -0.01593 -0.005107  0.009607   0.1434

Coefficients:
              Value Std. Error  t value  Pr(>|t|)
(Intercept) -1.1876     0.2014  -5.8959    0.0000
    loggas  -0.3134     0.1707  -1.8357    0.0696
    logso2   0.3861     0.0147  26.2552    0.0000
    logphi   0.3871     0.0523   7.3968    0.0000
    loggpm   0.7678     0.1711   4.4879    0.0000

Residual standard error: 0.02484 on 94 degrees of freedom
Multiple R-Squared: 0.9693
F-statistic: 741.4 on 4 and 94 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)   loggas   logso2   logphi
loggas -0.9743
logso2 -0.8075        0.7106
logphi -0.2658        0.2801   0.0663
loggpm  0.9596       -0.9970  -0.7086  -0.2780
> plot(mlsdcap10.fit)
Hit <return> to see next plot
> coefficients(mlsdcap10.fit)
  (Intercept)      loggas    logso2     logphi      loggpm
    -1.187585  -0.3133721  0.386108  0.3871053   0.7677725
------------------------
> gpmdata<-data.frame(loggpm,logrr,loggas,logphi)
> gpmdata.fit<-lm(loggpm~logrr+loggas+logphi,gpmdata)
> summary(gpmdata.fit)


Call: lm(formula = loggpm ~ logrr + loggas + logphi, data = gpmdata)
Residuals:
      Min       1Q     Median        3Q      Max
 -0.02823 -0.008853 -0.0006518  0.008155  0.05482

Coefficients:
              Value Std. Error   t value  Pr(>|t|)
(Intercept) -0.9313     0.0252  -37.0211    0.0000
      logrr -0.0304     0.0029  -10.5200    0.0000
     loggas  0.9960     0.0077  130.1636    0.0000
     logphi  0.0915     0.0289    3.1654    0.0021

Residual standard error: 0.01435 on 95 degrees of freedom
Multiple R-Squared: 0.9944
F-statistic: 5649 on 3 and 95 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)   logrr    loggas
 logrr   0.0575
loggas  -0.9923      -0.0870
logphi  -0.1479       0.1661   0.0391
> coefficients(gpmdata.fit)
  (Intercept)      logrr     logso2      logphi
    0.5769822  0.2541736  0.5254942  -0.1273146
```

```
> mlsdcap20<-data.frame(mlsdc20,loggas,gpm)
> mlsdcap20.fit<-lm(mlsdc20~loggas+gpm,mlsdcap20)
> summary(mlsdcap20.fit)

Call: lm(formula = mlsdc20 ~ loggas + gpm, data = mlsdcap20)
Residuals:
      Min        1Q     Median       3Q      Max
 -0.06925 -0.006807 -0.0008049  0.01105  0.03276

Coefficients:
              Value Std. Error  t value  Pr(>|t|)
(Intercept) -1.3913     0.0976 -14.2492    0.0000
    loggas   0.8550     0.0351  24.3300    0.0000
       gpm  -0.0010     0.0001 -12.4265    0.0000

Residual standard error: 0.01625 on 96 degrees of freedom
Multiple R-Squared: 0.9652
F-statistic: 1330 on 2 and 96 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept) loggas
loggas -0.9989
   gpm  0.9577      -0.9694
> coefficients(mlsdcap20.fit)
  (Intercept)      loggas        gpm
    -1.391273 0.8549951 -0.000957515
------------------------
>  mlsdcap30.fit<-lm(mlsdc30~loggas+logphi,mlsdcap30)
>  mlsdcap30.fit<-lm(mlsdc30~loggas+logphi,mlsdcap30)
>  summary(mlsdcap30.fit)

Call: lm(formula = mlsdc30 ~ loggas + logphi, data = mlsdcap30)
Residuals:
       Min        1Q     Median       3Q      Max
 -0.009252 -0.004613 -0.000621 0.003649 0.01376

Coefficients:
              Value Std. Error   t value  Pr(>|t|)
(Intercept) -1.1522     0.0097 -118.8588    0.0000
    loggas   0.6042     0.0029  205.3551    0.0000
    logphi  -0.0128     0.0110   -1.1603    0.2488

