ABSTRACT

THE ADJUSTMENT OF ELECTRIC POWER GENERATION
TO ALTERNATIVE SO_2 STANDARDS: A CASE STUDY
IN ENVIRONMENTAL PROTECTION REGULATION

By

James Michael Falvey

The object of this study was to compare the costs of generation under two forms of environmental protection standards. The first form is the ambient standard and restricts hourly average ground level concentration of SO_2 to one part per million or less. The second form is the emission standard, and in this case, is assumed to be a uniform restriction on the sulphur content of the fuel itself. The allowable sulphur content was set so that hourly average ground level concentrations would not exceed one ppm.

A case study approach was utilized using the generating system of Consumers Power Company as the case in point. Atmospheric dispersion estimation equations were selected after a review of the dispersion literature. The distribution functions of the relevant atmospheric variables were estimated using past weather data for the mid-Michigan area or the opinion of the state climatologist where datum was lacking. In addition to the atmospheric variability, temporal variation in the demand for power was considered.

Against this background of natural and man-made variation, the emission standard has to consider worst conditions (i.e., worst atmospheric conditions and highest system output) as determining the allowable sulphur

content of the fuel. The ambient standard, however, allows ongoing fuel adjustment to match varying weather and load conditions; it also allows exploitation of differences in station design. With the price of fuel inversely related to sulphur content, it was expected that the ambient standard would result in substantially lower fuel costs.

Under the uniform emission standard, simulated fuel costs were 37 percent above fuel costs under the ambient standard. This saving under the ambient standard results from the inclusion of both natural and man-made variability. In spite of these savings the conclusions of this study point out the problems of enforcing an ambient standard, and lend some support for the predominance of emission standards seen in the real world.

In an attempt to capture strengths of each of these standards, a station specific fuel restriction was simulated. This third form of regulation, in addition to capturing the enforcement ease characteristic of emission standards, can also exploit the design differences between stations. This third alternative was encouraging, costing only 12 percent more than the ambient standard.

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James Michael Falvey

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DEDICATION

To Wallace and Clair Murphy -

from whom I have learned much.

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CHAPTER I

INTRODUCTION

1.1 The Purpose of the Study

This is a study to compare the estimated costs of two different environmental quality protection schemes. The costs estimated will be only the fuel costs faced by the firm being regulated.

The two specific methods of regulation investigated are both assumed to have the same objective: the control of environmental damage caused by ground level SO_2 concentrations resulting from fossil-fuel-fired steam electric power generation.

The first regulation is set in terms of a maximum allowable SO_2 concentration at ground level. The second regulation sets a maximum allowable sulphur per BTU standard on the fuel burned. The firm in question is Consumers Power Company, whose generating capacity includes 24 conventional fossil fuel units in six principal plants -- it will be these units to which the two forms of regulation will be applied in order to compare relative costs.

Although this study is of a specific type of environmental regulation imposed on a specific firm, it is really no more than a single case study in the area of regulation in general. Although a large amount of effort will be expended in understanding and describing the underlying natural phenomena, the technical aspects of power generation, and the behavior of

the firm, the object of the study is the evaluation of regulation. Evaluation can only be carried out after a general understanding of the underlying features unique to the particular example used as a case study.

1.2 Environmental Regulation

The assumption was made above that the point of environmental protection policy is to control environmental damage. The additional question of how much damage is optimum is not considered; only the question of damage protection versus regulation is addressed here.

1.2.1 Pollution: A Working Definition and Some Implications

> Definition: An energy or material input to the environment can be defined as a pollutant if it, in some sense, negatively affects human use of that environment. The effect may be either direct or indirect, local or global, reversible or irreversible, and the use affected may be something as ill defined as a pleasant view. The point is the same; the value of the environment has been damaged.

The distinction to be made in this definition is the separation between stimuli and effects. It is the effects that are of concern; stimuli are of interest only because of effects. Unfortunately, from the point of view of the regulator, environmental regulation is often more easily enforceable at the point of introduction of the stimuli into the ecosphere. This is especially true of production processes in which the effluent is introduced through a pipe or smoke stack of fixed location.

If damage is a single valued function of effluent flow alone, then effects can be accurately controlled by controlling the flow of effluent. If, however, there are many other variables that influence effects in addition to the flow rate of effluent, control of the effluent alone may be a rather crude approach, especially if not polluting is costly.

These are all questions pertinent to the choice of damage protection standard. The literature notes two basic classes of standards. One is the ambient standard, and defines regulation in terms of the receiving body; ground level concentration regulation used in this study is essentially an ambient standard. The second general regulation type is the effluent standard, which defines the permissable behavior in units of effluent output, or effluent causing input. The sulphur per BTU standard to be evaluated in this study is such a standard. The controversy over the two types of standards has been both confused and bitter.[1]

1.2.2 The Two SO_2 Regulations to be Evaluated

The first scheme of SO_2 regulation considered is a standard defined in terms of concentrations at the point of maximum ground level concentration, irrespective of the location of that point. Standards of this type are usually specified in terms of an allowable mean concentration level over some stipulated time span.[2] The time interval in this study will be arbitrarily set at one hour. Hence the first regulation considered will impose the restriction on the generating company that the maximum one hour mean concentration of SO_2 at ground level shall not exceed some specified intensity.

The second form of regulation considered will be a restriction on the chemical composition of the fuel burned; the firm is constrained to burn only those fuels which demonstrate a sulphur/BTU ratio less than or equal to some specified figure.

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[1] See Engdahl [1973] for a brief history of the problem and a summary of current regulation in the U.S., or Schorr [1973] for a statement of the current position of the E.P.A., which favors movement toward ambient standards, and Senator Edmund Muskie's attack on that position.

[2] For example, the secondary standards set by the E.P.A. specified three separate means for three time intervals:

0.02 ppm maximum annual arithmetic mean concentration
0.1 ppm maximum 24-hour mean concentration
0.5 ppm maximum 3-hour mean concentration.

1.2.3 Evaluation

In the above description of the two SO_2 regulations, numerical values for both the concentration level and the sulphur/BTU ratio have intentionally been left out. In selecting values to use, one is immediately faced with the question of what is the optimum damage level. As mentioned previously, no attempt will be made in this study to address that question. The approach, rather, will be to focus on the respective values chosen for each standard with the object being that the numbers used should result in equal environmental damage under either standard, irrespective of the damage level itself. Comparison of costs to the firm will be meaningless unless damages are equated under both standards.

The problem of equating damages still has to be solved. Unfortunately SO_2 damage is a complex phenomenon -- it depends on ground level concentrations over extended time periods as well as relatively short term fluctuations. It will be assumed here that the effects of short-term fluctuations are dominant, and that the one-hour mean concentration level is an adequate descriptive statistic. The implication of this assumption is that to equate damages under the two standards, both the standard set in terms of maximum allowable hourly mean concentration and the standard set in terms of a maximum allowable sulphur/BTU ratio, should be set so that the maximum hourly mean concentration level will be the same under either standard.

The difference in fuel costs under the two standards will be due to the amount of variability in the load on the generating system and the degree of variability of meterological conditions (meteorology will have a strong influence on dispersion of the stack gas). The standard set in terms of ground level concentrations allows the generating company to vary both fuel burned and the location of load generation, and thus should result

in lower costs of generation. The question is: how great will the difference in costs be?

The philosophical question underlying all of this pertains to the object of regulation: What is the justification for regulation? The only tenable reason for environmental regulation is that which has been assumed above: environmental regulation exists to control environmental damage. If this is accepted, then regulation should be on effects rather than on behavior. If ground level concentration of SO_2 is the best available proxy for damage, then SO_2 regulations should be specified in terms of that proxy.

In contrast to the concentration standard, the restriction on the sulphur/BTU ratio of the fuel is a behavioral restriction. It takes no account of other adjustments the firm could make to decrease damage.

On the surface, the sulphur/BTU regulation appears clearly inferior to the first standard. However, it has two strong advantages: it is simple and it is easily enforced. For these two reasons it is a real alternative, especially from the viewpoint of the regulator.

1.3 The Organization of the Study

The remainder of the thesis is in five chapters. Most of the material in those chapters will be concerned with developing either input information for, or the implications of, the SO_2 constraint set in terms of ground level concentration. This is due to the complexity of operationalizing that regulation.

1.3.1 Chapter II: Theory

The theory chapter will examine the optimization problem faced by the firm restricted to keeping SO_2 concentrations below some specified level.

1.3.2 Chapter III: Meteorology and Dispersion

This chapter will describe the effect of meteorology on the dispersion of stack gases. The relationship between ground level concentrations of SO_2 and total SO_2 leaving the stack will be estimated.

1.3.3 Chapter IV: The Generating System

This chapter will describe the fossil-fuel-fired segment of Consumer's Power Company. Production functions will be estimated for each of the 24 units. Parameters necessary in using the dispersion equations of the previous chapter will be developed. The load pattern faced by the system will be estimated.

1.3.4 Chapter V: Analysis

The analysis chapter will take the material developed in Chapters II, III and IV and estimate the costs of generation under the two sets of regulation.

1.3.5 Chapter VI: Results and Conclusions

The final chapter will discuss the relative costs estimated, particularly in light of the narrowness of the analysis. General conclusions pertaining to environmental regulation will be drawn.

CHAPTER II

THEORY

2.1 Introduction

This chapter attempts to provide a conceptual framework within which the costs of power generation, subject to a maximum allowable ground level SO_2 concentration standard, can be estimated. The previous chapter postulated an alternative standard set in terms of equivalent SO_2 released per BTU input. Consideration of the alternative standard will be postponed until Chapter V.

2.2 Description of the Functional Parts of the Generating System

The generating system of an electric power company consists of all the generating units the firm has available to meet the power requirements of the system. In a system consisting of m thermal generating units, the j^{th} unit ($j = 1,2,\ldots,m$) displays a unique relationship between megawatt hour output, K_j, and BTU input such that $K_j = f_j(BTU_j)$ is monotonically increasing up to its capacity, R_j. If transmission losses are assumed to be zero, then the load on the system, K_T, is equal to the sum of the individual outputs, or $K_T = \sum_{j=1}^{m} K_j$. Although the typical generating system consists of a mixture of hydro, nuclear and fossil fuel generating units, the concern here is exclusively with conventional fossil-fuel-fired units.

In most generating systems, several fossil fuel units are usually located at the same location in order to obtain economy in the use of common subsidiary equipment such as transportation and transmission facilities. This group of contiguous units is referred to as a generating station. Typically the system will consist of several generating stations scattered over its operating area.

2.3 Profit Maximization for the Firm

It is assumed that the electric utility, although regulated, attempts to maximize profits -- regulation being merely a constraint on the ways in which maximizing behavior can be displayed. This behavioral assumption is generally applied to all firms, but the background conditions against which the electric power company attempts to maximize profits are not typical of most firms. The two main features that distinguish electric utilities are: (1) the price of its output is fixed by a regulatory commission in the short run, and (2) it is legally bound to meet the demand for its output.

Since the firm cannot control the demand for its output and since the price of its output is fixed, profit maximizing behavior can only be directed toward the cost term of the profit equation. Assuming labor and capital to be fixed, profit maximization reduces to fuel cost minimization. Assuming a generating system made up of m generating units, with each unit free to operate on a fuel mixture[3] of n potential fuels, the objective function can be written as

$$\min z = \sum_{j=1}^{m} \sum_{i=1}^{n} c_{ij} p_{ij} \tag{1}$$

where c_{ij} denotes the number of units per time of the i^{th} fuel burned at the j^{th} generating unit and p_{ij} denotes the corresponding price per unit of that fuel.

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[3]That is, the units will operate with no loss in thermal efficiency, and the mixing process will be costless.

2.3.1 The Power Constraint

In Section 2.2 reference was made to the fact that electric utilities are legally bound to meet the demand for power. This means that the firm is constrained to generate power equal to consumer demand, or in equation form

$$\sum_{j=1}^{m} K_j = K_T \,, \tag{2}$$

where K_j is the megawatt (MW) output of the j^{th} unit and K_T is the total demand on the system. This equation ignores transmission losses which are assumed to be zero throughout.

At the individual unit level there is an additional constraint on output -- each unit is constrained to a range of output between zero and capacity, R_j. Thus the system power constraint is more accurately written

$$\sum_{j=1}^{m} (K_j \leq R_j) = K_T \,. \tag{3}$$

As was mentioned previously, each generating units displays a monotonically increasing relationship between BTU input and MW output (the point where $\frac{dMW}{dBTU} \leq 0$ might in fact be used as a definition of capacity). Thus there are m production functions, $K_j = f_j(BTU_j)$, which can be converted into MW fuel relationships, $K_j = f_j(\sum_k c_{ij}b_{ij})$, where again c_{ij} denotes units per time of the i^{th} fuel burned in the j^{th} generating unit and b_{ij} is the corresponding BTU content of the fuel. Thus the power constraint can be rewritten

$$\sum_{j=1}^{m} (f_j(\sum_{i=1}^{n} c_{ij}b_{ij}) \leq R_j) = K_T. \tag{4}$$

One additional feature peculiar to electric production warrants mention here: unlike material producing firms, electric utilities have no cheap way of stockpiling output.[4] There is no easy way to dampen the oscillations of demand for electric energy -- production must follow demand through time, and the temporal variation is wide. Thus the innocuous appearing K_T may present serious problems in the analysis.

2.3.2 The SO_2 Constraint

In this chapter the SO_2 constraint level, S, is assumed to be a single uniform maximum allowable parts-per-million (ppm) concentration of SO_2 at ground level. It is further assumed that there is independence <u>between</u> stations with respect to SO_2 concentrations, but that <u>within</u> any station the contribution to SO_2 concentrations of each unit sums arithmetically to the total local concentration.[5]

Ground level concentrations of SO_2 depend on two things: (1) the total amount of SO_2 in the stack gas and (2) the degree of dispersion to which the SO_2 is subjected. The total SO_2 depends simply on the sulphur inputs to the furnace, or the sulphur content of the fuel, times the amount of fuel burned. Dispersion is much more complex. It depends upon the release conditions of the stack gas (stack height, exit temperature and exit velocity), and the condition of the atmosphere (meteorological state) into which the gas is released.

For already installed units, stack height is fixed, and although exit velocity and temperature are not constant, their relationship to the rate of BTU utilization is fixed by the design of the unit. The meteorological state is a random variable whose distribution would depend upon the geographic location of the generating system.

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[4]Pumped storage units are an exception. A pumped storage unit utilizes unused capacity of base load units during off peak hours to pump water to an elevated reservoir. When needed, this water is released to drive a generator.

[5]The second assumption becomes less valid as the number of units, stacks, and other design parameters increase.

Letting D_j = some measure of the degree of dispersion for the j^{th} unit, i.e., total SO_2 out divided by the resulting ground level concentration,

and M = meterological state,

then dispersion can be expressed as a function of the rate of BTU consumption and the meteorological state in the following form:

$$D_j = g_j(\sum_i c_{ij}b_{ij}, M), \tag{5}$$

where the function g_j incorporates the stack height and stack and furnace design characteristics of the j^{th} unit. To express the contribution of the j^{th} unit to station SO_2 concentration levels, D_j must be combined with a measure of the total SO_2 emitted by the j^{th} unit.

Let s_{ij} = SO_2 content of the i^{th} fuel burned at the j^{th} unit,[6]

S_j = parts per million of SO_2 at ground level contributed by the j^{th} unit,

then

$$S_j = \frac{\sum_{i=1}^{n}(c_{ij}s_{ij})}{D_j} . \tag{6}$$

The assumption of independence between stations but additivity within stations makes the SO_2 constraint a <u>station</u> constraint. For a station of q units, the SO_2 constraint can be written as

$$\sum_{j=1}^{q} S_j = \sum_{j=1}^{q} \frac{\sum_{i=1}^{n}(c_{ij}s_{ij})}{D_j} \leq S . \tag{7}$$

2.3.3 Cost Minimization with SO_2 Constraints

The effect, on the firm, of the SO_2 regulation is that it adds one additional constraint (equation 7) for each station in the generating system.

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[6] Thus $\sum_{i=1}^{n} c_{ij}s_{ij}$ = total SO_2 output per unit time from the j^{th} unit.

Thus for a system of t generating stations where station 1 consists of units 1 to a, station 2 consists of units (a+1) to b,...,station t consists of units (v+1) to m, the constrained optimization problem can be written

$$\min z = \sum_i \sum_j (c_{ij} p_{ij}) \tag{1}$$

subject to

$$\sum_j (f_j(\sum_i c_{ij} b_{ij}) \leq R_j) = K_T \tag{4}$$

and subject to

$$\sum_{j=1}^{a} \left[\frac{\sum_i c_{ij} s_{ij}}{D_j}\right] \leq S, \quad \sum_{j=a+1}^{b} \left[\frac{\sum_i c_{ij} s_{ij}}{D_j}\right] \leq S, \ldots, \quad \sum_{j=v+1}^{m} \left[\frac{\sum_i c_{ij} s_{ij}}{D_j}\right] \leq S. \tag{7}$$

2.4 Fuel Selection

It has been assumed throughout that capital (particularly the basic operating piece, the generating unit[7]) is fixed. This implies that the shape of each of the m production functions, $K_j = f_j(\sum_i c_{ij} b_{ij})$, and the m dispersion functions, $D_j = g_j(\sum_i (c_{ij} b_{ij}), M)$, are fixed. In addition, the SO_2 constraint level, S, and the load characteristics, K_T (more accurately the distribution of K_T), are determined exogenously. In addition, the variable M is stochastic. This leaves the firm able to affect optimization mainly through fuel selection.

2.4.1 Conceptualization of the Fuel Selection Problem

The firm is viewed as having to choose t sets of fuels, one set at each of its t stations. Each of the fuel sets is chosen from n possible fuel types, each with known price, BTU content and sulphur content. It is assumed that there is some degree of irreversibility involved in the

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[7] The term "generating unit" includes everything from the furnace to and including the generator.

choice of fuels -- once contracted for, the firm can only change the fuel set at considerable expense. The reason for this assumption is that most fuel contracts are for an extended time period.

The size of the fuel set (i.e., the number of fuels included in the set) cannot, in theory, be determined _a priori_. There are, however, cost factors that should limit the size of the maintained fuel set. One factor is the cost of maintaining fuel stocks. It seems intuitively clear that the physical storage space alone will limit the number of fuels. Another factor is due to scale economies in both purchase and transportation of fuels which would dictate against using small amounts of each of a large number of fuels. This suggests that an additional problem exists in determining the price per unit of any particular fuel, since price will depend not only on the fuel itself, but also on the quantity used. If fuels are considered 1,2,...,n at a time, the price of a particular fuel would change as the size of fuel set changed, due to changes in the amount of that particular fuel that was used. For our purposes, the price of a particular fuel can be considered constant, so long as the number of fuels in the fuel set is constant.

Thus far the choice of fuels has been approached at the station level. Whatever fuel set that is chosen for the station is available to each of the units there. However, any two generating units at the same station may vary with respect to operating characteristics to the extent that the same fuel may have different price characteristics due to differing amounts of fuel treatment necessitated by differing furnace designs. Thus the fuel choice for the station must ultimately be based on the individual units. That group of t fuel sets which simultaneously meets the system power constraint and the t SO_2 constraints and yields minimum costs is the optimum.

2.5 A Procedure to Choose Fuel Sets

The optimum fuel set at any single station depends on the fuel sets chosen at the remaining (t-1) stations.[8] Thus a single station cannot be looked at in isolation.

The approach used here will be to compare all the possible fuel set combinations for the t stations. For this comparison estimates of K_T and M will be used. If the least cost use of each of the combinations can be determined, the problem is solved -- we merely pick that combination which yields minimum system fuel costs.

Given n fuel types at t stations the number of combinations to be considered could be astronomical. The number of fuel sets, C_s, to be considered at a single station would be

$$C_s = \sum_{r=1}^{n} \frac{n!}{(n-r)!(r)!} ,$$

where r is the number of fuels considered at a time. Given C_s fuel sets at each of the t stations, the number of combinations to be considered for the system, C_S, would be

$$C_S = (C_s)^t .$$

Unless both n and t are numerically small, the problem appears to be overpowering.

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[8] The optimum fuel set at any one station depends on its share of the total system load, K_T. Its share is K_T minus output of the (t-1) remaining stations. The load carried by the (t-1) stations will depend upon comparative costs of generation, or ultimately on the (t-1) fuel sets they are burning.