Residual standard error: 0.005538 on 96 degrees of freedom
Multiple R-Squared: 0.9977
F-statistic: 21160 on 2 and 96 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept) loggas
loggas -0.9927
logphi -0.1599      0.0545
> coefficients(mlsdcap30.fit)
  (Intercept)      loggas      logphi
    -1.152234 0.6042322 -0.01276179
------------------------
> mlsdcap60<-data.frame(mlsdc60,logso2,gpm)
> mlsdcap60.fit<-lm(mlsdc60~logso2+gpm,mlsdcap60)
> summary(mlsdcap60.fit)

Call: lm(formula = mlsdc60 ~ logso2 + gpm, data = mlsdcap60)
Residuals:
     Min       1Q     Median       3Q      Max
 -0.1144 -0.02676 0.0004279 0.02777 0.1226

Coefficients:
```

```
                Value  Std. Error    t value  Pr(>|t|)
(Intercept)   -1.7423     0.0610    -28.5822    0.0000
     logso2    0.4841     0.0182     26.5557    0.0000
        gpm    0.0016     0.0001     31.1580    0.0000
```

Residual standard error: 0.04462 on 96 degrees of freedom
Multiple R-Squared: 0.9464
F-statistic: 847.7 on 2 and 96 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
        (Intercept)  logso2
logso2 -0.9789
   gpm -0.1794       -0.0116
```
> coefficients(mlsdcap60.fit)
```
 (Intercept)      logso2        gpm
   -1.742325 0.4840697 0.001617525
```

> mlsdcap70<-data.frame(mlsdc70,loggas,logso2,logphi)
> mlsdcap70.fit<-lm(mlsdc70~logso2+logphi+gpm,mlsdcap70)
> summary(mlsdcap70.fit)

Call: lm(formula = mlsdc70 ~ logso2 + logphi + gpm, data = mlsdcap70)
Residuals:
```
       Min        1Q    Median        3Q       Max
 -0.004277 -0.001334 -0.000121 0.001049 0.005389
```

Coefficients:
```
                Value  Std. Error    t value  Pr(>|t|)
(Intercept)   -0.3249      0.0026  -122.7418    0.0000
     logso2   -0.0089      0.0008   -11.0659    0.0000
     logphi   -0.0177      0.0039    -4.5273    0.0000
        gpm    0.0002      0.0000    72.8277    0.0000
```

Residual standard error: 0.001935 on 95 degrees of freedom
Multiple R-Squared: 0.9829
F-statistic: 1823 on 3 and 95 degrees of freedom, the p-value is 0

Correlation of Coefficients:
```
        (Intercept)  logso2  logphi
logso2 -0.9690
logphi  0.0542       -0.1968
   gpm -0.1779       -0.0156  0.0216
```
> coefficients(mlsdcap70.fit)
Syntax error: ";" used illegally at this point:
coefficients(m;
> coefficients(mlsdcap70.fit)
```
 (Intercept)        logso2        logphi          gpm
   -0.3249075 -0.008920925 -0.01772185 0.0001639735
```

> mlsdcap80<-data.frame(mlsdc80,loggas,logso2)
> mlsdcap80.fit<-lm(mlsdc80~loggas+logso2,mlsdcap80)
> summary(mlsdcap80.fit)

Call: lm(formula = mlsdc80 ~ loggas + logso2, data = mlsdcap80)
Residuals:
```
       Min        1Q    Median        3Q       Max
 -0.001402 -0.0004677 1.395e-05 0.0004553 0.001564
```

Coefficients:
```
                Value  Std. Error    t value  Pr(>|t|)
(Intercept)   -0.9107      0.0015  -620.5126    0.0000
     loggas    0.3003      0.0003   877.3901    0.0000
     logso2   -0.0053      0.0003   -19.9439    0.0000
```

Residual standard error: 0.0006428 on 96 degrees of freedom

Multiple R-Squared: 0.9999
F-statistic: 389400 on 2 and 96 degrees of freedom, the p-value is 0

Correlation of Coefficients:
        (Intercept)   loggas
loggas -0.8084
logso2 -0.6536   0.0850
> coefficients(mlsdcap80.fit)
  (Intercept)   loggas   logso2
  -0.9106584 0.300299 -0.00525553

Appendix B: PETC Contractors Meeting Paper

The Integrated Environmental Control Model

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Introduction

The capability to estimate the performance and cost of emission control systems is critical to a variety of planning and analysis requirements faced by utilities, regulators, researchers and analysts in the public and private sectors. The computer model described in this paper has been developed for DOE to provide an up-to-date capability for analyzing a variety of pre-combustion, combustion, and post-combustion options in an integrated framework. A unique capability allows performance and costs to be modeled probabilistically, which allows explicit characterization of uncertainties and risks.