The numerical value of t is equal to the number of generating stations in the system. A quick survey of power systems in the U.S. shows that few systems have more than ten stations and most have between three and six stations. The value of n is potentially larger, but in most cases some fuels can be discarded off-hand as being uneconomic. It also may be possible to find station fuel combinations that dominate all other fuel sets at that station. These possibilities depend on the data and cannot be evaluated *a priori*. At this point it is assumed that the number of combinations is manageable, and the problem of valuation of the different fuel sets is considered.

Any comparison of fuel sets must make certain that the figures being compared represent minimum cost usage of those fuel sets. In order that a group of fuel sets be used in an efficient manner, there are three necessary conditions:

(1) The station SO_2 constraint, S, must be optimally allocated between the units at each generating station.

(2) The production level at the station must be optimally allocated between the generating units at that station.

(3) The demand load on the system, K_T, must be optimally allocated between stations.

If these conditions are met, the fuel sets are being used in an optimal manner.

2.5.1 The Optimum SO_2 Allocation Between Units

Assume that an arbitrarily chosen fuel set is considered at a station consisting of two generating units. The fuel set can be visualized in two dimensional space as follows.

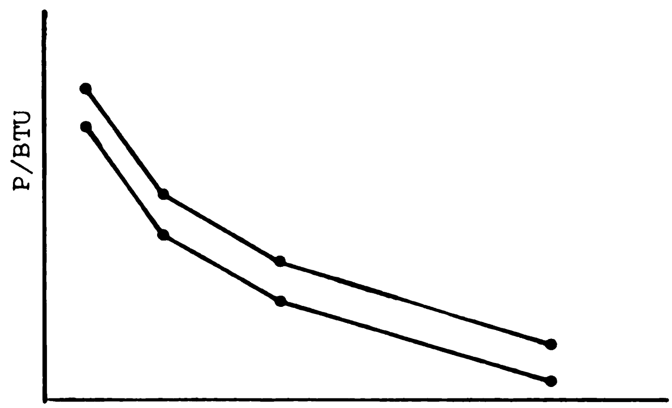

Figure II-1. Four Fuel Price-SO_2 Relationship

In the diagram we are looking at the price, SO_2 relationship for an assumed fuel set of four fuels. Two separate relationships are shown to symbolize use in two different units, with unit 2 demanding more fuel treatment than unit 1. It can be shown that the relevant price-SO_2 relationship lines will always be convex. Any fuel lying northeast of a line between any two other fuels can be thrown out as uneconomic since any point on the line can be reached by mixing. The negative slope implies that the cost minimizing firm will always use the highest sulphur fuel possible. The question for the firm to answer is: How should the sulphur constraint, S, be split between the operating units?

Assume two units are operating at given outputs, $\bar{K}_1$ and $\bar{K}_2$. Assume further that sulphur output of each unit can be varied at will, so long as $(S_1 + S_2) = S$.[9] How should the mix of fuels be set to yield the least cost solution?

Fixed values of K_1 and K_2 imply that the input of BTU's to units 1 and 2 are constant. It also implies that the values of D_1 and D_2 are fixed for any specific meteorological state (see Section 2.3.2 and equation (5)).

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[9]Although the regulation allows $S_1 + S_2 \leq S$, the least cost solution demands $S_1 + S_2 = S$. This is implied by the inverse relationship between SO_2/BTU and Price/BTU.

Since the output of each unit is fixed, and meteorological conditions are assumed constant, the only variable in the SO_2 constraint equation is the sulphur content (SO_2/BTU) of the fuel mix used. Rewriting the SO_2 constraint (equation 7) as

$$\frac{(SO_2/BTU)_1 BTU_1}{D_1} + \frac{(SO_2/BTU)_2 BTU_2}{D_2} = S \ , \tag{8}$$

and realizing that $\Delta S_1 + \Delta S_2 = 0$ we have

$$\frac{\Delta (SO_2/BTU)_1 BTU_1}{D_1} + \frac{\Delta (SO_2/BTU)_2 BTU_2}{D_2} = 0 \ . \tag{9}$$

Rewriting equation (9) yields the required relationship between changes at the two units as

$$\Delta (SO_2/BTU)_1 = (D_1/D_2)(BTU_2/BTU_1)\Delta (SO_2/BTU)_2 \ . \tag{10}$$

The change in total cost associated with any such change in SO_2/BTU will depend on the slope of the SO_2/BTU, Price/BTU relationship of the particular fuel set considered.[10] Let z denote fuel costs:

$$z = (P/BTU)_1 \cdot BTU_1 + (P/BTU)_2 \cdot BTU_2 \ . \tag{11}$$

The change in fuel costs due to altering the SO_2 outputs of the two units can be written as

$$\begin{aligned} \Delta z = {} & \Delta (SO_2/BTU)_1 [\Delta (P/BTU)_1 / \Delta (SO_2/BTU)_1] BTU_1 \\ & - \Delta (SO_2/BTU)_2 [\Delta (P/BTU)_2 / \Delta (SO_2/BTU)_2] BTU_2 \ . \end{aligned} \tag{12}$$

Substituting (10) into (12) and setting $\Delta z = 0$ yields

$$\begin{aligned} & [(D_1/D_2)(BTU_2/BTU_1)\Delta (SO_2/BTU)_2][\Delta (P/BTU)_1 / \Delta (SO_2/BTU)_1](BTU_1) \\ & = \Delta (SO_2/BTU)_2 [\Delta (P/BTU)_2 / \Delta (SO_2/BTU)_2](BTU_2) , \end{aligned} \tag{13}$$

which reduces to

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[10]Although the fuel set is fixed and individual fuel prices are fixed, changes in both price and SO_2 can be affected by changing the fuel <u>mixture</u>.

$$\frac{D_1}{D_2} = \frac{\dfrac{\Delta(P/BTU)_2}{\Delta(SO_2/BTU)_2}}{\dfrac{\Delta(P/BTU)_1}{\Delta(SO_2/BTU)_1}} \; . \tag{14}$$

Thus the optimal allocation of S to the two units occurs where the contributions of the two units equal S and the ratio of the dispersion values is inversely equated to the slopes of the price-SO_2 lines.

The strength of the optimizing rule is that it is independent of output levels, and so holds for all levels of output.

This result must hold for any two units at the same station. Thus for optimum allocation of the SO_2 constraint to each of the units located at a station consisting of q units,

$$\sum_{i=1}^{q} S_i = S \text{ and}$$

$$\frac{D_i}{D_j} = \frac{\dfrac{\Delta(P/BTU)_j}{\Delta(SO_2/BTU)_j}}{\dfrac{\Delta(P/BTU)_i}{\Delta(SO_2/BTU)_i}} \quad \text{for all } i \neq j \; (i = 1,2,\ldots,q; \; j = 1,2,\ldots,q).$$

In the case under consideration each of the price-SO_2 relationships are piecewise linear relationships, discontinuous at each of the pure fuel points, with constant slopes existing between the pure fuel points. Thus, in general, equality between dispersion ratios and slopes will not be attainable. These considerations do not change the results except that instead of equality between dispersion ratios and slope ratios, we have to come as close to equality as the fuel lines and dispersion functions permit. In general there will be an optimum where, with q units, there will be at least q-1 of the units operating on the points of discontinuity (i.e., on a single fuel rather than a mixture), and at most, 1 unit mixing fuels.

2.5.2 The Optimum Allocation of Station Load to Individual Units

The problem of allocating any arbitrarily chosen level of station output, K_S, to the individual units at that station is complicated by the SO_2 constraint. This is a result of the BTU input itself being an argument in both the production function and the dispersion function -- a change in output for any particular unit necessitates a change in BTU input, which in turn implies a change in dispersion.

Starting again with a simple case, assume that the station consists of but two units, with combined output fixed and equal to K_S. For fixed meteorological conditions, the outputs of units 1 and 2, K_1 and K_2 respectively, imply known unique values of D_1 and D_2. The relative values of D_1 and D_2 imply unique fuel prices for the two units, so long as equations [8] and [14] are satisfied, and the price/BTU, SO_2/BTU relationship of the fuel is known. Total fuel costs are simply

$$z = BTU_1 \left(\frac{P}{BTU}\right)_1 + BTU_2 \left(\frac{P}{BTU}\right)_2 .$$

The problem lies in evaluating changes in fuel cost due to changing the allocation of K_S to the two units. Both BTU levels and prices will change as a result of the new allocation.

Assuming that the production functions, the dispersion functions, and the fuel price-SO_2 relationships are all continuously differentiable, the change in cost due to changing the output of unit 1 can be expressed as

$$\frac{dz}{dK_1} = \frac{dBTU_1}{dK_1} \cdot P_1 + \frac{dP_1}{dK_1} \cdot BTU_1 + \frac{dP_1}{dK_1} \cdot \frac{dBTU_1}{dK_1} \tag{15}$$

The last term can be ignored since it is the product of two derivatives, leaving the usual result of the rule for differentiation of the product of two functions.

The cost of the change in output at unit 2 will be identical in form; only the subscripts will change. The change in total costs will be the difference between the two or:

$$\left[\frac{dz}{dK_1} - \frac{dz}{dK_2}\right] = \left[\frac{dBTU_1}{dK_1} \cdot P_1 + \frac{dP_1}{dK_1} \cdot BTU_1\right] - \left[\frac{dBTU_2}{dK_2} \cdot P_2 + \frac{dP_2}{dK_2} BTU_2\right]. \quad (16)$$

Both the sign and the magnitude of P_i, BTU_i, and $\frac{dBTU_i}{dK_i}$ can be determined. The problem lies in evaluating $\frac{dP_i}{dK_i}$.

The change in price per unit of fuel depends upon: 1) the effect of changes in K_i on D_i (ΔK_i implies ΔBTU_i implies ΔD_i), 2) the effect of equal and opposite[11] changes in K_1 and K_2 on the ratio of their respective dispersion values ($\frac{D_1}{D_2}$), and 3) the relationship between SO_2/BTU and price/BTU of the fuel set -- in particular, the rate of change of the slope of that relationship.

In order to get the combined effects, the fuel mix has to be reoptimized, i.e., equations (8) and (14) have to be satisfied for each load allocation. Unless there exist special properties of the production functions, dispersion functions or the fuel set, neither the sign nor the magnitude of $\frac{dP_i}{dK_i}$ can be evaluated before reoptimizing via (8) and (14). Unfortunately such a procedure would be exceedingly tedious.

An alternative approach would be to temporarily assume that $\frac{dP_i}{dK_i}$ was small enough to have no effect on the change in costs. Thus starting at any arbitrarily chosen value of K_1 and K_2, with equations (8) and (14) determining P_1 and P_2 at that point, a comparison of $(\frac{dBTU}{dK_1} \cdot P_1)$ and

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[11]Since the point of focus is the change in allocation of K_S between K_1 and K_2, any increase in K_1 must be offset by an equal decrease in K_2, and vice versa.

$(\frac{dBTU}{dK_2} \cdot P_2)$ can be used[12] to determine the direction of movement of the change in allocation of K_S to K_1 and K_2.

Let $A = (\frac{dBTU}{dK_1} \cdot P_1)/(\frac{dBTU}{dK_2} \cdot P_2)$. If $A > 1$, the direction of movement is towards increased output in unit 2 and equally decreased output in unit 1. Using P_1 and P_2 as constants, output can be changed (while recalculating new values for $\frac{dBTU}{dK_1}$ and $\frac{dBTU}{dK_2}$) until either $A = 1$ or $K_1 = 0$.

If the point is reached were $A = 1$, then a new set of values for P_1 and P_2 have to be determined by applying (8) and (14). With the new values of P_1 and P_2, A should then be recalculated.

If the change in allocation leads instead to the result $K_1 = 0$, a different procedure is necessary. When $K_1 = 0$, then K_2 must be equal to K_S. It is entirely possible that even though $A > 1$, the direction of movement may be wrong. If the two production functions cross, and K_S is less than that level of output at which they cross, the ratio of derivatives may be misleading. Figure II-2 is instructive.

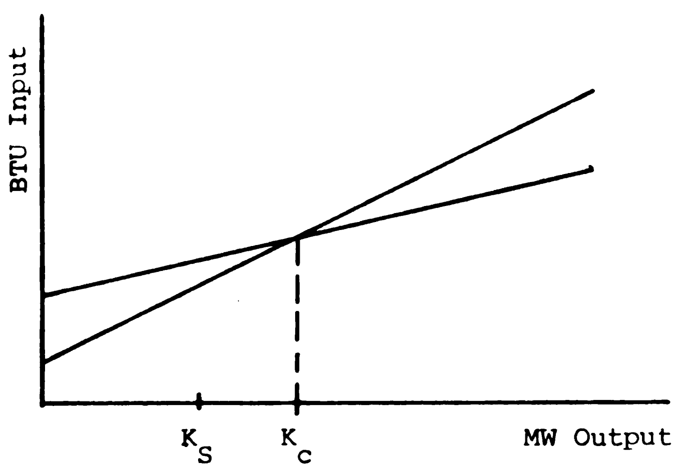


Figure II-2. Two Intersecting Linear Production Functions

---

[12] Throughout this section is is assumed that d^2BTU/dK_i^2 is either ≤ 0 or ≥ 0 for all $i = 1,2,\ldots,q$ units. This implies that there can be, at most, one point of intersection of production functions for any two units. The assumption will be checked against the production functions estimated in Chapter IV.

The diagram shows a simple case of linear production functions intersecting at output K_c. At any level of station output less than K_c ($K_1 + K_2 = K_S < K_c$), $\frac{dBTU}{dK_1} < \frac{dBTU}{dK_2}$. Unless $P_2 > P_1$ by an amount greater than the divergence in derivatives, strict adherence to the value of the ratio A would lead to $K_1 = K_S$, $K_2 = 0$, which would not be the least cost allocation. This result is due to the production functions intersecting the BTU axis at points where BTU > 0. To correct for this error, whenever $K_S < K_c$ and the A ratio drives either K_1 or K_2 to zero, costs at that point must be compared to costs of reversing the allocation (i.e., if $K_1 = 0$, $K_2 = K_S$ then calculate costs for $K_1 = K_S$, $K_2 = 0$). So long as $K_S \geq K_c$, this problem does not exist.

Due to the problems of determining changes in prices caused by changes in power allocation, the above analysis has been concerned heavily with comparative thermal efficiencies of units followed by after-the-fact determination of prices. It appears that, since the emphasis is so heavily on the production function, the best procedure would be to choose the initial allocation of K_S to K_1, K_2 with complete disregard for prices, i.e., based on thermal efficiencies. Thus, instead of starting with arbitrary values of K_1, K_2, start at the point where $\frac{dBTU}{dK_1} = \frac{dBTU}{dK_2}$. If equality does not exist, expand output of the unit with the smaller derivative until its output is equal to K_S. In the case of $K_S < K_c$ (Figure II-1), slope has no meaning as mentioned earlier, and comparative total BTU inputs of ($K_1 = K_c$, $K_2 = 0$) versus ($K_1 = 0$, $K_2 = K_c$) must be calculated. Once the initial point is chosen based on thermal efficiency, then prices can be determined using equations (8) and (14).

Equation (8) sets the sum of the SO_2 contributions equal to the regulation and equation (14) splits the regulated amount optimally between the units. When equations (8) and (14) are satisfied, the resulting fuel prices, P_1 and P_2, are the optimum fuel mix prices. These prices will, in general, necessitate a change in the allocation of power between units from the original allocation based on thermal efficiency. The new power allocation is the start of the next iteration.

It may be instructive to look at a simplified expansion path in some detail. Assume that we consider a station consisting of three generating units, each with a linear production function, and each choosing from the same two fuels. Assume further that the firing order of the three units is predetermined, that the dispersion efficiencies are identical and that output is not an argument in the dispersion functions. In Chapter V these assumptions will be relaxed.

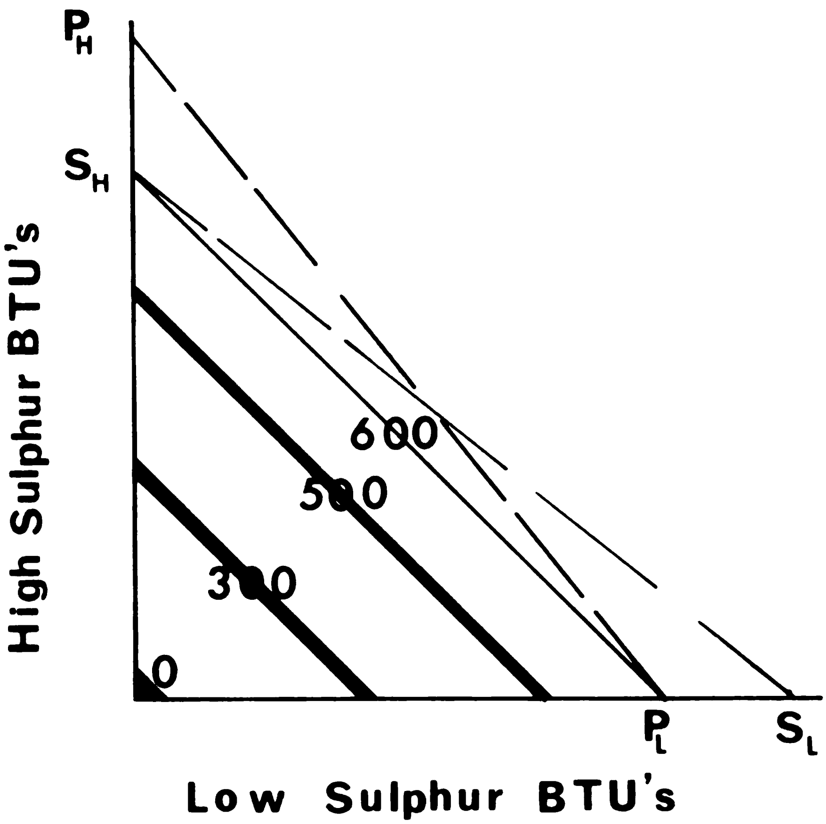
In Figure II-3, isoquants are drawn in two-fuel space. They are straight lines running at a 45° angle to the axes, because the factor inputs are perfect substitutes in production. It is assumed in the diagram that the three generating units are of 300, 200 and 100 MW capacity, with production functions of the form $MW_i = \alpha_i + \beta_i(BTU)$, $(i = 1,2,3)$. Although the quadrant is dense with isoquants, those drawn in are of particular interest. The isoquants labelled 0, 300 and 500 are "thick" -- this thickness is the graphical representation of the absolute size of α_1, α_2 and α_3 respectively.

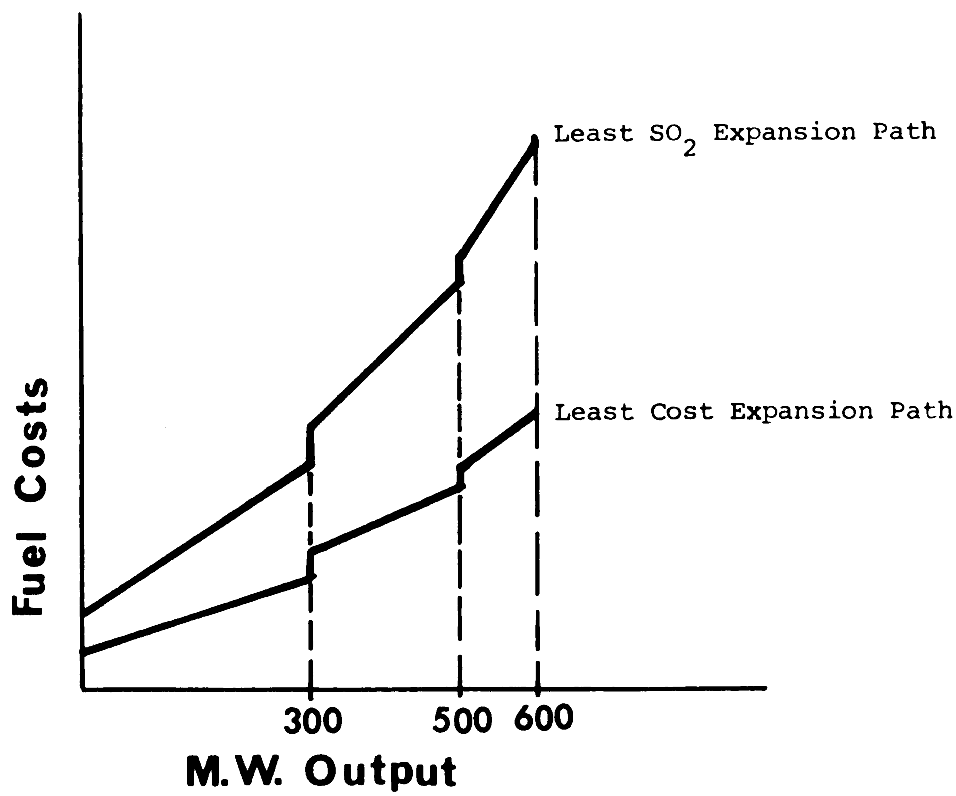
In Figure II-4, two separate expansion paths are derived directly from Figure II-3. The price line $P_H P_L$ would yield an expansion path of corner solutions along the high sulphur coal axis. Given the relative prices depicted, the least cost expansion path is derived in Figure II-4.

The least SO_2 expansion path is likewise derived from Figure II-3, where the line $S_H S_L$ shows the relative sulphur contents of the two coals.

Figure II-3. Isoquant map of a three unit generating station with superimposed isocost and isoSO_2 lines.

Figure II-4. Expansion paths traced out from the isocost line and the isoSO_2 line.


P
H
S
H
High Sulphur BTU's
600
500
300
0
P
L
S
L
Low Sulphur BTU's


Least SO_2 Expansion Path
Least Cost Expansion Path
Fuel Costs
300
500
600
M.W. Output

As in the least cost expansion path, the least SO_2 expansion path is derived from corner solutions except in this case, they occur along the low sulphur coal axis.

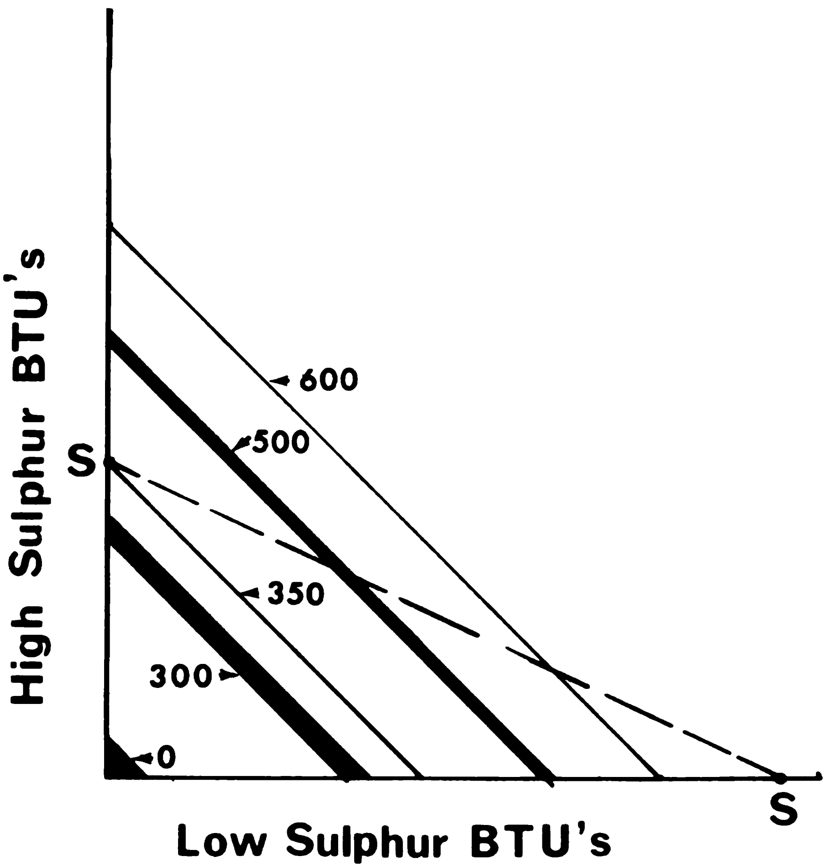
In Figure II-6, L_SL_S and L_CL_C are the least SO_2 and least cost paths taken from Figure II-4. What is new in Figure II-6 is the constrained least cost expansion path. The derivation of this comes from Figure II-5.

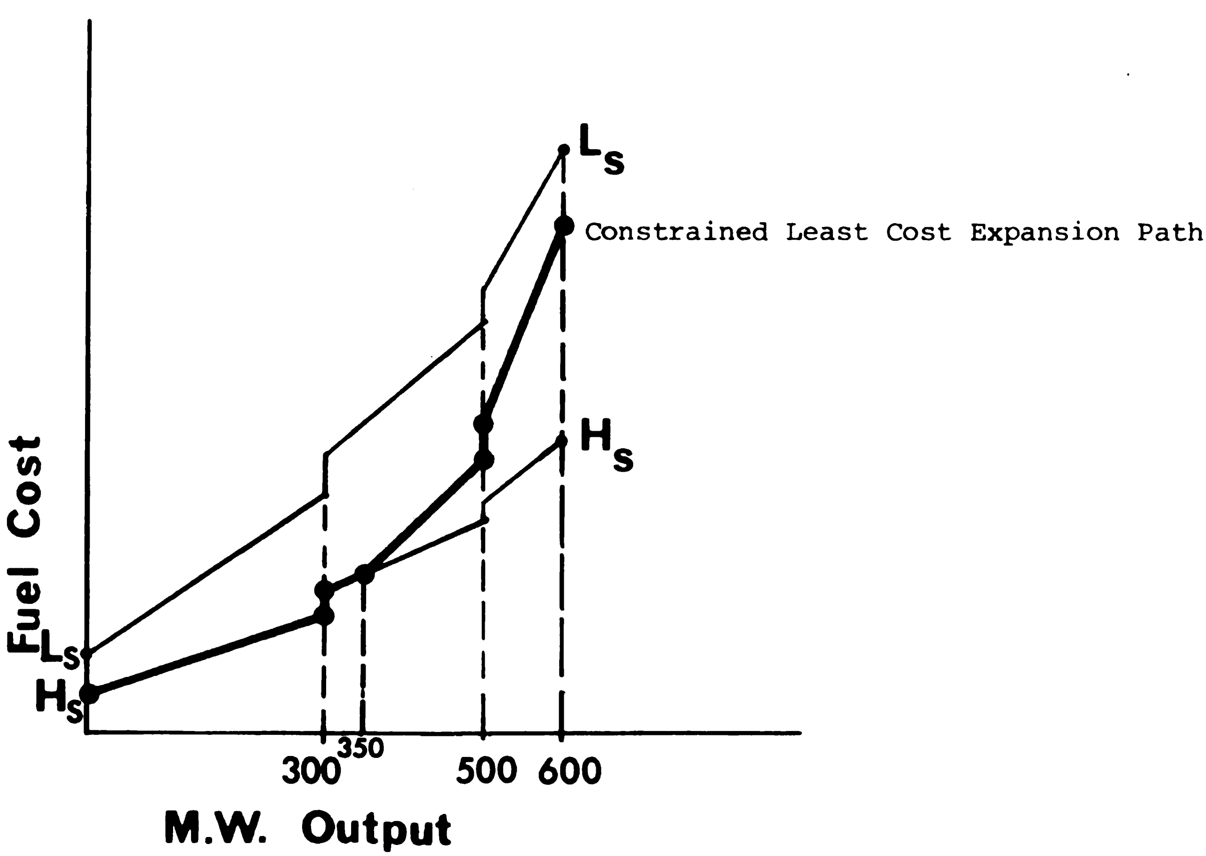
Given the assumption that the dispersion of SO_2 from each of the three units is identical and independent of output, then for any particular meteorological state, ground level concentration is a linear function of the combined sulphur inputs to the three furnaces. The slope of the line in our two-fuel space is the ratio of sulphur per BTU of the two fuels, and the position of the line is determined by the regulation level itself and the meteorological state. As drawn in Figure II-5, the constraint line SS intersects the high sulphur axis at the point of intersection of isoquant 350 with that axis. For all output levels less than 350, the constraint is irrelevant, and the least cost expansion path would proceed along the high sulphur coal axis. Beyond 350, the coal mix will be determined by following the SS constraint line. As can be seen, not only will increased output be produced completely with low sulphur coal, but, low sulphur will be substituted for high sulphur over part of the previous 350 units of output, i.e., the absolute amount of high sulphur coal burned will decrease. This substitution is referred to as "back mixing" in Chapter V. It is because of this phenomenon that the constrained least cost expansion curve shows costs increasing faster than the L_S curve beyond 350 units of output in Figure II-6.

Without the simplifying assumptions, the effect of the SO_2 constraint on the allocation of station load between units is unpredictable. However,

Figure II-5. Isoquant map and SO_2 constraint line SS.

Figure II-6. Constrained least cost expansion path.


High Sulphur BTU's
S
600
500
350
300
0
S
Low Sulphur BTU's


Ls
Constrained Least Cost Expansion Path
Hs
Fuel Cost
Ls
Hs
300
350
500
600
M.W. Output

a few observations can be made. First, the relationship between dispersion functions and production functions is crucial. If dispersion efficiency is directly related to thermal efficiency, the effect of the SO_2 constraint will be to strengthen the motivation for using the thermally most efficient unit mix. Second, the shape of the dispersion function is important. It can safely be assumed that the first derivative of dispersion with respect to BTU input is non-negative. The sign of the second derivative is at this point unknown. If the sign is positive, there will be a tendency for the SO_2 constraint to lead to generating the load with fewer units. If negative, the tendency will be to use more units. The shape of production functions will also be crucial. The next two chapters will answer some of these questions.

2.5.3 The Allocation of System Load to Individual Stations

The problem of system load allocation is dependent entirely on the results of sections 2.5.1 and 2.5.2. Once the least cost expansion path of output is determined for each station, the problem of allocating system load between stations is solved by simply comparing individual station output expansion paths -- equating marginal station generating costs will yield the optimum solution.

2.6 Consideration of Stochastic Factors

2.6.1 Meteorology

All references to meteorology made thus far have alluded to the fact that the meteorological "state" heavily influences the dispersion of stack gas. This state can be conceptualized as a multidimensional vector with the values assumed by each component determining the state. The values assumed by each component are beyond the control of the firm and display a wide range of variability. A listing of components would include such things as temperature, wind speed, and an atmospheric stability parameter. The next chapter will deal with these components in depth, but for now, all that is necessary is to recognize that the meteorological state is multidimensional with the value of each component being a random variable. The probability distribution of the individual components is inconsequential; what is necessary is an estimate of their joint distribution.

2.6.2 Load Pattern

The load demanded of the generating system varies greatly over time. There is a daily, a weekly, and an annual cycle involved in this variation. In contrast to the joint distribution of meteorological effects, the load distribution function should be easily estimated from past history.

2.6.3 Treatment of Stochastic Factors

Once the probability distribution estimates have been made for both the system load and the meteorological state, each of the distributions can be broken into intervals, with the number of intervals being determined by the degree of accuracy desired.

Assume that the load pattern probability distribution and the meteorological probability distribution are broken into m and n intervals respectively. Using the midpoint of the interval as the value of each interval and assigning probability to each value based on the area under the curve over each interval will yield m and n discrete values with attached probabilities.

The analysis of sections 2.5.1, 2.5.2, and 2.5.3 will yield solutions to the problem of minimizing fuel costs for known values of the system load (K_T) and the meteorological state (M). Having discretized the two probability functions, the problem now is to minimize fuel costs for m separate values of K_T and n separate values of M.

The approach that will be used will be to take each of the m values of K_T, one at a time, and produce cost estimates for each of the n meteorological states, weighted by the probability of that state occurring. Likewise the cost figure will be weighted for each of the m values of K_T by the probability of that value of K_T occurring. The total costs of generation will be fuel costs summed over both K_T and M.

2.7 Results

All of section 2.5 (2.5.1-2.5.3) and 2.6 (2.6.1-2.6.3) deal with solving the problem of estimating fuel costs of electric power generation, or more accurately, minimum costs of power generation. It should be borne in mind that so far we have only estimated minimum costs for a <u>single fuel set</u>. Returning to section 2.5 on pages 14 and 15, it is clear that the whole procedure of 2.5.1-2.6.3 has to be repeated numerous times (C_S times) in order to choose the <u>optimum fuel set</u>. That fuel set which gives minimum fuel costs is the optimum, and the associated cost is the cost of power generation for our system of given parameters, subject to the hypothesized SO_2 constraint.

2.8 Conclusions

The conversion of this chapter into a practical vehicle for estimating dollar costs depends heavily on many factors that have thus far been left indefinite. Two of these factors are the specified form and parameter values of the individual unit production and dispersion functions. The next two chapters will deal with these problems. In Chapter V the results of Chapters III and IV will be combined with the material of this chapter towards a computational solution procedure.

CHAPTER III

METEOROLOGY AND DISPERSION

3.1 Introduction

The purpose of this chapter is to clarify and describe the relationship between the generation of electric power and the resulting ground level concentrations of SO_2. The actual concentration level experienced will be a result of two distinct conditions: 1) the amount of SO_2 emitted and 2) the degree of atmospheric dispersion to which that quantity of SO_2 is subjected.

The amount of SO_2 put out in conjunction with power generation is relatively simple to quantify. Given the thermal efficiency of a generating unit and the level of output that unit is operating at, a known level of BTU input is implied. If, in addition, the sulphur/BTU ratio of the fuel burned is known, one simply multiplies total BTU input times twice[13] the sulphur/BTU ratio to get the total SO_2 output of the unit. The dispersion conditions are more complex.

The dispersion of SO_2 in the atmosphere is determined by both the release conditions of the SO_2 and the condition of the atmosphere into which it is released.

The release conditions can, for each unit, be adequately described in terms of four parameters: 1) the point of release in the vertical

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[13] On a mass basis, sulphur has a molecular weight twice that of oxygen. Thus upon combustion, the mass of SO_2 will be twice the original mass of sulphur.

dimension (stack height), 2) the velocity of the stack gas at exit, 3) the temperature of stack gas and 4) the diameter of the stack. Parameters 2, 3 and 4 determine what is referred to as bouyancy flux. Of these four parameters, 1 and 4 are fixed and 2 and 3, although variable, vary in a known direct relationship with output of that unit.

The state of the atmosphere into which the stack gas is released is crucial in effecting ground level concentration intensities. Ambient temperature, wind velocity and directional variability in both the horizontal and vertical plane, and the vertical temperature profile all strongly influence dispersion. They represent stochastic processes which are beyond the control of the firm. In view of their impact on dispersion, these meteorological phenomena will be treated first and in more depth than the release conditions.

3.2 Meteorology

3.2.1 Introduction

> The essential relation between meteorology and atmospheric dispersion involves the wind in the broadest sense of the term. Wind fluctuation over a very wide range of time and space scales accomplish dispersion and strongly influence other processes associated with it [ASME, 1968].[14]

Wind, as defined in lay language, plus the condition of the atmosphere to either suppress or enhance vertical motion are the main determinates of atmospheric dispersion. This tendency to resist or suppress vertical motion is referred to as the stability of the atmosphere. The degree of stability is crucial to dispersion estimates.

3.2.2 Stability

If a small volume of air is forced upwards in the atmosphere, it will, in theory, encounter lower pressure, expand and cool. Assuming no exchange

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[14] The bulk of the material in this chapter is from this publication.

of heat between the small volume of air and its atmospheric environment, the rate at which the small volume cools due to expansion is defined as the dry adiabatic lapse rate, and is equal to -1 degree centigrade per 100 meters of ascent. Although there is always some exchange of heat in the atmosphere, the concept is an important one.

The stability of the atmosphere is determined by a comparison of the actual vertical temperature profile with the dry adiabatic lapse rate. The actual temperature stratification is known as the environmental lapse rate. If the environmental lapse rate is greater (absolutely, e.g., $-2^{o}/100$ m) than the dry adiabatic lapse rate, the volume of gas released upward will tend to become less dense than the surrounding atmosphere and upward motion will be enhanced. This is referred to as an unstable atmosphere. Alternatively, a stable atmosphere exists when the environmental lapse rate is less than the dry adiabatic lapse rate, and a neutral atmosphere is one in which the two lapse rates are nearly identical.

Another measure of atmospheric stability is known as the potential temperature. The potential temperature θ, is defined as the temperature that would be assumed by a parcel of dry air brought adiabatically from its initial elevation in the atmosphere to a standard pressure of 1000 mb. A potential temperature that increases with elevation denotes a stable atmosphere; if it decreases with elevation the atmosphere is unstable.

The atmospheric condition receiving the most attention from pollution authorities is the phenomenon referred to as a thermal inversion. An inversion exists when the vertical temperature profile is reversed, resulting in increased temperature readings as the elevation increases. When an inversion occurs, vertical motion is severely resisted. However, much of the concern with low level inversions is only pertinent to pollutants released at ground level. Since an inversion is simply an extremely stable situation, pollutants released at ground level will stay at ground level, where the damage potential is highest. In the case of power plant emissions, gases are released at an elevation provided by the stack height itself. With vertical motion resisted in either direction, the SO_2 will tend to stay above ground level, and so yield extremely low ground level readings, except in areas of high topographic relief.

3.3 Calculation of Dispersion

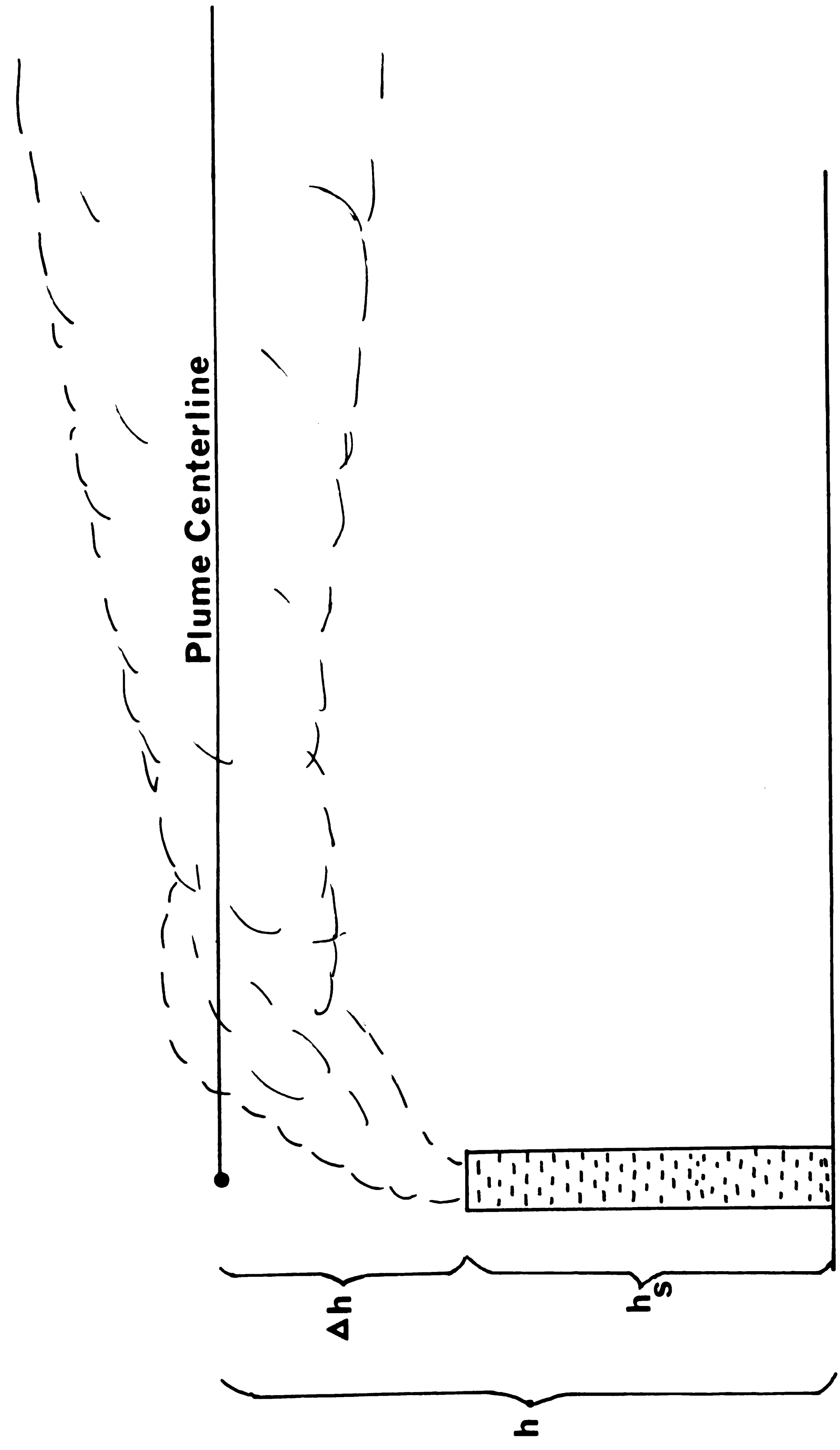
3.3.1 Introduction

In calculating the dispersion of a gas from an elevated point source, the dispersion process is separated into two sequential parts. The first step is to calculate the effective stack height, which includes the rise of the plume above the actual stack height. This establishes a theoretical origin of the plume. The second step is to calculate dispersion using the theoretical origin as the point source of the effluent.