Modeling Framework

Previous reports have described earlier development and applications of the Integrated Environmental Control Model (IECM).[1,2] The IECM provides a systematic and integrated treatment of emission control options employing pre-combustion, combustion and post-combustion control methods. The model was developed to provide preliminary performance and cost estimates for new coal-fired power plants. Of particular interest were a number of advanced environmental control technologies being supported by DOE. For comparative purposes, however, a set of "baseline" technologies representing current commercial systems also is part of the IECM framework. Table 1 lists the technologies currently included. For each technology, a process performance model was developed to account for all energy and mass flows (including air pollutants and solid wastes) associated with that process. Coupled to each performance model, an economic model was developed to estimate the capital cost, annual operating and maintenance (O&M) costs, and total levelized cost of each technology. The technology models developed for the IECM in the mid-to-late 1980s now are being updated and enhanced to reflect more recent design criteria and associated performance and costs. The status of major IECM components is briefly reviewed in the paragraphs below.

Coal Cleaning Processes. The IECM includes models of both conventional and advanced coal cleaning processes. The conventional processes include four plant designs of increasing complexity, which provide increasing capability for sulfur as well as ash removal. Each of these plant designs (referred to as cleaning levels 2, 3, 4 and 5) can be optimized to achieve a target sulfur or ash reduction while maximizing overall yield (thus, minimizing costs). Data requirements for these models includes coal-specific washability data plus cleaning circuit design parameters such as top size and bottom size for different coal fractions.

Models of several advanced physical coal cleaning processes also have been developed based on limited data for several U.S. coals. While these processes are capable of achieving higher levels of sulfur and ash reduction than conventional processes, their costs also are higher. Several of these processes have been developed to provide "super-clean" coal for use in coal-liquid mixture fuels, which compete with other premium fuels such as oil or gas.

Table 1. Emissions control technology options for the IECM

Plant Area	Baseline Processes	Advanced Processes
Physical Coal Cleaning	• Level 2 Plant • Level 3 Plant • Level 4 Plant • Froth Flotation	• Selective Agglomeration • Heavy Liquid Cyclones • Coal-Pyrite Flotation • Magnetic Separation
Combustion Controls	• Low NO_x Burners	• Reburning (gas)[a] • Slagging Combustors[a]
Post-Combustion Controls	• Selective Catalytic Reduction (Hot-side and Cold-Side)	• NOXSO • Copper Oxide • Electron Beam • Advanced SO_2/NO_x Removal[a]
	• Wet Limestone FGD • Wet Limestone with Additives • Wet Lime FGD • Lime Spray Dryer	
	• Electrostatic Precipitator (Cold-side) • Reverse Gas Fabric Filter • Pulse Jet Fabric Filter	
Waste Disposal & By-Product Recovery	• Landfill • Ponding	• Sulfur Recovery • Sulfuric Acid Recovery • Gypsum

[a] To be completed in project Phase II.

Base Power Plant. Performance and cost models of a base power plant are needed to accurately characterize the cost of integrated emission control systems, particularly when coal cleaning is employed. The IECM base plant performance model includes detailed mass and energy balances, fuel combustion equations, and thermodynamic relationships to calculate flue gas flow rates, plant efficiency, and net power generation. The environmental performance of the furnace also is determined from mass and energy balances where possible, or from empirical relationships where necessary, as in the case of NO_x emissions. A detailed model of the air preheater also has been developed to properly account for energy credits when advanced environmental control processes are used.

Revised cost models for the base power plant have been developed based on recent data from EPRI for three furnace designs related to coal rank (bituminous, subbituminous and lignites). The new cost algorithms estimate capital costs and annual O&M costs as a function of key design parameters.

NO_x Controls. The IECM includes both in-furnace and post-combustion NO_x control options. Currently, the in-furnace combustion controls include low NO_x burners for a new power plant meeting or exceeding federal New Source Performance Standards. Additional combustion options suitable for NO_x retrofits currently are being developed and will be implemented in the IECM during 1995.