3.3.2 Calculation of Effective Stack Height

The theoretic estimation of stack gas dispersion demands consideration of not only the actual height of the stack from which the gas is emitted, but also consideration of the rise of the gas above stack height. This rise above stack height is due to the initial velocity of the gas emerging from the stack (the range of velocity for the generating units under consideration is from about 13 ft/sec. to nearly 120 ft/sec.), and a buoyancy effect due to exit gas temperature which is well above ambient (again, for the units considered, the range is from approximately 230°F to 330°F). The actual stack height plus the resulting rise of the center line of the plume is defined as the effective stack height. The following diagram is instructive.

Figure III-1. Effective stack height.


Plume Centerline
Δh
h_s
h

The theoretic origin, as shown in Figure III-1, is used for the computation of dispersion. The A.S.M.E.'s "Recommended Guide for the Prediction of Airborne Effluents" suggests using two different equations for the calculation of the rise of plumes.

For plumes rising in a stable atmosphere the rise above stack height (Δh) is estimated by

$$\Delta h = 2\left(\frac{F}{\bar{u}G}\right)^{.33} .$$

For neutral and unstable conditions the equation recommended is

$$\Delta h = 150\,\frac{F}{\bar{u}^3} .$$

Terms in the above equations are

$\bar{u}$ = mean wind speed at actual stack height (m/sec)

F = buoyancy flux = $gV_s\left(\frac{D}{2}\right)^2\left[\frac{T_s - T_a}{T_a}\right]$ where

g = acceleration due to gravity (m/sec^2)

V_s = vertical efflux velocity (m/sec)

D = stack diameter (m)

T_s = stack gas temperature ($^\circ$K)

T_a = ambient temperature at stack height ($^\circ$K)

and G = stability parameter = $\frac{g}{\bar{\theta}_o}\,\frac{\Delta\bar{\theta}}{\Delta z}$,

where

$\bar{\theta}_o$ = potential temperature at stack height ($^\circ$K)

$\frac{\Delta\bar{\theta}}{\Delta z}$ = lapse rate of potential temperature ($^\circ$K)

The authors suggest extreme caution should be used when interpreting results for low speed wind conditions, and state that they are unreliable when the wind speed at stack height is less than 7 m/sec.

3.3.3 Calculation of Dispersion Incorporating Effective Stack Height

The two atmospheric flow features of greatest importance to the dispersion of stack gases are the wind speed and the turbulence characteristics the stack gas is subjected to. The wind speed acts to disperse the gas by providing separation between gas molecules. The turbulence acts to spread the gas out in the plane perpendicular to wind direction.

The ASME manual advises the use of a simple form of the basic Gaussian distribution equation:

$$X_{(x,y,o)} = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} e^{-\{h^2/2\sigma_z^2 + y^2/2\sigma_y^2\}}$$

where $X_{(x,y,z)}$ = concentration (units/m^3, e.g., gm/m^3) of pollutant at (x,y,z) where x is the distance directly downwind, y is distance in the cross wind direction and z is the distance vertically.

Q = pollutant release rate (units/sec., e.g., gm/sec.)

σ_y, σ_z = crosswind and vertical plume standard deviations (m)

$\bar{u}$ = mean wind speed at stack height (m/sec.)

h = effective stack height = $h_s + \Delta h$ where

h_s = actual stack height.

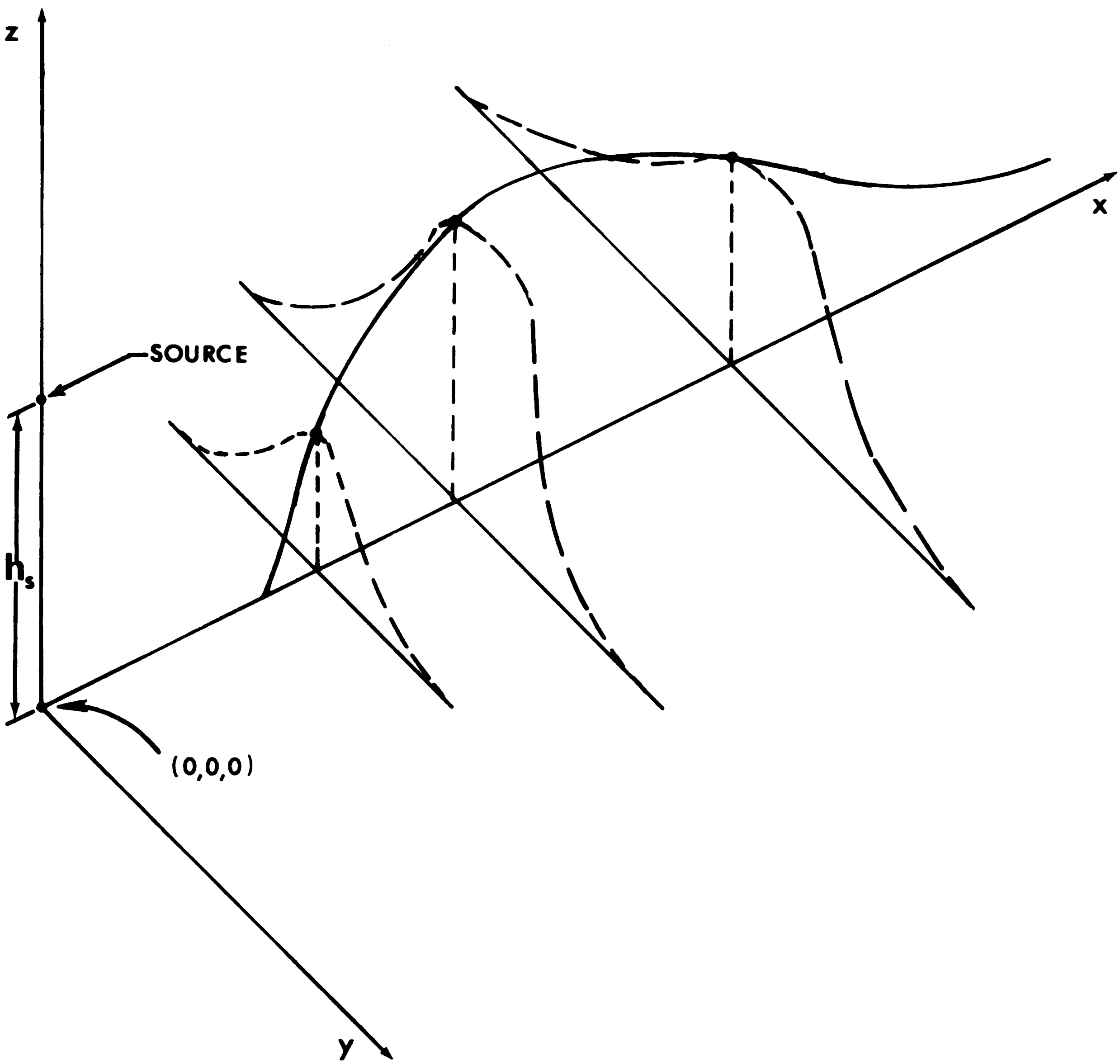
Since we are interested in ground level concentrations only, z has been set equal to zero. By setting y = 0, we will obtain concentrations directly down wind.

$$X_{(x,o,o)} = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} e^{-\{h^2/2\sigma_z^2\}} .$$

This equation is more suitable, since the highest values will always be found directly downwind (y = 0).

Figure III-2 shows the crosswind distribution of ground level centrations as a gradually broadening set of bell-shaped curves. The

Figure III-2. Distribution of Ground level concentrations of SO_2 released from an elevated source.


z
SOURCE
h_s
x
(0,0,0)
y

quantities σ_y and σ_z are the crosswind and vertical standard deviations of the dispersing plume and are functionally related to the distance downwind. One means of estimating σ_y and σ_z often used where instrumentation is lacking is to use a power law relationship of the form

$$\sigma = bx^q$$

where the coefficient b and the exponent q vary according to meteorological conditions. The graphs and values for b and q are shown below. They are intended for estimating hourly mean concentrations, and are acceptable for our purposes (see Figures III-3 and III-4).

The equation for the maximum ground level concentration is

$$X_{max} = \frac{2Q}{e\pi \bar{u} h^2} \frac{\sigma z}{\sigma y}$$

with the point of maximum concentration occurring at the distance where $\sigma_z = h/\sqrt{2}$.

Two additional ground level concentration equations are put forward in the ASME manual:

1) Inversion fumigations:

$$X_{1F} = \frac{0.4Q}{h\sigma_y \bar{u}} .$$

The reader is cautioned on the use of this equation with the statement that the answers derived may be off by as much as a factor of 5.

This equation attempts to estimate concentrations that occur during the breakup of low-level temperature inversions. This phenomenon is usually of short duration, ranging from a few minutes to an hour. Unless frequently experienced in Michigan, it can be ignored.

2) Multiple Sources

In many cases, and particularly with respect to generating units, ground level concentration levels depend upon the contribution of not a

Figure III-3. Horizontal standard deviations of a plume.
[Source: ASME, 1968]

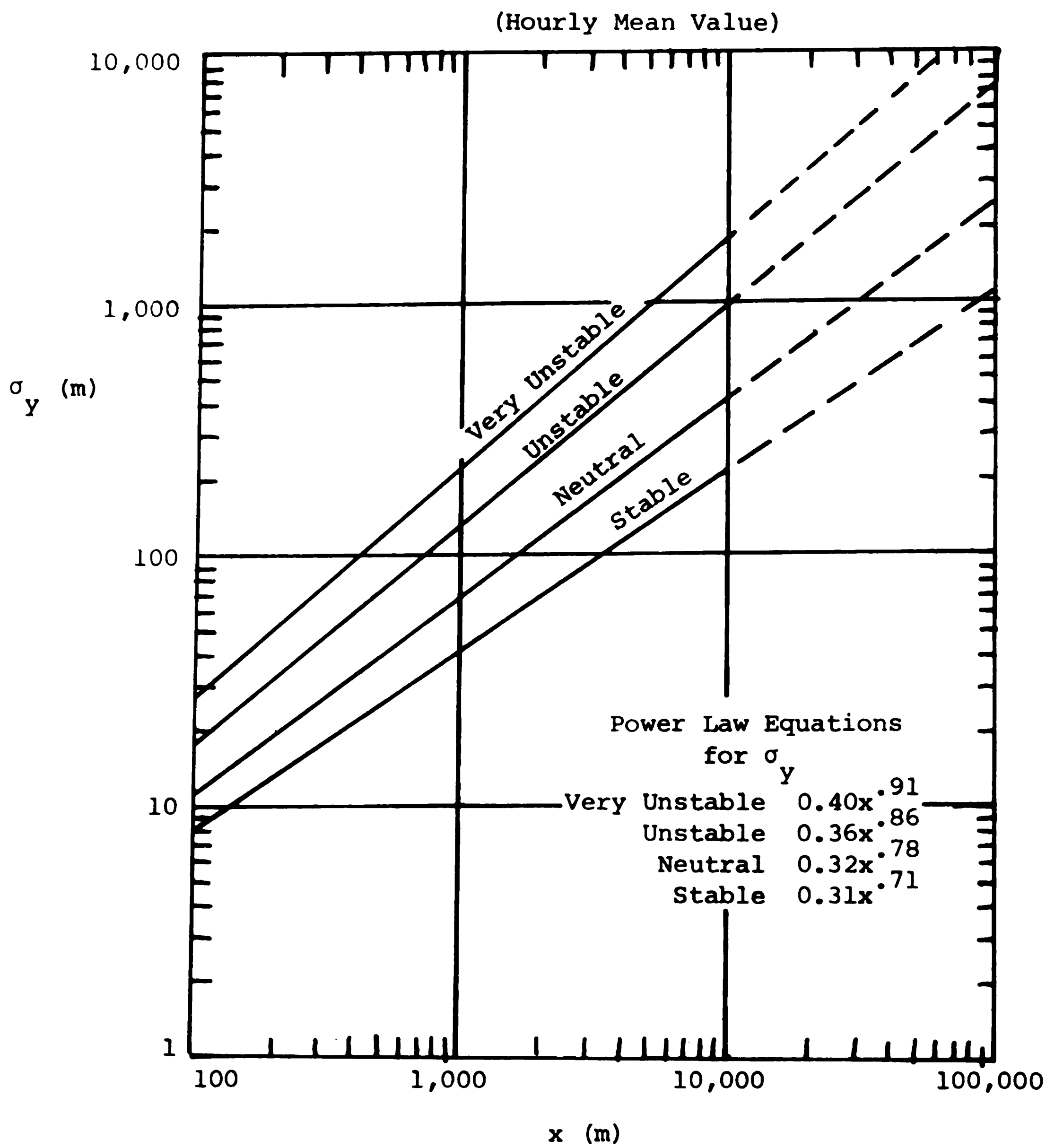
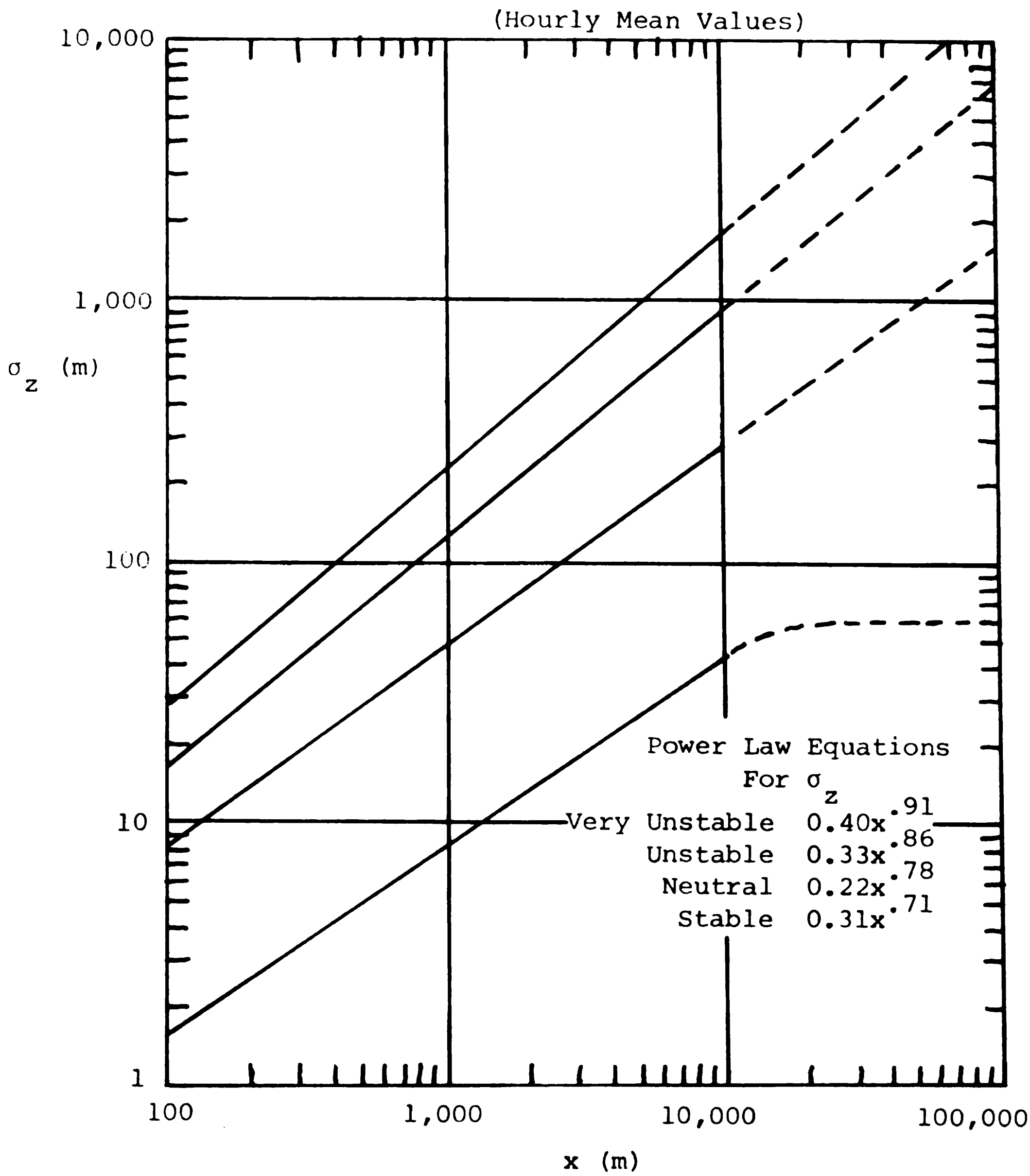

(Hourly Mean Value)
10,000
1,000
100
10
1
σ_y (m)
100
1,000
10,000
100,000
x (m)
Very Unstable
Unstable
Neutral
Stable
Power Law Equations
for σ_y
Very Unstable $0.40x^{.91}$
Unstable $0.36x^{.86}$
Neutral $0.32x^{.78}$
Stable $0.31x^{.71}$

Figure III-4. Vertical standard deviations of a plume.
[Source: ASME, 1968]


(Hourly Mean Values)
10,000
1,000
100
10
1
σz (m)
100
1,000
10,000
100,000
x (m)
Power Law Equations
For σz
Very Unstable 0.40x.91
Unstable 0.33x.86
Neutral 0.22x.78
Stable 0.31x.71

single stack, but several stacks (i.e., the generating station). The ASME manual suggests the following equation but cautions that knowledge of the problem is extremely limited

$$X_{max(N)} = X_{max(1)} N^{0.8},$$

where $X_{max(1)}$ is the maximum concentration determined for a single stack and N is the number of stacks.

This estimate of concentration seems intuitively untenable for our purposes, unless the stacks are the same height, have the same conditions of release (velocity, temperature) and the corresponding generating units are operating at the same levels of output.

Referring back to Figure III-2, in the case of multiple stacks we have as many concentration surfaces as we have stacks -- the ground level concentration at any point in the x,y plane is the vertical sum of the heights of the individual concentration surfaces overlying that point. The point of global maximum has to be found, and its height determined.

This assumes that one stack does not affect the dispersion of the other stacks. This is, in fact, probably not true -- multiple stacks seem to enhance the dispersion of each individually. Thomas et al. [1963] present data which indicate this.

Given the lack of information on interactions between units, the assumption made in Chapter II (Section 2.3.2) will be retained: maximum ground level concentration is the simple arithmetic sum of the individual unit maxima. This assumption will yield estimates of the global maximum that will be biased toward overstatement of concentration levels.

3.3.4 Concentration Versus Time

All the equations presented above represent estimates of one hour mean concentrations. Short-term peaks may be substantially higher, but since the concern here is only with one hour mean concentration levels (i.e., the regulation is written in terms of hourly mean concentrations), transient peaks will be ignored.

3.4 Summary of Meteorology and Dispersion Estimation

3.4.1 The State of the Art

It should be evident from Section 3.3 that the equations put forth are, at best, rough approximations. There are many reasons for this fact.

Very little comprehensive empirical work has been done on stack gas dispersion to date. A large-scale study initiated by the Tennessee Valley Authority in 1963 probably represents the most complete experimental work done so far, but even there, the design of much of the work is not applicable to this study.

The paucity of empirical work with results that can be generalized is due heavily to the complexity of the phenomenon itself. The dispersion process, between exit of the stack gas and resulting ground level concentration, takes time. Over this time interval, meteorological conditions may be changing. The rise of the plume is difficult to accurately document. The instrumentation to simultaneously measure ground level concentrations and temperature and wind velocities at many different heights is extensive. The effects of unique local terrain may be crucial.

The ASME approach which is adopted in this study is derived theoretically from the physics of the problem, starting with the mechanics and thermodynamics inherent in the dispersion of a large volume of gas released into the atmosphere with known initial temperature and velocity. The model assumes a level uncomplicated terrain, an assumption which is not badly violated in most of Michigan's Lower Peninsula.

3.4.2 Use of the Dispersion Model - A New Direction

Historically, dispersion models have been used by electric utilities to determine adequate stack height, and as such they are usually employed in the planning stage, prior to construction of the unit. Given the firm's criterion of allowable concentrations of SO_2, and given the sulphur content of the fuel to be used, the engineer uses the dispersion estimate to determine how high the stack should be built so as not to exceed the allowable concentration with some degree of confidence.

The use of the dispersion equation in this paper is fundamentally different. In this study, already installed units are considered, with given fixed stack heights. The equation will be used here to determine allowable sulphur content of the fuel. In addition to changing the dependent variable, there is another dimension of difference. Whereas dispersion equations were developed to estimate worst probable cases (i.e., generating unit running at full capacity, meteorological conditions such as to give highest concentration levels), the equations used here will be employed for a range of both load and meteorological conditions.

3.4.3 The Use of the Dispersion Model - Conceptual Significance

In spite of the misgivings voiced on the accuracy of results derived from the dispersion model, the attempt to predict dispersion is important. First, it seems obvious that even in the case where SO_2 regulation is phrased in terms of an SO_2/BTU ratio, some implicit idea of the relation between output at the stack and ground level concentration must be envoked, even if never explicitly stated. The explicit statement used here is at least open to criticism and debate.

The dispersion model is more significant from an ecological point of view. Ecologists put a great deal of emphasis on the concept of "environmental capacity." This is the natural capacity of the environment to tolerate and process stimuli without being damaged by that stimuli. The dispersing ability of the atmosphere is very close to this concept. Therefore the dispersion model can be viewed as an attempt to estimate this capacity. As would be expected, this capacity to disperse would vary from area to area, and conclusions reached for the Michigan region may not hold for other regions. With this in mind we now turn to the necessary assumptions on the probability distribution of meteorological conditions (the local determinants of atmospheric dispersion) for the Michigan area.

3.5 Meteorological Parameter Values Used

3.5.1 Hourly Mean Wind Velocity

Four hourly mean velocity ranges of equal probability have been estimated from wind rose data gathered over a five-year period at Capital City Airport, Lansing, Michigan. This data was gathered at a 52' elevation above ground level and has been multiplied by 2 to approximate wind velocity at stack height. It is assumed that the four range means are representative of wind distributions for all five coal fired station locations. The estimates are as follows:

i	$\bar{u}_i$ (meters/sec.)	$P(u_i)$
1	5.36	.25
2	10.73	.25
3	14.30	.25
4	19.67	.25

3.5.2 Ambient Temperature

As in the case of wind velocity, ambient temperature has been estimated from data gathered at Capital City Airport. The data used are average daily temperature readings for each day of the year over the 30-year period 1931-1960. The range of temperatures was broken into four segments of equal probability with the average value in each range selected to represent that range.

i	T_{A_i} (^{o}K)	$P(T_{A_i})$
1	269	.25
2	277	.25
3	287	.25
4	294	.25

3.5.3 Atmospheric Stability

Unlike temperature and wind velocity, there is no good historical documentation of stability conditions for the mid-Michigan area. For this reason estimates have been made which rely heavily on informal conversations with the state climatologist. The necessary information is listed below. The values of $\sigma z/\sigma y$ have been taken directly from Figures III-3 and III-4.

Classification	($\sigma z/\sigma y$)	($\Delta\theta/\Delta z$)	Probability
Stable	0.1935	1.3^{o}C./100m.	.40
Neutral	0.6875	n.a.	.30
Unstable	0.9167	n.a.	.25
Very unstable	1.0000	n.a.	.05

3.5.4 Meteorological Assumptions

In using the above estimates, two assumptions will be made for analytic simplicity. The first assumption is that the three meteorological variables, $\bar{u}$, T_A, and $\sigma z/\sigma y$ are independently distributed. Thus the joint probability is merely the product of the three individual probabilities. The second assumption is that at any instant, all five coal burning stations experience

identical meteorological conditions. These two assumptions are simplifying assumptions made about phenomena for which the data necessary to estimate the true distributions is totally lacking.

3.6 Summary

In Chapter II, section 2.3.2, the dependence of ground level concentrations on both the amount of SO_2 in the stack gas, and the degree of dispersion which the stack gas is subjected to, was emphasized. It was further noted that that dispersion itself depends upon release conditions (determined by the design of the machine, i.e., within the realm of the firm's control) and the state of the atmosphere into which the SO_2 is released (beyond the firm's control). This chapter attempts to describe the interrelation between release conditions and the receiving atmosphere. The description provided in the equation used to estimate ground level concentrations identifies those variables in the natural world for which input numbers are needed. The last sections of this chapter specify those chosen and the assumptions under which they will be used.

This chapter has essentially dealt with the natural world half of the phenomena. It remains for the next chapter to describe the man-made side of the dichotomy.

CHAPTER IV

THE GENERATING SYSTEM

4.1 Introduction

The fossil-fuel-fired steam-electric segment of Consumers Power Company's generating capacity consists of 24 units located at six principle generating stations. These units range in size from 35 MW to 385 MW with the combined capacity of the units being 2,816 MW. The dates of installation of the 24 units range from 1939 to 1966. This capacity made up more than 80 percent of total company capacity as of 1971. The remainder consisted of 71 MW of nuclear, 135 MW of hydro and 406 MW of gas turbine peaking units. In addition to company owned capacity, Consumers Power Company can, as a member of the Michigan Power Pool, draw on outside capacity. The exchange of power via the pool will be essentially ignored in this study, as will be spinning reserve requirements and both scheduled and non-scheduled downtime for maintenance of units.

4.2 System Load

The demand for power faced by the generating company is largely beyond its control. As noted in Chapter II, both the absolute amount of power demanded and the fluctuations in demand heavily influence the cost of power generation.

In order to estimate the distribution function of the annual system load, actual load figures for the year 1971 will be used. However, these figures represent total system load, whereas the concern in this study is completely with the conventional steam generating segment of that system. To adjust the system figures, the 71 MW of nuclear generation and 136 MW of hydro generation will be assumed to be base load capacity and subtracted out of the total load figures. The figures below represent the adjusted data broken into ten segments of equal probability, with the mean of each interval being used to represent the entire segment.

SYSTEM LOAD (K_S)

K_S	$P(K_S)$
1324 MW	.1
1589 MW	.1
1728 MW	.1
1880 MW	.1
2089 MW	.1
2377 MW	.1
2631 MW	.1
2768 MW	.1
2886 MW	.1
3063 MW	.1

4.3 Thermal Efficiency

As noted in the introduction to this chapter, there is a wide range in both size and date of installation of the 24 conventional units. These variations are paralleled by an equally wide range of underlying design differences, and thus, as should be expected, thermal efficiencies vary widely.

Although no two units, no matter how similar in design, can be expected to exhibit an identical range of thermal efficiencies, units can be grouped together without much loss of accuracy in estimating production functions. Consumers Power Company has provided data on the 24 conventional units broken into five groups. The criteria of inclusion in one of the five groups is based on steam temperature and pressure; this grouping is sufficient for the needs of this study.

In addition to the five groups provided, a sixth group has been created by combining three pairs of units at the Weadock station. This simplification is justified since the units within any pair are identical and both are served by the same stack. Although the two units at the Campbell station are also served by a single stack, the design of the two units is different, and so the two units are treated individually.

The entire gas turbine capacity has been thrown into one group for simplicity. Although individual heat rates range from roughly 12,000BTU/KWH to 15,000 BTU/KWH, all are arbitrarily treated as a single, 406 MW unit with constant returns of 13,500 BTU/KWH.

Although the BTU-MWH relationship for the standard thermal units was thought to be non-linear a priori, a visual check of the points portrayed in two dimensional space suggested that a linear approximation of the MW-BTU relationship would be sufficient. A linear regression equation of the form $Y_i = \alpha + \beta X_i$ (with Y_i = BTU x 10^6 input and X_i = MW output) was used. Although the differences between the estimated value of BTU input and the actual BTU value $(Y_i - \hat{Y}_i)$ vary systematically over the range of output, which would suggest a curvilinear relationship, the size of the maximum difference never exceeded three percent. Table IV-1 at the end of this chapter shows the estimated production function equations (column 5).

Graphs of two of the equations relative to the data points are shown at the end of this chapter. Figure IV-1 is for the 385 MW number 2 unit at the Campbell station; Figure IV-2 is for the seven standard units which range from 35-66 MW capacity. (It should be noted that the axes in the two figures are not the same.)

A few observations are relevant at this point. First, along with increases in steam pressure and temperature have come improved incremental thermal efficiency. Thus, as temperature and pressure increase, the estimated curve will become less steep. This phenomenon is entirely consistent with a priori knowledge. Second, as pressure and temperature increase the value assumed by the constant term, α, increases. This at first appears somewhat puzzling -- why should a more efficient technology result in a larger constant term? Part of the explanation lies in the fact that for the units considered, higher pressures and temperatures are found in the larger units. The size of the constant term is probably directly related to the size of the unit. One would expect the BTU input necessary to keep the unit spinning to be positively related to the size of the unit. Third, the inverse relation between the size of α, the constant term, and the size of β, the slope, implies that the production functions for any two units of different pressure and temperature values will intersect at some positive output level. This possibility was mentioned in section 2.5.2 of Chapter II, and is shown in Figure IV-3 at the end of this chapter.

4.4 Dispersion Characteristics of Generating Units

The observation was made in Chapter III that the dispersion of stack gases depends upon atmospheric conditions and release conditions, with release conditions determined by the design of the unit and the rate at which the unit is operating. It is those design characteristics of the unit which affect dispersion that are of concern here.

The design characteristics affecting dispersion are those that contribute to plume rise, or in the language of Chapter III, effective stack height. They are denoted in the dispersion estimation equations as h_s

(actual stack height), D (stack diameter), V_s (exit velocity), and T_s (exit temperature). The values of h_s and D are shown in columns 6 and 7 of Table IV-1. The estimated relationships of V_s and T_s to thermal input to the furnace are shown in columns 8 and 9 respectively.

It should be noted in Table IV-1 that some of the units at the Weadock station have been combined and/or renumbered; unit 1 as shown in the table is made up of two identical 35 MW units; unit 2 is two identical 50 MW units and unit 3 consists of two identical 66 MW units. Units 4 and 5 are unaltered except for a change in identification number (true identification is number 7 and 8 respectively). The reason for the three pairs of units is that each of the pairs is served by a single stack. At the Campbell station, units 1 and 2 are also served by a single stack. In this case the design of the two units is quite different, and so each is treated individually when considering the thermal to electrical energy conversion. Consideration of dispersion characteristics treats the two units as one, and assumes that unit 2 (being thermally more efficient) will always be fired first and run up to capacity before unit 1 is fired up. Exit velocity and temperature become a function of the sum of the BTU inputs to the two furnaces.

4.5 Summary

This chapter deals with the man-made half of the output and dispersion dichotomy. Whereas Chapter III dealt with the atmosphere as the nonpassive receptacle into which the SO_2 is dumped, this chapter deals with the conditions under which the SO_2 is released. It provides a spatial orientation of the generating units, and through the production functions and the system load figures, provides the background information necessary to determine both release conditions and amounts. One further piece of information is lacking before the analysis can be undertaken and that is the fuel set with which the firm is operating. This information will be provided in the next chapter.

Table IV-1. Generating Unit Characteristics.

STATION	UNIT	CAPACITY (MW)	DATE OF INSTALLATION	PRESS.-TEMP. CLASSIFICATION[1]	PRODUCTION FUNCTION (y = 10^6 BTU INPUT, x = MW OUTPUT)	STACK HEIGHT (m)	STACK DIAMETER (m)	EXIT VELOCITY (V_s in m/sec, y = 10^6 BTU INPUT)	EXIT TEMPERATURE (T_s in ° KELVIN, y = 10^6 BTU INPUT)
Campbell	1	265	1962	B	$y = 210 + 8.170x$	123	5.8	$V_s = .0065y$	$T_s = 401 + .002(y-273)$
	2	385	1966	A	$y = 273 + 7.788x$				
Whiting	1	100	1952	D	$y = 67 + 8.822x$	91	3.6	$V_s = .0197y$	$T_s = 374 + .038(y-67)$
	2	100	1952	D	$y = 67 + 8.822x$	91	3.6	$V_s = .0197y$	$T_s = 374 + .038(y-67)$
	3	125	1953	D	$y = 84 + 8.822x$	91	3.6	$V_s = .0164y$	$T_s = 374 + .030(y-84)$
Weadock[2]	1	70	1940	F	$y = 18 + 12.210x$	74	5.2	$V_s = .0110y$	$T_s = 361 + .071(y-18)$
	2	100	1943, 1948	F	$y = 27 + 12.210x$	74	5.5	$V_s = .0098y$	$T_s = 346 + .062(y-27)$
	3	132	1949	F	$y = 35 + 12.210x$	74	5.7	$V_s = .0074y$	$T_s = 351 + .057(y-35)$
	4	156	1955	C	$y = 110 . 8.370x$	74	4.3	$V_s = .0115y$	$T_s = 352 + .069(y-110)$
	5	156	1958	C	$y = 110 + 8.370x$	74	4.3	$V_s = .0115y$	$T_s = 352 + .069(y-110)$
Karn	1	265	1959	B	$y = 210 + 8.170x$	107	5.5	$V_s = .0081y$	$T_s = 390 + .005(y-210)$
	2	265	1961	B	$y = 210 + 8.170x$	107	5.5	$V_s = .0081y$	$T_s = 382 + .009(y-210)$
Cobb	1	66	1948	E	$y = 23 + 12.210x$	76	3.7	$V_s = .0100y$	$T_s = 369 + .076(y-23)$
	2	66	1948	E	$y = 23 + 12.210x$	76	3.7	$V_s = .0100y$	$T_s = 369 + .076(y-23)$
	3	66	1950	E	$y = 23 + 12.210x$	76	3.7	$V_s = .0100y$	$T_s = 369 + .076(y-23)$
	4	156	1956	C	$y = 110 + 8.370x$	91	4.6	$V_s = .0100y$	$T_s = 377 + .024(y-110)$
	5	156	1957	C	$y = 110 + 8.370x$	91	4.6	$V_s = .0100y$	$T_s = 377 + .024(y-110)$
Morrow[3]	1	35	1939	E	$y = 12 + 12.210x$				
	2	35	1939	E	$y = 12 + 12.210x$				
	3	50	1941	E	$y = 18 + 12.210x$				
	4	66	1949	E	$y = 23 + 12.210x$				
Gas Turbine		406			$y = 13.500x$				

[1] Original data specified in terms of steam pressure and temperature category: A = Supercritical, B = Subcritical (2400 psig), C = Subcritical (2000 psig), D = Standard. Classification F is for grouped standard units (see 2).

[2] Units sharing common stack have been combined. Units 1+2, 3+4, and 5+6 become 1, 2 and 3, respectively. Units 7 and 8 have been renumbered as 4 and 5, respectively.

[3] Morrow station burned natural gas in 1971. Since sulfur content is zero, stack characteristics are unnecessary.

Figure IV-1. Input output relation for Campbell unit 2.

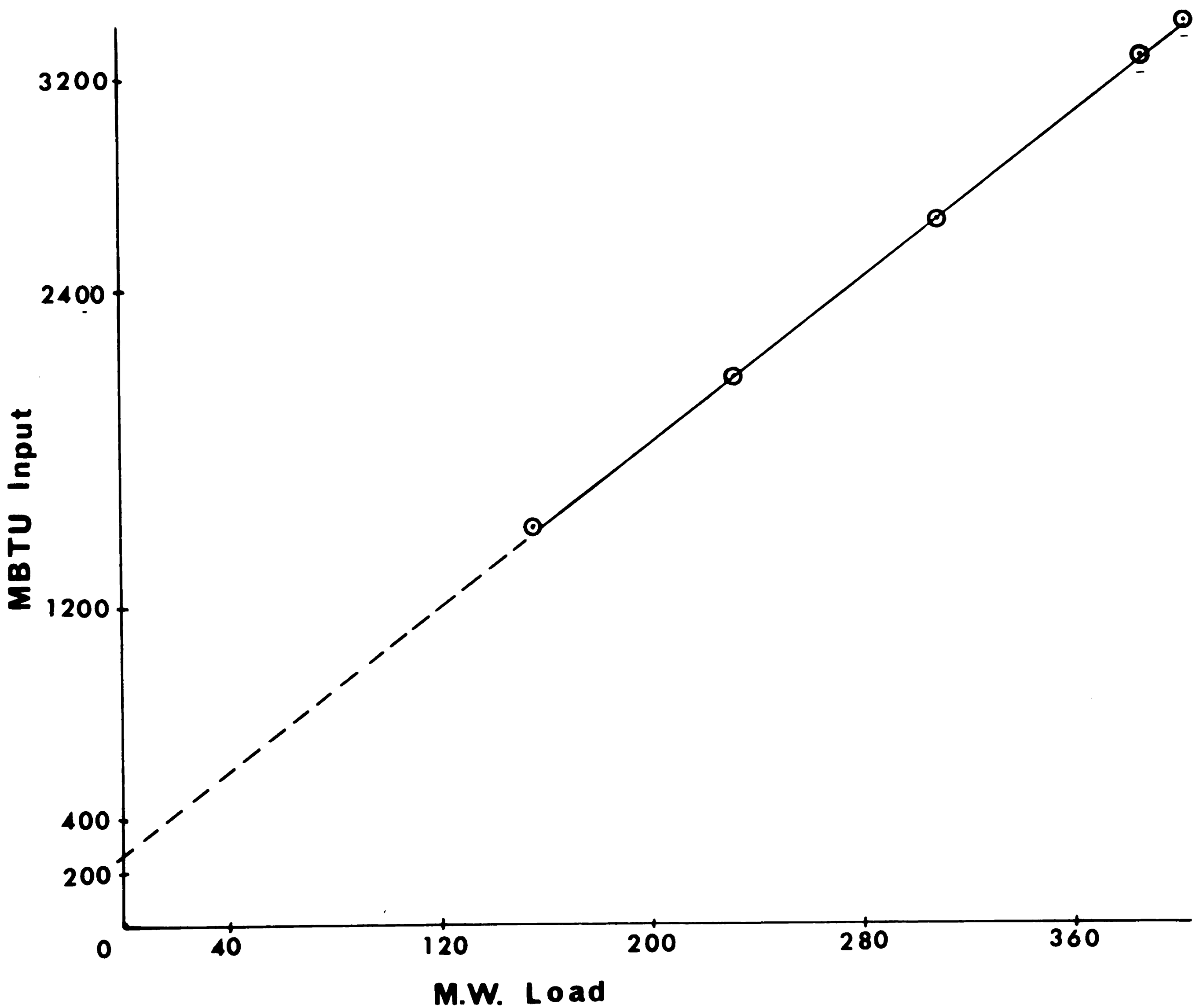

MBTU Input
3200
2400
1200
400
200
0
40
120
200
280
360
M.W. Load

Figure IV-2. Input output relation for standard units.