Post-combustion control methods include both "hot-side" and "cold-side" selective catalytic reduction (SCR) systems. New SCR performance and cost models incorporate recent data

and experience from SCR units worldwide. The revised models contain a larger number of system design parameters, a more detailed characterization of catalyst activity, and additional details related to capital cost and O&M cost parameters.[4] While SCR systems on coal-fired plants are only now emerging commercially in the United States, their widespread use in Europe and Japan, often in combination with FGD, represents the benchmark design for comparisons with advanced emissions control systems being developed by DOE.

Particulate Emission Controls. The IECM includes performance and cost models of cold-side electrostatic precipitators and fabric filters. Performance and cost models for both technologies recently have been updated to reflect current applications.[4] The revised ESP performance model calculates total particulate removal as a function of ash composition and flue gas properties, while fabric filter performance is related primarily to the air-to-cloth ratio. The latter models also have been expanded to include both reverse gas and pulse jet fabric filter designs. Recent EPRI studies have been used to update the economic models for all particulate collectors in the IECM.

Flue Gas Desulfurization Systems. Substantial improvements in FGD system design, accompanied by reductions in cost, have been seen over the past decade, and recent enhancements to the IECM modules now reflect these changes.[5] New FGD performance and cost models have been developed for the IECM for four common types of FGD systems: (1) wet limestone with forced oxidation; (2) wet limestone with dibasic acid additive; (3) magnesium-enhanced wet lime system; and (4) a lime spray dryer system. The new cost models reflect the results of recent studies for EPRI, while the new performance models represent the capabilities of modern commercial systems.

Combined SO_2/NO_x Removal Processes. A key element of DOE's Clean Coal Technology program focuses on advanced processes for combined SO_2 and NO_x removal to achieve high performance goals at lower cost than the conventional combination of SCR plus FGD. Models of three SO_2/NO_x control systems have been developed for the IECM: the fluidized-bed copper oxide process, the NOXSO process, and the electron beam process. The copper oxide and NOXSO processes are of continuing interest to DOE, and earlier versions of the performance and cost models for these two processes are being refined and updated at the present time.

Waste Disposal and By-Product Recovery Systems. IECM revisions treat solid waste disposal as a variable cost item associated with a particular control technology, consistent with the costing method used by EPRI and others. Thus, boiler bottom ash disposal is included in the base plant model, fly ash disposal costs are incorporated in the ESP or fabric filter models, and FGD wastes or by-product credits are treated in the FGD cost models.

Advanced processes employing combined SO_2/NO_x removal produce by-product sulfur or sulfuric acid rather than a solid waste. Because the sulfur or sulfuric acid plant is a significant part of the overall plant cost, separate engineering models have been developed for these two components. These models are sensitive to input gas composition and other parameters affecting overall process economics.

Probabilistic Capability

A unique feature of the IECM is its ability to characterize input parameters and output results probabilistically, in contrast to conventional deterministic (point estimate) form. This method of analysis offers a number of important advantages over the traditional approach of examining uncertainties via sensitivity analysis. Probabilistic analysis allows the interactive effects of variations in many different parameters to be considered simultaneously, in contrast to sensitivity analysis where only one or two parameters at a time are varied, with all others held constant. In addition, probabilistic analysis provides quantitative insights about the *likelihood* of certain outcomes, and the probability that one result may be more significant than another. This type of information is generally of greater use than simple bounding or "worst case" analyses obtained from sensitivity studies, which contain no information on the likelihood of worst case occurrences.

The ability to perform probabilistic analysis comes from the use of a new software system which uses a non-procedural modeling environment designed to facilitate model building and probabilistic analysis. In addition to a number of standard probability distributions (e.g., normal, lognormal, uniform, chance), the IECM can accommodate any arbitrarily specified distribution for input parameters. Given a specified set of input uncertainties, the resulting uncertainties induced in model outputs are calculated using median Latin Hypercube sampling, an efficient variant of Monte Carlo simulation. Results typically are displayed in the form of a cumulative probability distribution showing the likelihood of reaching or exceeding various levels of a particular parameter of interest (e.g., emissions or cost).

Model Applications

The IECM is intended to support a variety of applications related to technology assessment, process design, and research management. Examples of questions that can be addressed with the IECM include the following:

- What uncertainties most affect the overall costs of a particular technology?
- What are the key design trade-offs for a particular process ?
- What are the potential payoffs and risks of advanced processes vis-a-vis conventional technology?
- Which technologies appear most promising for further process development?
- What conditions or markets favor the selection of one system design (or technology) over another?
- How can technical and/or economic uncertainties be reduced most effectively through further research and development?

The IECM also has been modified to allow estimation of retrofit costs as well as new plant costs. A series of user specified "retrofit factors" may be applied at the process area level for a particular system to estimate the higher costs of retrofit facilities. To operate the IECM, a new graphical interface has been developed which provides an extremely user-friendly mode of operation. As currently configured, the IECM runs on a Macintosh computer.

Illustrative Results

Here we present results illustrating the probabilistic capabilities of the IECM as applied to a single power plant as shown in Figure 1. This case corresponds to an Appalachian medium sulfur (2.1%S) coal for a power plant with a net capacity of 300 MW. Table 2 shows the input parameter values and uncertainty distributions assumed for this example. The plant is

assumed to achieve 95% SO_2 removal employing a wet limestone FGD system with forced oxidation.

Cost results are shown in Figure 2. These figures show the cumulative effect of uncertainties in different model parameters. For example, for capital cost (Figure 2a),
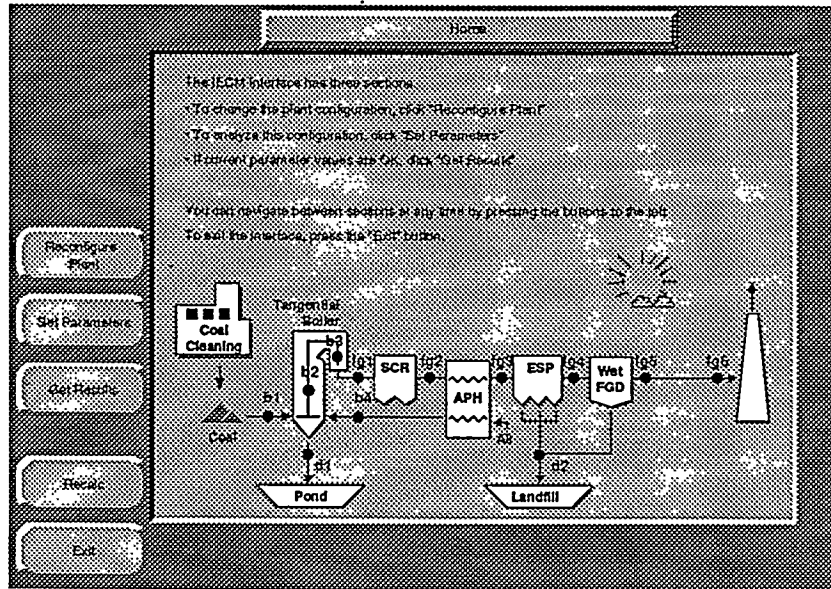

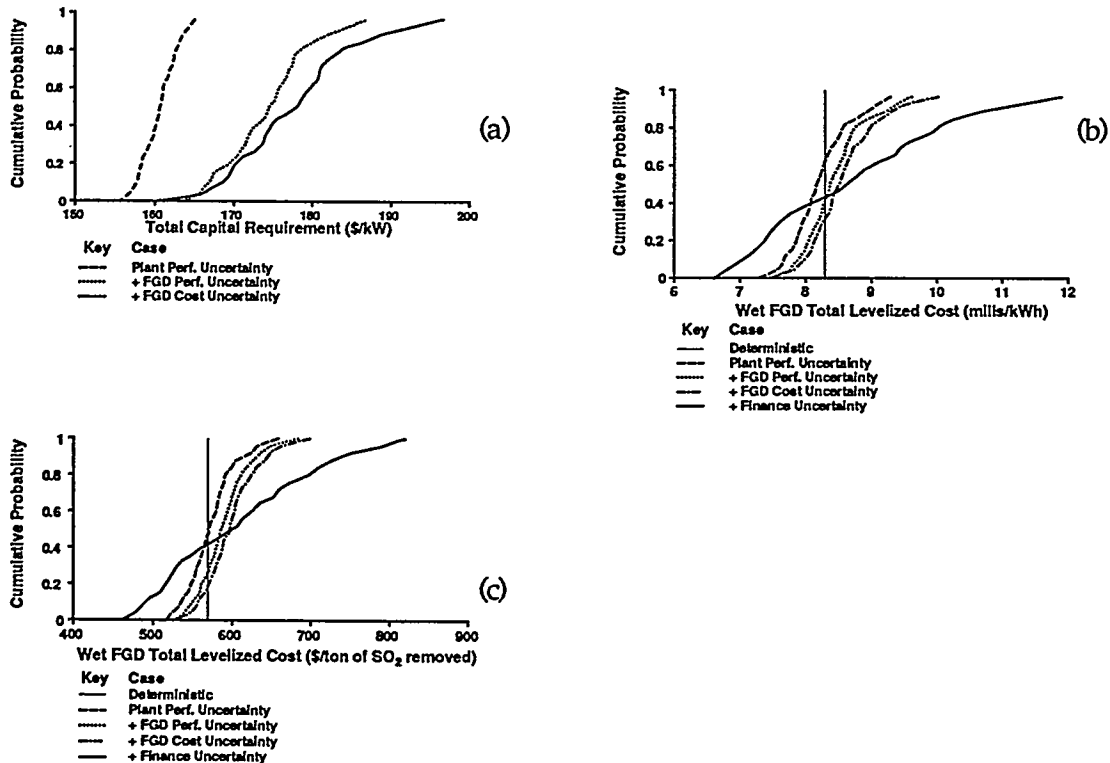Figure 1.   User interface screen showing the case study plant configuration.