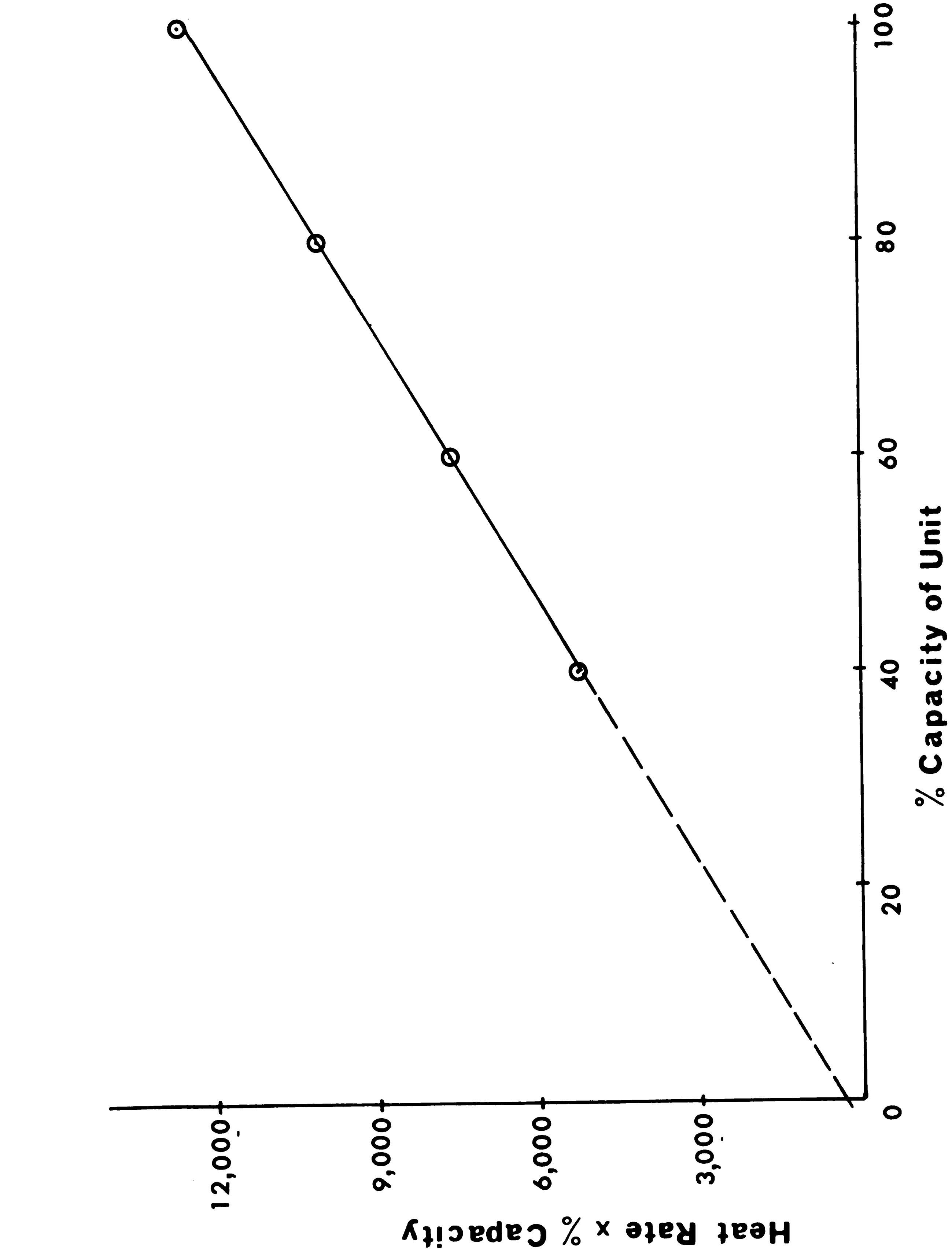
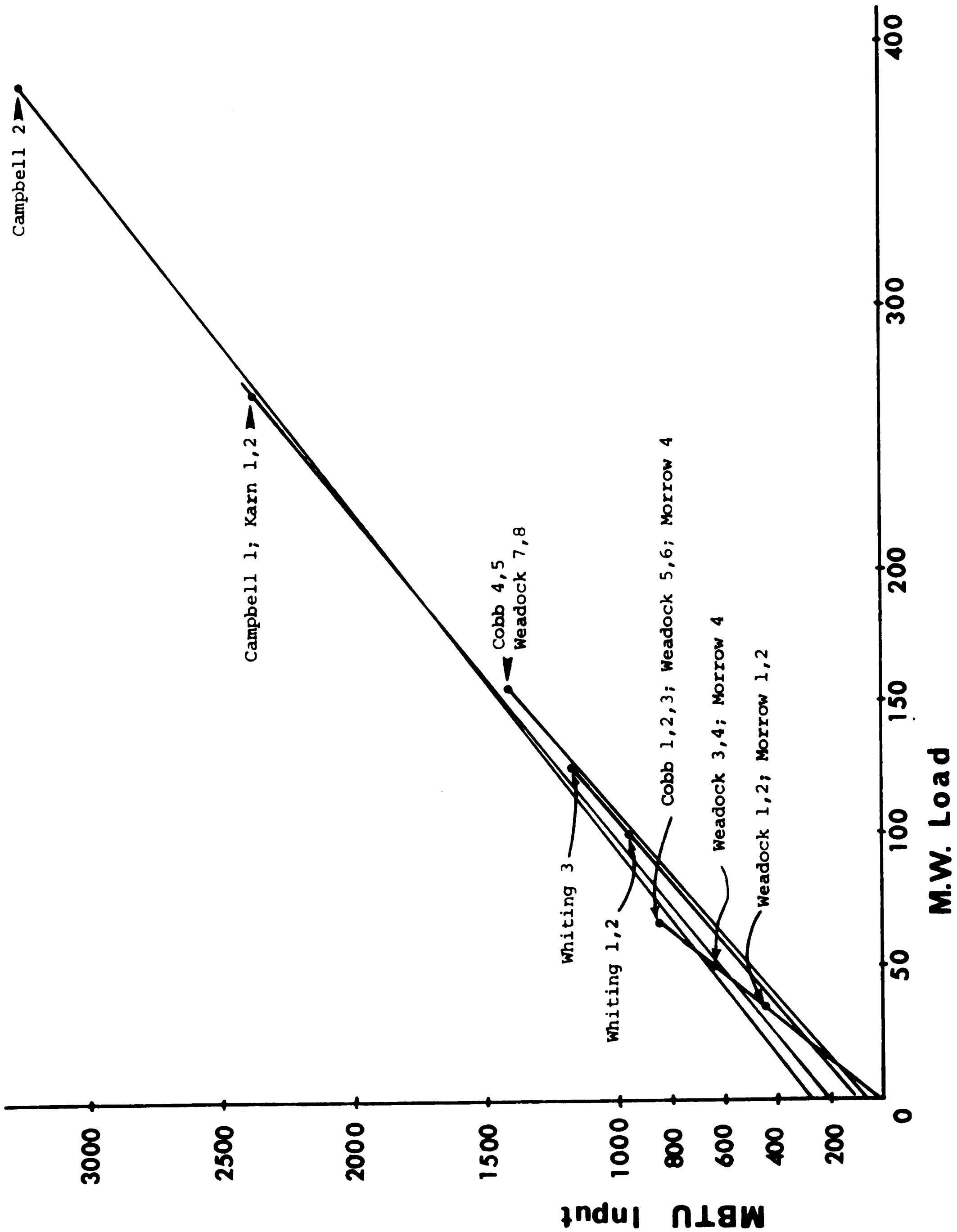

Heat Rate x % Capacity
12,000
9,000
6,000
3,000
0
20
40
60
80
100
% Capacity of Unit

Figure IV-3. Comparison of input output relationships for all units.


Campbell 2
Campbell 1; Karn 1,2
Cobb 4,5
Weadock 7,8
Cobb 1,2,3; Weadock 5,6; Morrow 4
Weadock 3,4; Morrow 4
Weadock 1,2; Morrow 1,2
Whiting 3
Whiting 1,2
M.W. Load
0
50
100
150
200
300
400
MBTU Input
200
400
600
800
1000
1500
2000
2500
3000

CHAPTER V

ANALYSIS

5.1 Introduction

The purpose of this chapter is to combine the material of Chapters II, III and IV so that the object of the study, as stated in Chapter I, can be accomplished.

In Chapter II a general conceptual approach to determine the costs of power generation subject to SO_2 restrictions was developed. The treatment of the problem was intentionally kept as broad as possible. In this chapter the scope will be narrowed considerably in order to yield a tractable analysis of the problem. New assumptions will be introduced together with some that have already been stated in previous chapters.

5.2 A Restatement of the Problem

The generating company, Consumers Power Company, is assumed to attempt to minimize the total costs of power generation subject to the following three constraints:

1) Capital equipment (the basic generating units) is fixed.

2) The load, K_T, on the system is exogenously determined and the firm is legally bound to meet that load.

3) The firm is faced with one of two possible regulations aimed at controlling damage from SO_2 emissions. One regulation is set in terms of

a maximum allowable SO_2/BTU ratio on the fuel burned. The other regulation is a maximum allowable ground level concentration of SO_2.

The problem for analysis is the difference between these two standards; specifically, the difference in costs of generation to the generating company is to be estimated.

Before getting into the analysis, a number of assumptions, some of which have been stated elsewhere, will be stated here.

5.3 The Assumptions

The assumptions to be stated fall into five groups, depending upon the level at which they enter the analysis. The natural separation is preserved in the listing which follows.

5.3.1 The Generating System Assumptions

1) The system is assumed to operate in isolation from other generating systems, i.e., there is no cooperative power pooling arrangement to provide additional generating capacity.

2) The firm has complete knowledge of the time path of system load over the relevant future.

3) There is no spinning reserve requirement maintained by the firm.

4) Transmission losses are zero over the entire franchise area.

5.3.2 Generating Station Assumptions

1) There is complete independence between any two generating stations with respect to SO_2, i.e., the output of SO_2 at any single station has no effect on the concentration of SO_2 at any other station location.

2) Within any station, the maximum ground level concentrations of SO_2 is the sum of the maximum ground level concentrations that would result from the individual units.

5.3.3 Generating Unit Assumptions

1) For each steam unit, the relationship between BTU input and MW output is of the form BTU = $\alpha + \beta(MW)$.

2) All units will operate without failure over the relevant time period, i.e., zero down time.

3) The gas turbine units are not treated individually, but are lumped together as if there was a single gas turbine whose production function was BTU = $\beta(MW)$.

5.3.4 Fuel and Fuel Use Assumptions

1) For the coal types considered, thermal efficiency of the unit is not affected by the choice of coal, whether a single type or a mixture is used: the BTU-MW relationship is independent of fuel choice.

2) Coal mixing can be accomplished instantaneously and costlessly.

3) In this analysis, two coals and natural gas are the only three fuels considered. The relevant characteristics are listed below.[15]

Fuel type	Cost	BTU (as received)	Sulphur content
Low sulphur coal	\$8.00/ton	12,500/lb	1.1%
High sulphur coal	\$5.30/ton	11,800/lb	3.3%
Natural gas	\$ .50/1,000ft^3	1,000/ft^3	0%

5.3.5 Meteorological Assumptions

1) In Chapter III, three meteorological parameters were found to have significant influence on dispersion. Each of the three, wind speed, ambient temperature and atmospheric stability, are seen as random variables,

---

[15] The two coals listed are respectively the lowest sulphur coal and the lowest priced coal from a 1971 listing supplied by Consumers Power Company. The gas data is only approximate. See Appendix I for a complete list of fuels and the reason for choosing these two coals.

and for the purpose of this analysis these three random variables are assumed to be independent of each other.

2) At any point in time, the meteorological conditions are assumed to be identical at every one of the six generating stations.

5.4 The Analysis

5.4.1 Introduction

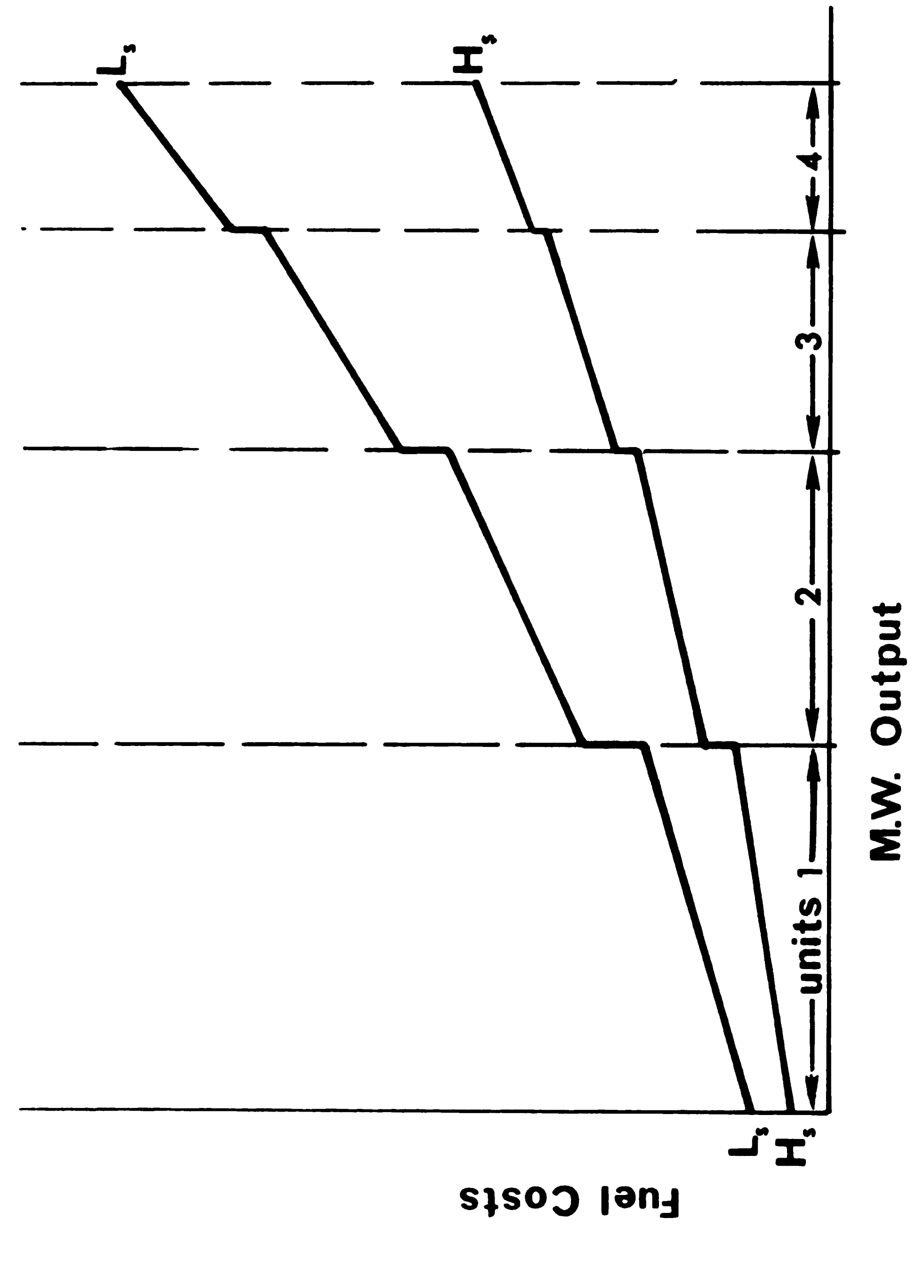
In searching for an algorithm to yield a numerical solution to the optimization problem set up in Chapter II, an approach less precise than the iterative procedure suggested there has been selected. The lack of precision can be justified by the relative simplicity of the following approach.

5.4.2 The Generating Station Output Expansion Path

To begin with, suppose one looks at an output expansion path for a hypothetical generating station made up of four coal burning units in Figure V-1. The least cost output expansion path would use only high sulphur (H_s) coal and utilize units in descending order of thermal efficiency. It is due to this ordering that the slope of each successive generation cost segment is steeper than the previous one. If the no load input (α in the production function) is ignored, H_sH_s is the least cost expansion path for that station, and will be the path followed so long as the SO_2 constraint is not operative.

A second path, L_sL_s, has been drawn which represents the minimum SO_2 output expansion path. Because the order of thermal efficiency and dispersion efficiency are assumed here to be the same, the minimum SO_2 expansion path is merely a projection of the minimum cost expansion path. Each point on the L_sL_s path is merely (price L_s/price H_s) times the equivalent output

Figure V-1. Least cost and least SO_2 expansion paths.

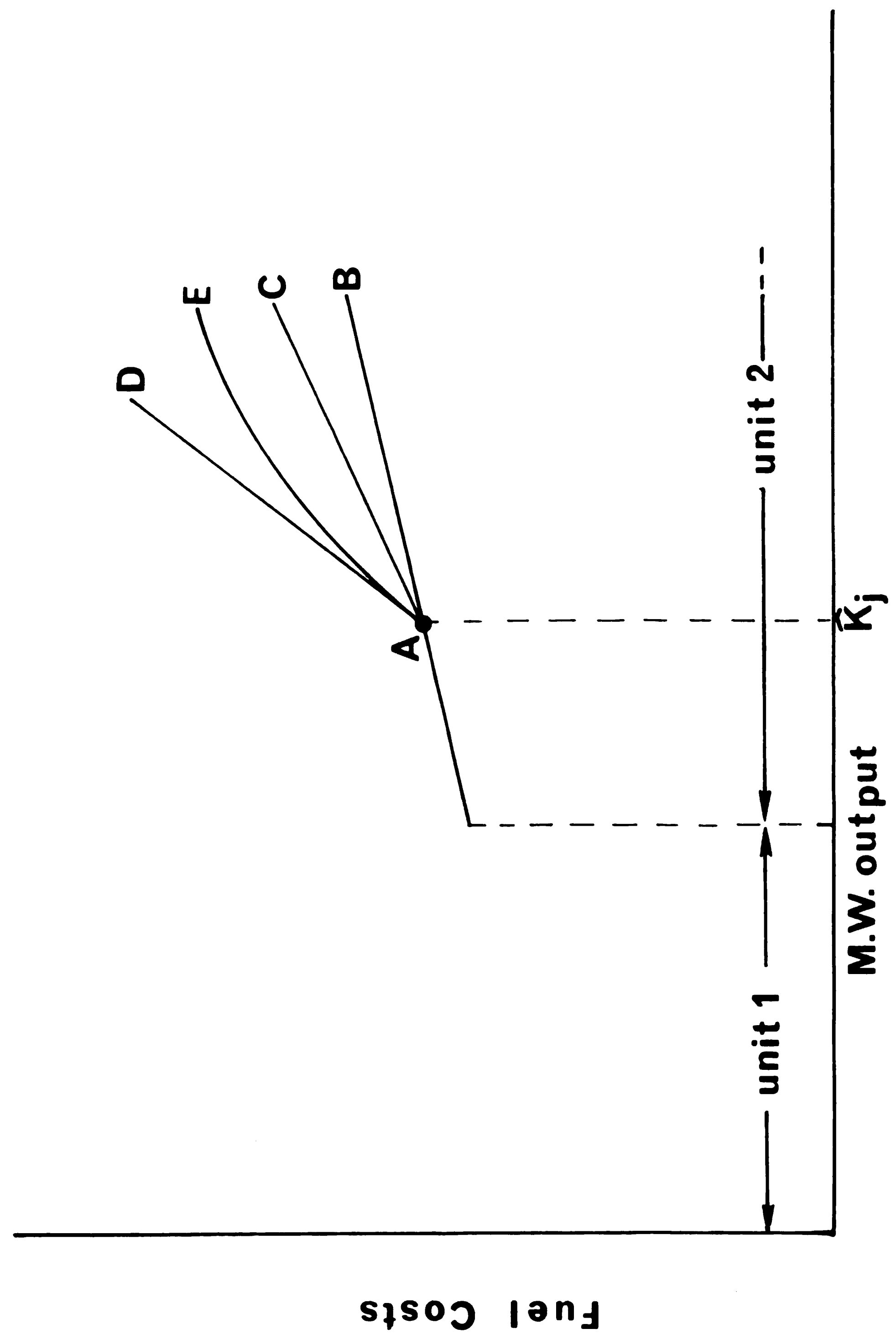

L_s
H_s
L_s
H_s
units 1
2
3
4
M.W. Output
Fuel Costs

point on the H_sH_s curve. The derivation of Figure V-1 is similar to that of Figure II-4 in Chapter II.

It is obvious a cost minimizing firm would expand output along the H_s path if that alternative was open. Therefore the H_s line is the relevant output expansion path up to the point where the SO_2 constraint is reached. The output level at which the constraint is reached will depend on the meteorological state (64 different meteorological states will be considered). Once the SO_2 constraint is reached, further increases in power output will necessitate coal mixing to satisfy the constraint. The mixing process and the resulting generation costs are worth looking at in detail at this point. The simplifying assumptions used in Figures II-5 and II-6 will be dropped here.

Let us call the point of maximum allowable output, using 100 percent H_s coal, $\hat{K}_j$ (j = 1,...,5 to denote station number). What will happen to costs as power output is increased beyond $\hat{K}_j$? Equation (14) in Chapter II implies that the unit with the lowest dispersion capability should use the low sulphur coal. Therefore the expanded output should be produced from low sulphur coal. This is depicted in Figure V-2 by the counter-clockwise rotation of the cost line AB to a new position AC. There is, in addition, a second cost increase due to "back mixing" of fuel. In spite of the fact that low sulphur coal is used in moving to the right from point A, the total output of SO_2 from the stack increases. This will necessitate using low sulphur coal on "previous" units of output, i.e., once the point A is reached, movement to the right of that point, even though utilizing low sulphur coal will dictate corresponding mixing to the left of that point also. Thus the change in costs will be greater than the ratio of prices of the two coals, since each expansion of output would necessitate mixing on

Figure V-2. Actual output expansion about the constraint point.