Figure 2.   Probabilistic results for case study: (a) FGD capital cost; (b) total levelized cost; (c) cost per ton of SO_2 removed. All costs are in constant 1993 dollars.

Table 2. Performance and cost parameter uncertainties for case study

Model Parameter	Nominal Value	Probability Distribution[a]	Parameter Range[b]
Gross Capacity	330 MW (300 MW net)	None	
Coal Sulfur Content[c]	2.13 wt%	None	
Steam Cycle Heat Rate	7880 Btu/kWh	Neg. Half Normal (1,0.018)	(7599, 7871)
Capacity Factor	65%	Normal (1,0.07)	(58, 72)
Excess Air (boiler)	20%	Uniform (0.75,1.25)	(15,25)
Air Preheater Leakage	19%	Triangle (0.4,1,1.25)	(9, 23)
Economizer Outlet Temp.	700 °F	Normal (1,0.03)	(666, 734)
Air Preheater Outlet Temp.	300 °F	Normal (1,0.03)	(285, 315)
Energy for Coal Pulverizers	0.6% MW_g	Normal (1, 0.03)	(0.57, 0.63)
Energy for Steam pumps	0.65% MW_g	Normal (1, 0.03)	(0.61, 0.68)
Energy for Fans	1.5% MW_g	Normal (1,0.03)	(1.4, 1.6)
Energy for Cooling Towers	1.8% MW_g	Normal (1,0.03)	(1.7, 1.9)
Energy for Misc. Equip.	1.3% MW_g	Normal (1,0.03)	(1.2, 1.4)
SO_2 Removal Efficiency	95 %	None	
Particulate Removal Efficiency	50 %	None	
Reagent Stoichiometry	1.03	Triangular (0.99,1,1.05)	(1.02,1.03,1.08)
Capacity of each Absorber	50%	Uniform(1,1.2)	(50, 60)
Gas Temp. Exiting Reheater	152 °F	None	
Total Pressure Drop	10 in H_2O	Normal (1,0.03)	(9.5, 10.5)
Chloride Removal Efficiency	90 %	None	
Gen. Facilities Capital	10% PFC	Lognormal(1,1.3)	(6.3, 15.9)
Eng. & Home Off. Fees	10% PFC	Half Normal (1,0.17)	(10.1, 13.3)
Project Contingency	15% PFC	Normal (1,0.11)	(12.3, 17.9)
Process Contingency	2% PFC	Half Normal (1,0.5)	(2.0, 4.0)
Limestone Cost	$15/ton	Uniform(0.7,1.3)	(10.5, 19.5)
Disposal Cost	$8.15/ton	Normal(1,0.1)	(6.8, 9.5)
Operating Labor Rate	$20/hr	Uniform(0.75,1.25)	(15,25)
Inflation Rate	0%	None	
Plant Book Life (years)	30 yrs	None	
Real Return on Bonds	4.6%	None	
Real Return on Com. Stock	8.7%	None	
Real Return on Pref. Stock	5.2%	None	
Real Cost Escalation Rate	0%/yr	None	
Federal Tax Rate	36.7 %	None	
State Tax Rate	2 %	None	
Property Tax Rate	2 %	None	
Investment Tax Credit	0%	None	
Fixed Charge Factor	0.0877	Uniform(0.7,1.3)	(0.06, 0.11)
O&M Levelization Factor	1.00	Normal (1,0.03)	(0.95, 1.05)

[a] For normal distributions the values in parenthesis are the mean and the standard deviation normalized on the nominal value. Uniform distributions show the range, and triangular distributions the range and mode also normalized on the nominal value.

[b] The parameter range for the normal distribution encloses two standard deviations or about 95% of the values.

uncertainties in only the base power plant parameters introduces some skewness to the curve, reflecting primarily the input distribution for steam cycle heat rate. That heat rate distribution (see Table 2) reflects a potential for improved plant efficiency relative to the nominal (deterministic) case. Additional uncertainties in the FGD system performance parameters introduce a larger variation in plant capital costs, and this is expanded further when uncertainties in model cost parameters also are added. In this case, the shift to the right toward higher costs reflects the parameter input distributions used for this example, in particular the assumptions of possible vessel oversizing, higher contingency costs, and higher reagent stoichiometry relative to the nominal design values. As a result of these more conservative design assumptions, Figure 2a shows a 95 percent confidence interval ranging from $163 to $196/kW, compared to the nominal (deterministic) value of $165/kW.

Similar results are seen in Figures 2b and 2c for the total levelized cost and cost per ton of SO_2 removal. Here, the cumulative probability distributions also show the effect of additional uncertainties in plant operation and financial parameters which affect annual revenue requirements. Again, the input assumptions in this example reflect a greater potential for higher rather than lower costs relative to the nominal parameter values. Thus, in Figure 2c the cost per ton of SO_2 removed varies from $470 to $805/ton for the 95 percent confidence interval, compared to a nominal value of $570/ton with no uncertainties. Figure 2c shows about a 60 percent chance that the uncertainties assumed in this example will lead to a higher cost per ton than the deterministic value.

While one can see graphically in Figures 2 that certain sets of parameters have a more pronounced effect on overall uncertainty than others, more formal mathematical methods can be used to identify the key parameters whose uncertainty most affects the outcome. The importance of an input variable is derived by assessing its influence on the output variable of interest. For linear relationships this can be accomplished by the use of partial correlation coefficients. For nonlinear relations, such as those involved here, it becomes more difficult to assess the importance of individual variables. However, if the model output is a monotonic function of the input then it is possible to linearize the relationship by using rank transformations on the input and output values. The transformation involves replacing each value of a variable by its rank. Now the partial correlation coefficient on the rank transformed variables (PRCC) can be used to assess the importance of each input variable.

The results of such an analysis are shown in Table 3 for the plant in this example. In general, plant size and coal sulfur content are the variables that most affect plant costs. However, other parameters also strongly affect either capital cost, O&M costs, or total levelized cost in this example. For instance, the design absorber capacity — which varies from 50 to 60 percent of the flue gas flow rate in this analysis — is the second most important parameter affecting FGD capital cost for this plant. Note that the rank order of different variables may vary from case to case, depending on the magnitude and uncertainty in each parameter. Because a large number of technical and economic factors affect the performance and cost of environmental control systems, PRCC analysis can be especially useful for identifying key process variables whose uncertainty might be reduced through targeted research and development, especially for advanced environmental control technologies.

Table 3. Results of partial rank correlation coefficient (PRCC) analysis showing the five most important model parameters affecting FGD cost for the illustrative example

Model Parameter	Capital Cost (M$)	O&M Cost (M$)	Total Levelized Cost (mills/kWh)	SO$_2$ Removal Cost ($/ton)
Gross Capacity	1	1	1	2
Coal Sulfur Content	3	2	3	1
Capacity Factor		4	4	5
Fixed Charge Factor			2	3
Absorber Capacity	2			
Reagent Stoichiometry	4			
Electricity Cost		3	5	4
Limestone Cost		5		
General Facilities Cost	5			

Conclusion

This paper has described an integrated modeling framework for evaluating the cost and performance of power plant emission control systems. While the illustrative examples in this paper focus on modern FGD systems, a key purpose of these models is to facilitate comparisons between alternative systems, particularly advanced technologies that may offer improved performance and/or cost characteristics. In such cases, the probabilistic capability of the models described here can be especially helpful in quantifying the risks as well as potential payoffs of advanced technologies, investment strategies, and R&D priorities.

Acknowledgments

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