Fuel Costs
M.W. output
unit 1
unit 2
A
B
C
D
E
$\hat{K}_j$

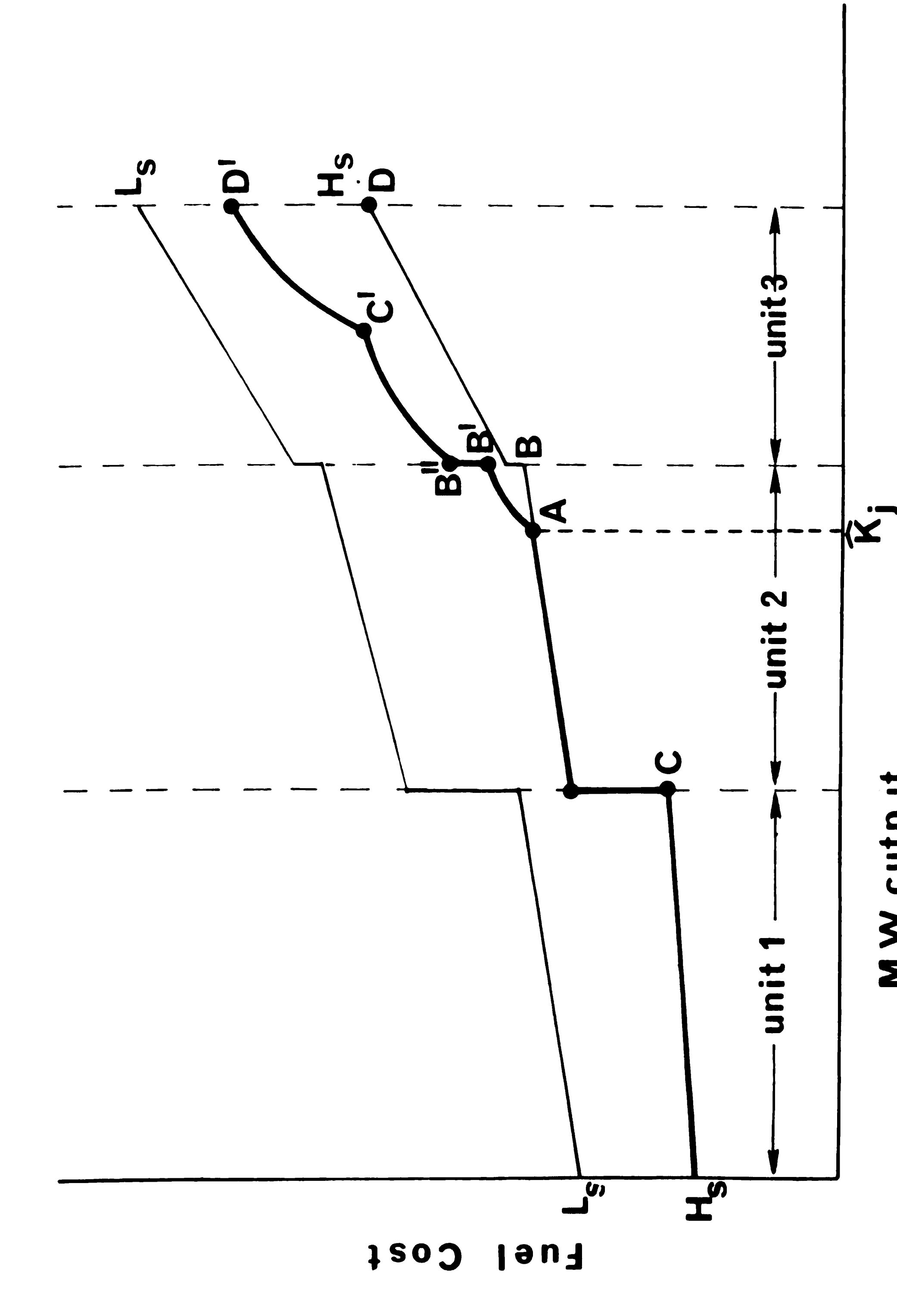
previous units of output. Thus the costs of the increase in output beyond $\hat{K}_j$ might be visualized as a parallel leftward shift of line segment AC; for each expansion of output a new position of AC is determined and the corresponding fuel cost is read off the newly positioned AC line. This is, of course, wrong. The output expansion path for all output less than $\hat{K}_j$ is the original H_sH_s line. The expansion path at output greater than $\hat{K}_j$ can be determined by shifting AC to the left, but the actual path must be a rotation of AC counter-clockwise about the point A. This rotation is indicated by the line segment AD.

Complicating the rotation of line segment AB through AC to AD is the effect of increased output on the dispersion of stack gas. This was assumed away in Figures II-5 and II-6. From the dispersion equations of Chapter III it is obvious that the relationship is nonlinear. It can be shown that under those meteorological conditions which result in high concentration levels, the increase in dispersion resulting from increased output is slight. Incorporating this effect into the graph will yield the curve AE. The exact shape of the curve is of little consequence here. The important point is that slope is decreasing throughout. This will have important implications for the analysis.

Up to this point we have been focusing on relatively small increases in output. It is now necessary to move out further along the output expansion path. This is depicted in Figure V-3.

Moving to the right from A, the slope of AB' should be decreasing as pointed out above. At B' unit 2 has reached capacity and unit 3 is brought on line. Over both curve segments AB' and B"C', increased SO_2 outputs will be compensated for by back mixing on unit 2. At some point C', back mixing on unit 2 is no longer possible; unit 2 is operating on 100 percent L_s coal and increased SO_2 output to the right of C' can only be compensated for by

Figure V-3. Actual output expansion to station capacity.


Fuel Cost
M.W. cutput
unit 1
unit 2
unit 3
L_s
H_s
C
A
B
B'
B''
C'
D
D'
$\hat{K}_j$

lowering the SO_2 output of unit 1, i.e., back mixing is initiated at unit 1. The discontinuity at point C' depicts the effect of the difference in dispersion efficiencies between unit 1 and unit 2.

At point D', station generating capacity is reached. Units 2 and 3 are burning 100 percent L_s coal and unit 1 is mixing fuel. This agrees with one of the findings in Chapter II: at most, 1 out of q units at the station would operate on a fuel mix, the remaining q-1 will use pure fuels (either 100 percent H_s or 100 percent L_s).

Under sufficiently less favorable meteorological conditions the pathway H_sD' would intersect the L_sL_s pathway. Given only those two fuels, output would have to be curtailed at that point, since increased output even with all units burning 100 percent L_s would exceed the constraint level. Atmospheric dispersive capacity would have been surpassed before station generating capacity was reached.

5.4.3 Allocation of System Load Between Stations

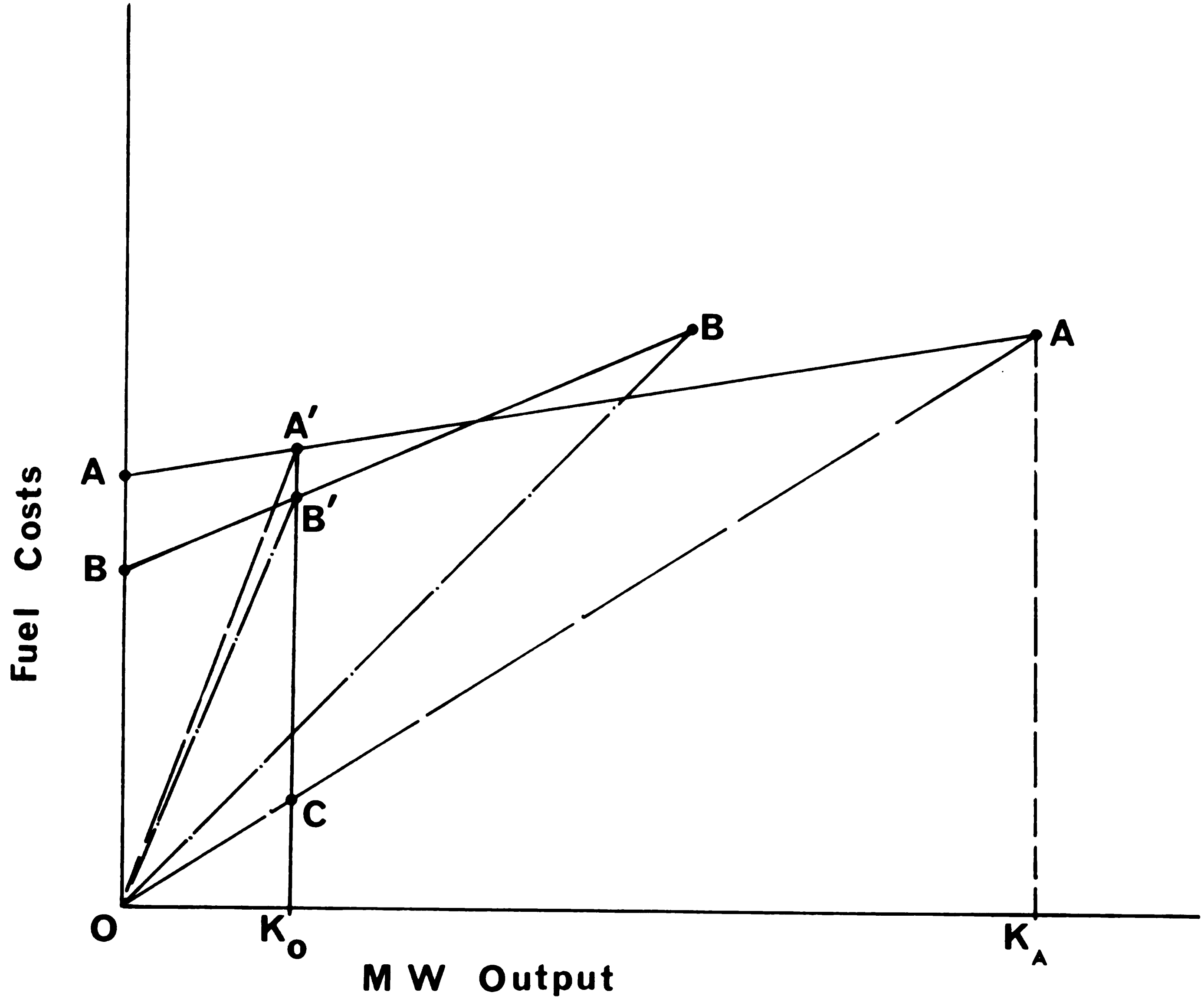
In the simplest case meteorological conditions are sufficiently favorable to allow all coal units to operate on 100 percent H_s coal. With the knowledge of fuel prices and the requisite production function information, average cost can be calculated for each unit, assuming the unit operates at full capacity. The procedure used here will be to bring units on line in order of their average costs. The emphasis on comparing average costs rather than marginal costs is necessitated by the characteristics of the production functions. It will be recalled from Chapter IV that the estimated relationship between BTU input and MW output was $Y = \alpha + \beta X$, and further, an inverse relation between the size of α and the size of β was noted there (section 4.3) for the units being considered. If one were to start at zero output and build up output incrementally, α would dominate, and units would be added in order of α size, from smallest to largest. This could lead to the least efficient load allocation. The average cost comparison will circumvent this problem; it could, in fact, be interpreted as a marginal cost approach with the size of the output change restricted to capacity size increments.

In general, if units are brought on line in order, with each unit run up to capacity before another unit is added, system load will be met with the last unit added running at less than full capacity. However, the order in which that unit was brought on line was based on average costs at full capacity. A new average cost figure must be calculated at the particular partial load, and compared to the cost of generating that output on the remaining units. The unit with the lowest cost will be chosen. This will not necessarily lead to the precise optimum, but given the range of units considered it will not only be close, but the maximum possible error can be determined.

In Figure V-4 we assume that the first n units have been fired in order of average costs, and that the sum of their capacity outputs has left us K_o MW short of system demand. Assume two unused units remain in the system. The above procedure would first look at the average cost OA, then come back along AA to point A'; calculate the slope of OA' and compare it to the respective average costs, OB', for unit B. The costs are obviously lower for unit B to produce K_o output than for unit A to produce K_o.

This is not necessarily the optimum solution. Under the developed firing order of units, the point 0 in Figure V-4 represents the combined output of the most efficient n units. It is truly an optimum allocation of units to produce that level of output. Further, given that we start with that allocation of output 0, unit B becomes the most efficient way

Figure V-4. Graphic determination of the maximum possible error in optimum load allocation.

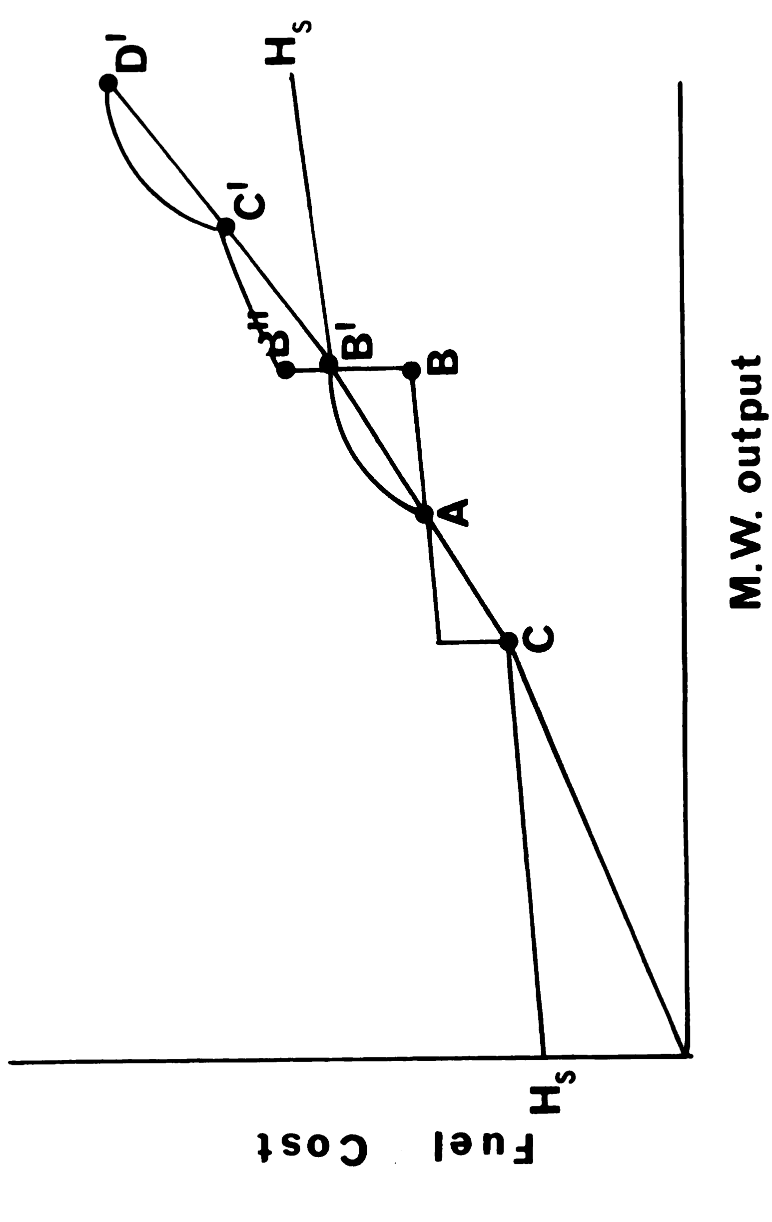

Fuel Costs
A
B
A′
B′
B
A
C
O
K_o
K_A
MW Output

to produce an additional K_o of output. However, this does not imply that the n units producing output 0 and unit B producing output K_o is the optimum way to produce the system demand $0 + K_o$. However, the furthest our solution could be from the true optimum would be represented by the distance B'C. This would only occur if the n^{th} unit added had capacity equal to (K_A-K_o) and an average cost at capacity equal to the average cost of unit A running at capacity.

In the more complex case, at least one of the five coal burning stations reaches the SO_2 constraint before system load is met. In this event the procedure used in the simple case can be utilized except that instead of dealing with linear cost curves, the cost curves will, in general, be nonlinear beyond the point where fuel mixing begins. Again a diagram is helpful.

Figure V-5 is essentially copied from Figure V-3 with the end points of each curve connected by a straight line. The slope of the connecting lines yields the average cost of output over the entire curve segment. So long as the whole curve segment is taken, the straight line is an adequate representation. This leads to an approach almost identical to the allocation procedure to deal with the simpler case above. Instead of dealing with the average slope of a linear function plus a constant, here the concern is with the average slope of a non-linear function. Analytically there is little difference. Each curve segment is treated as if it were an individual unit. The only real difference is that at any of the five coal burning stations the order of consideration of curve segments within the station is fixed; C'D' cannot be considered until B'C' has been utilized. The way the optimum solution will be approximated is the same as in the case without operative SO_2 constraints. The average cost figures,

Figure V-5. Piecewise linear approximation of the discontinuous nonlinear constrained output expansion path.


D'
H_s
C'
B''
B'
B
A
C
M.W. output
H_s
Fuel Cost

calculated between end points, are used. Output will expand along the path of lowest average cost until system demand is reached. At this point, costs for the last unit (which will generally be operating between end points) must be recalculated, and compared to the cost of generation on other units, at that particular output level. Again, as in Figure V-4, the maximum error will lie between the original average cost line considered and the lowest average cost at actual output.

CHAPTER VI

RESULTS AND CONCLUSIONS

6.1 Introduction

The object of this study, as has been repeatedly stated, is to compare alternative forms of SO_2 regulation. The two forms of regulation are: 1) a regulation defined in terms of a maximum allowable ground level concentration of SO_2 (henceforth abbreviated as MAGLC) measured in parts per million (ppm), and 2) a uniform system-wide fuel regulation (USWF) specified in terms of a maximum allowable sulphur content per BTU, measured in grams sulphur per million BTU (S/MBTU).

In light of the lack of solid information on the full relationship between SO_2 concentrations and damage, it has been assumed that there is a one-to-one correspondence between damage and the maximum ground level concentration experienced. Additional dimensions such as frequency, duration, or the amplitude of fluctuations have been assumed to be inconsequential. Armed with these assumptions, one can set the two regulations on an equal damage basis merely by setting the S/MBTU ratio in regulation 2 at a level such that resulting ground level concentrations under worst conditions will equal the maximum allowable ppm under regulation 1.

6.2 Specific Results

Before examination of the cost figures resulting from the simulation of the alternative regulations, some base line information is helpful in establishing a point of reference.

6.2.1 Generation Without SO_2 Regulation

As a starting point a calculation was made assuming that the company was not restricted by any form of SO_2 regulation. The company was, however, restricted to a choice between the two coals selected in Chapter V for its five coal burning stations. Without SO_2 regulation the cheaper of the two coals ($.225 per MBTU) is the obvious choice. The choice of generating units is likewise simplified to a comparison of thermal efficiencies only.

The resulting expected annual cost of fuel is (to the nearest $1000) $44,271,000. This figure includes $4,711,000 worth of gas used to fire the gas turbine units and the gas burning conventional steam units at the Morrow station. The difference of $39,560,000 represents expenditure for coal. This figure represents an input of 175,822,222 MBTU and a resulting maximum system-wide ground level concentration of 3.014 ppm SO_2 which would occur at the Weadock station. Probability of occurrence would be .00125, or slightly less than 11 hours per year.

6.2.2 Generation Subject to MAGLC Regulation

For analysis of MAGLC regulation costs, the weather conditions of Chapter III and the load conditions of Chapter IV were used. The simulation was run with the firm restricted to some combination of the two coals selected in Chapter V. The constraint level was set at 1 ppm maximum hourly average.

Total fuel costs were calculated to be $45,538,000, of which $4,711,000 was again the expected expenditure on natural gas. The resulting $40,827,000 coal cost is 3.2 percent above the unrestricted case. All five coal burning stations were able to meet the constraint, with only Weadock, and to a lesser extent Cobb, coming close to not being able to meet the constraint.

Under worst weather conditions at Weadock ($\bar{\mu}$ = 14.3 m., T_A = 294°K, σ_z/σ_y = 1.000) a coal mix of nearly 98 percent low sulphur coal had to be used. At the other side of the spectrum, the Campbell station, using only high sulphur coal, did not come close to the constraint (.664 ppm under worst conditions). The ability of Campbell, and to a lesser extent, Karn, to operate on high sulphur coal combined with mixing being necessary at the remaining stations only 25 percent of the time is the reason that MAGLC costs are so close to the costs of unrestricted generation.

6.2.3 Generation Subject to USWF Regulation

Under this regulation a coal mix was determined which would, under worst conditions, result in concentration no greater than 1 ppm. Since the fuel regulation is uniform over all coal-burning stations, it is determined by the station whose characteristics yield the highest concentrations. Weadock is that station, under meterorological conditions listed in section 6.2.2 above. The necessary coal mix is one which has a sulphur content of 421 grams/MBTU. This mix is slightly lower in sulphur (i.e. more expensive) than would occur under identical meteorological and load conditions, but with MAGLC regulation. MAGLC would allow different mixes in different units (Equation [14] of Chapter II) where USWF is uniform not only across stations but also across all units. Cost per MBTU under USWF regulation is $.3176, and this cost is the same at all five coal-burning stations. As should be anticipated, total expected coal costs are high: $55,843,000.

6.2.4 A Third Alternative Regulation

Although the above two regulations were the only ones originally considered for study, the wide divergence in cost between the two prompted consideration of a third alternative, which it was hoped, would avoid the enforcement costs of MAGLC regulation while retaining some of its potential economy. This third alternative is, like USWF regulation, based on sulphur content of the fuel (easy enforcement), but the content is allowed to differ at each station. Each station must burn, at all times, a fuel of sufficiently low sulphur content so that under worst conditions, ground level concentrations will not exceed 1 ppm. This is a station-by-station fuel regulation (SSF). Being based on worst condition criteria, it will not allow the firm to take advantage of either favorable meteorological conditions or low load situations. However it does, at least, allow the company to take advantage of the superior dispersive capability of some stations -- Campbell does not have to pay according to the relatively poor dispersive capability of Weadock.

Under SSF, coal costs for the five coal-burning stations are a surprisingly low $45,918,000.

6.3 General Results and Comparisons

6.3.1 Comparison of Results

Table VI-1 below shows a summary of the values assumed by selected variables under the three cases of regulation and the initial no regulation case. The emphasis so far has been completely on the total coal costs. Table VI-1 shows more completely the tradeoffs between fuel costs, ground level concentrations, and use rates of high and low sulphur coal as effected by alternative regulation. The total MWH figures for each station are of interest because they show the effect of each regulation on the allocation of output between stations. Campbell and Karn are unaffected because their units are <u>both</u> thermally and dispersively most

Table VI-1. Results of Alternative SO_2 Regulation on Selected Items

Item	Generating Station: Campbell	Whiting	Weadock	Karn	Cobb	System Total
Case I: No Regulation						
Annual MWH Generated	5,694,000	1,809,816	3,369,972	4,642,800	3,320,040	18,836,628
Tons High Sulphur Coal	2,095,141	730,000	1,475,507	1,763,548	1,385,928	7,405,124
Tons Low Sulphur Coal	---	---	---	---	---	---
WC GLC SO_2 (ppm)[1]	.664	1.175	3.014	1.074	2.497	
Annual Fuel Costs	$11,125,200	$3,876,300	$7,834,944	$9,364,440	$7,359,276	$39,560,160
Case II: Ground Level Concentration < 1 ppm (MAGLC)						
Annual MWH Generated	5,694,000	1,826,917	3,335,466	4,640,366	3,339,879	18,836,628
Tons High Sulphur Coal	2,095,141	731,024	1,096,972	1,760,256	1,187,006	6,870,399
Tons Low Sulphur Coal	---	6,063	339,436	695	196,961	543,155
WC GLC SO_2 (ppm)	.664	1.000	1.000	1.000	1.000	
Annual Fuel Costs	$11,125,200	$3,930,239	$8,540,412	$9,352,521	$7,878,694	$40,827,066
Case III: Station-By-Station Fuel Regulation (SSF)						
Annual MWH Generated	5,694,000	2,688,444	2,762,028	4,642,800	3,049,356	18,836,628
Tons High Sulphur Coal	2,095,141	846,290	30,937	1,561,501	145,641	4,679,510
Tons Low Sulphur Coal	---	221,200	1,126,806	191,049	1,094,691	2,633,746
SC GLC SO_2 (ppm)	.664	1.000	1.000	1.000	1.000	
Annual Fuel Costs	$11,125,200	$6,263,400	$9,178,728	$9,819,960	$9,530,880	$45,918,165
Case IV: Uniform System-Wide Fuel Regulation (USWF)						
Annual MWH Generated	5,694,000	1,809,816	3,369,972	4,642,800	3,320,040	18,836,628
Tons High Sulphur Coal	52,940	18,448	37,276	44,554	35,003	188,221
Tons Low Sulphur Coal	1,928,196	671,911	1,357,695	1,622,782	1,274,889	6,855,473
WC GLC SO_2 (ppm)	.220	.390	1.000	.356	.828	
Annual Fuel Costs	$15,706,680	$5,473,248	$11,059,500	$13,218,840	$10,384,980	$55,843,248

[1] Worst case ground level concentration of SO_2.

efficient. Whiting versus Weadock and Cobb, on the other hand, show shifts. This is because Whiting is more efficient dispersively, but less efficient thermally.

6.3.2 Causes of Cost Differences Between Alternative Regulations

The three regulations looked at in this study give three distinctly different cost figures in spite of the fact that each regulation is based on ground level concentrations of SO_2 below 1 ppm. A brief outline of the reasons for the differences is presented below.

The differences in costs are a result of differences in flexibility allowed the firm in adjusting to certain background variability. This background variability is made up of meteorological variability, variability of unit design and their combination into stations, variability in the demand on the system and variability of price and sulphur content of the fuel itself.

1) Fuel Variation

In all four cases simulated (including the no regulation case) the necessary choice was between some combination of the same two fuels. The mixture possibility line in \$/MBTU, sulphur/MBTU space has the equation $Y = -.0001092X + .36357$ for $399 \leq X \leq 1269$. If there existed a greater range of variation between the two fuel prices, total fuel costs of generation would likewise show a greater range. Suppose, for example, the fuel mix line had the same equation, but that X was bounded on the upper end by 2000 (i.e., $Y = -.0001092X + .36357$ for $399 \leq X \leq 2000$). This would result in a new high sulphur coal cost of 14.5¢/MBTU or approximately 65% of the old price. Cost of no regulation generation would be reduced by this 65% figure. Costs under MAGLC restrictions, although not by the full 65%, would be greatly reduced. SSF would show reduced costs because Campbell could handle the higher sulphur content coal but USWF regulation would remain unchanged.

2) Meteorological Variation

Meteorological variation, to a large extent, determines the variability in the allowable amount of SO_2 that can be emitted. In addition to the background variation in meteorological conditions, there are two additional sources of variation that have been ruled out by assumption. The first is the possible difference between the probability distribution of meteorological variables at different locations. The second is even with identical distribution functions, the timing of conditions would be different at different locations, i.e. at any instant, identical conditions cannot be expected to exist across all stations.

The background variability is introduced by the probability distribution assumed for the meteorological variables. Under MAGLC regulation, the firm is allowed to take advantage of the variability; under both SSF and USWF regulation there is no way for the firm to exploit favorable meteorology.

3) Generating Unit and Station Design Variation

This variability is, in one way or another, "designed" into the generating system. Between units there are differences in thermal efficiencies and dispersion characteristics that are fixed by the underlying design of the unit. The way in which these units are grouped together to form stations displays a degree of variety. The three forms of regulation simulated respond to the variation in different degrees.

Under USWF regulation, the firm is saddled with having to meet not only worst weather conditions, but also worst station design conditions.

It is unable to capitalize on the dispersive capability of the Campbell station. With SSF regulation, station dispersion differences are captured, but variation between the dispersive capability of units is not. This is because all units at a particular station would burn the exact same mix of coals. If the regulation is a MAGLC constraint, both differences between stations and between units can be captured. Although this difference between units is not an obvious one it does exist. At the Cobb station, for example, worst conditions are $\bar{\mu} = 10.73$ m/sec, $T_a = 294^{\circ}K$, $\sigma z/\sigma y = 1.000$ and station output at full capacity. This calls for a single station wide fuel of 495.6 gm sulphur per MBTU and a total hourly station coal cost of \$1646. Under MAGLC, units 1-4 would be run on 100 percent low sulphur coal (399 gm per MBTU) and unit 5 would operate with mix yielding 911 gm. per MBTU. Total hourly cost would be \$1622 or \$24 cheaper.

4) Demand Variation

It has been mentioned repeatedly that the demand for electricity varies widely. To meet the changing demand the power output of the individual stations must shift accordingly. For any given fuel mix this implies that the total SO_2 output will fluctuate. At low levels of output the potential for utilizing a higher sulphur coal mix may exist. Under MAGLC, the firm is allowed to take advantage of this variation. Since both SSF and USWF are worst condition regulations (in this case, highest output) this dimension of variability is lost.

6.3.3 Summary of Comparative Results

What emerges from the above discussion is that MAGLC regulation leaves the firm flexible enough to take advantage of all four sources of variation: variation in fuels, in weather, in system design and in output demand levels. At the other extreme USWF regulation allows for none of the man-made or natural variations. The resulting cost difference is not surprising. The compromise regulation, SSF, although leaving the firm unable to react to meteorological or demand variation, does allow limited response to design variation. The surprising result is that under SSF regulation, costs are so <u>low</u>. This can be explained by the fact that nearly 55 percent of the total generation comes from Campbell (unaffected by SSF) and Karn (fuel price raised approximately 1¢ per MBTU).

6.4 Conclusions

6.4.1 Introduction

At the very outset of this study a distinction was drawn between what the two types of regulation represented. One is a behavioral regulation ("thou shalt not burn fuel containing more than x grams of sulphur per MBTU"); the other is a regulation on effects ("burn what you please, but do not exceed an hourly average concentration of 1 ppm").

Any environmental regulation can only really be rationalized for its control of effects; damage control is the end, behavioral regulation may or may not be a legitimate means to that end. It can only really be judged on its effectiveness in accomplishing the desired ends. Before the overall effectiveness of the three alternatives is evaluated, a separate, but related, means-end question will be addressed. The question is on the legitimacy of spatial dispersion of production facilities as a <u>general</u> damage control strategy. Although not a part of this study, the question is prompted by results of this work.

6.4.2 Implications for Spatial Dispersion

"All generalizations are false...including the generalization that all generalizations are false!"[16]

One of the general statements that has been made in the past pertaining to production facilities and environmental effects is the following: As the size of production units that release harmful effluents increases, environmental damage will increase. And further, not only will the damage increase monotonically with size, but damage will, at least beyond some point, begin to increase faster than size. From this implicitly assumed generality it is often argued that smaller production units scattered more uniformly about the countryside would result if the full costs (i.e., private costs plus external costs) of production facilities were used. From this position it is but a short step to the position that concentration in itself is bad, and dispersion becomes an end in and of itself. Such a confusion of means and ends, although logically sloppy does little harm unless the underlying implicit assumption is wrong. Then the dispersion of production facilities becomes counter productive, and because it is taken as an end in itself, it does not receive the close scrutiny it would have had it been properly recognized as merely a means to an end.

The results of this study show no clear relationship between size and damage (as approximated by ground level concentrations of SO_2). Size alone does not give sufficient information. This in itself does not devastate the assumed generality. However, the single most conspicuous

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[16] Quote is from a lecture in a political science course taught by Professor Frederick Schuman in the early 1960's; original source unknown.

piece of information coming out of the results is that the Campbell station with the largest MW capacity also has by far the lowest ground level concentrations of SO_2. This result does, in fact, emasculate the statement as a generality.

What are the reasons behind this curious result (i.e., largest station, lowest concentration)? The answer consists of essentially three parts: 1) The two units at the Campbell station are thermally very efficient; 2) stack height is the largest in the system (123 m); 3) both units are served by a single stack. All three warrant a closer look, especially as related to size and concentration.

1) Thermal Efficiency

The reason that thermal efficiency will effect SO_2 concentration is that there is a clear inverse relationship between thermal efficiency and SO_2 output, other things being equal. The relationship between thermal efficiency and size is less clear -- the larger units in the system are more efficient; they are also newer and thus utilize an improved technology. Unless the technology is size specific, there may be no relationship between size and efficiency.

2) Stack Height

The height of a stack is important in the dispersion of stack gas -- it has particular influence under restrictive weather conditions. There is no necessary technological connection between stack height and generating unit capacity. However, there is an economic connection: increased stack height is expensive, and cannot be justified for small units.

3) Single Stack Utilization

The use of a single stack by both generating units greatly increases the dispersive capability of both. This results from an increase in plume rise due to a greater buoyancy flux as a consequence of the larger volume of exit gas at higher temperature. It is this phenomenon that does the greatest violence to the generality: combining station SO_2 output into a single stack is the extreme boundary of spatial concentration, yet it results in greater dispersion and therefore less effect.

6.4.3 The Evaluation of the Alternative Regulations

A comparison of the simulated regulatory schemes are documented in Table VI-1 and their differences are analyzed in sections 6.3 through 6.3.3. Such comparisons are necessarily incomplete because they do not include the full costs faced by the firm, nor do they evaluate the effectiveness of the regulation itself.

1) Cost Discrepancies

There are two types of bias in the cost figures. The first type effects the total costs of each regulatory scheme but does not effect the comparative figures. This uniform bias is a result of understatement of all coal costs due to the omission of transportation costs and an understatement of generation costs as a result of simplifying assumptions with respect to reserve requirements and maintenance of units. It will not affect conclusions based on differences in costs.

The second bias introduced is that injected by the assumption of costless fuel mixing. This cost would be borne only in the MAGLC case, and thus makes ground level regulation appear cheaper than it is relative to the other forms of regulation. This point will be returned to again in the discussion of regulation itself.

2) <u>Regulation: Effects, Effectiveness and Enforcement</u>

From the introduction of this study the question of behavior versus effects has been a recurring theme. This study has shown that the potential savings to the firm from effects regulation (MAGLC) is great when compared to USWF regulation. However, this is not a fair comparison. The cost of detection and enforcement of a 1 ppm ground level concentration may be staggering, and in fact, when added to fuel mixing costs, may reverse the ordering of the two alternatives.

The third alternative, SSF regulation, is an attempt to bridge the gap between the two extremes: it captures some of the variation handled so well by ground level regulation, while at the same time taking advantage of the ease of regulation embraced in the station wide regulation.

The real question is the cost of regulation. If regulation costs were the same for each of the three alternatives, there would be no question of which form to take: regulation should be based on the criterion of ground level concentration. This would not imply that the firm mix fuels; it might act as if regulated by SSF and use a single fuel at each station. But this decision would be for the firm to make, and would depend upon the relative cost of the two responses. This is not a statement of the firm's rights, but merely a statement of efficiency.

APPENDIX

APPENDIX I

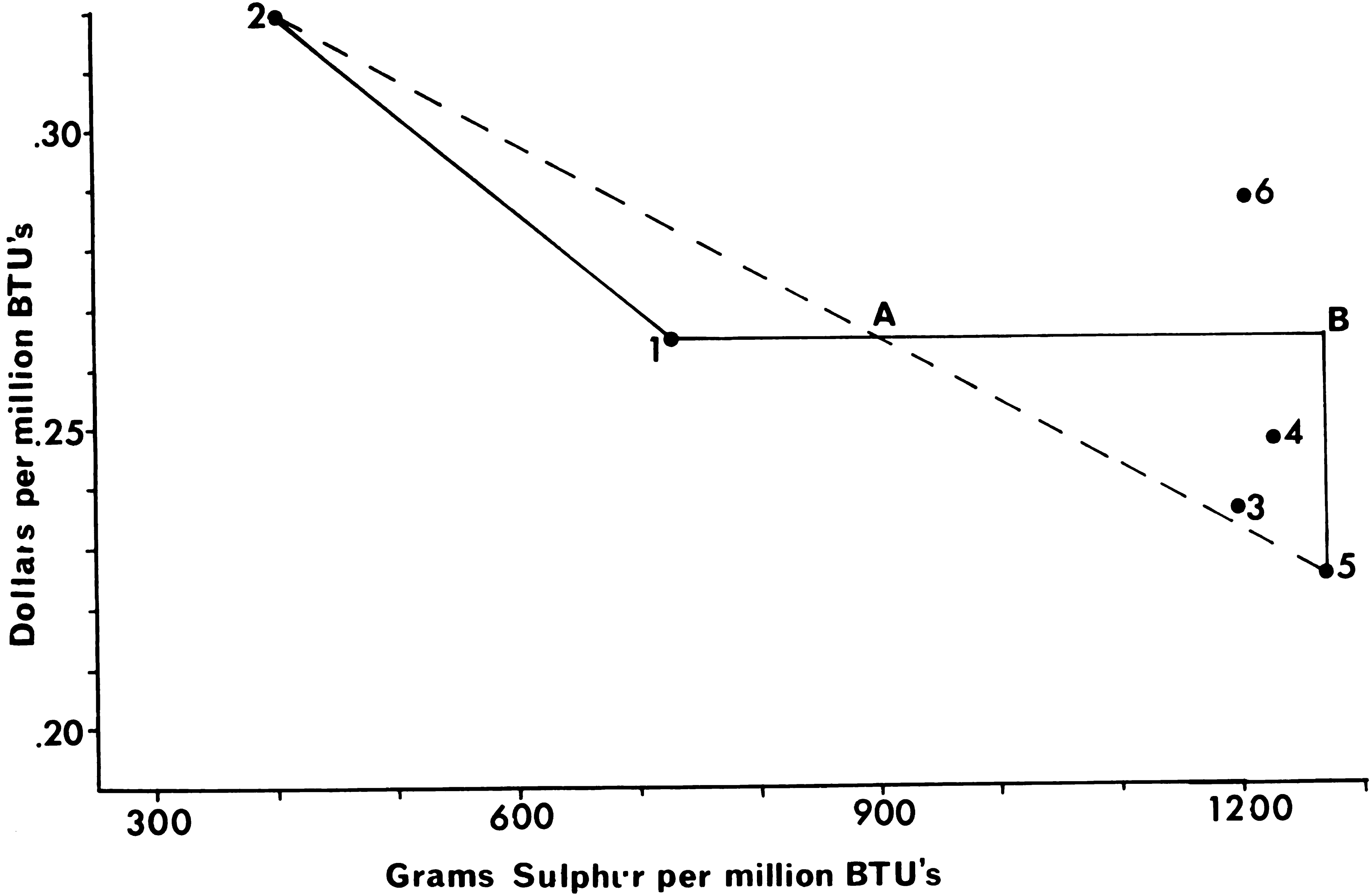
The list of fuels supplied by Consumers Power Company included six coals. For our purposes the relevant characteristics are as follows:

Item	Source	Type	Dollar Cost Per Million BTU's	Sulphur Per Million BTU's
1	District 8	Contract	$.265	727
2	District 8	Spot	.320	399
3	Ohio	Contract	.237	1194
4	Ohio	Spot	.248	1226
5	Midwestern	Contract	.225	1269
6	Midwestern	Spot	.288	1204

For this particular case study, we wish to select those two coals which will yield the minimum fuel cost while meeting the SO_2 constraint. The results of the actual analysis (as was discussed in Chapter VI) show that under worst weather conditions the Weadock generating station would have to be able to attain a fuel mixture of less than 421 gm. sulphur per 10^6 BTU's. This implies that of the two coals chosen for the system, one must be coal number 2 above. The question then is which of the remaining five coals should be chosen as the second coal.

Figure A-1 is helpful. The six points represent the six coals located in dollar-sulphur space. It is obvious that coals 3, 4 and 6 can be excluded at once: a combination of 5 and 2 can be utilized which would be both cheaper and of lower sulphur content. The only non-trivial choice is between 1 and 5. Should the two fuels be 2 and 1 or 2 and 5?

Figure A-1. Fuel price-sulphur characteristics.


2
1
A
B
6
4
3
5
.30
.25
.20
Dollars per million BTU's
300
600
900
1200
Grams Sulphur per million BTU's

If we use the usual convention of denoting line segments by the numbers or letters located at their end points, then it can be seen that by mixing coal 1 and coal 2 any combination of cost and sulphur content can be reached along the line 1,2. Similarly line 2,5 represents the possible combinations of coal 2 mixed with coal 5. If we now picture the sulphur axis as the allowable amount of sulphur, it is obvious that in the allowable range of approximately 400 to 725 grams sulphur per 10^6 BTU, the combination of coal 2 and coal 1 is the cheapest. However if the allowable output exceeds 725 grams, there can be no further decrease in cost per 10^6 BTU with coals 2 and 1 -- cost remains at $.265. At point A the two combinations are the same. Beyond an allowable output of roughly 900 grams sulphur, combination 2,5 is cheaper. The choice between combinations thus depends upon the frequency distribution of the allowable output. That in turn depends on the frequency distribution of the relevant meteorological conditions. As the computations of the actual analysis will show, the allowable output exceeds 1269 grams substantially more than half the time. Therefore the fuel combination chosen for the five coal burning stations is 2 and 5.

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