FEASIBILITY OF MARKETING ABATEMENT GYPSUM

FROM FOSSIL-FIRED POWER PLANTS

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I. INTRODUCTION

The electrical utility industry in the U.S. faces difficult problems and decisions in implementing the Clean Air Act of 1967 as amended in 1970, with respect to sulfur dioxide (SO_2) emissions. The U.S. Department of Interior has projected that net electrical generation by fossil-fired power plants will increase from 1,310 billion kilo-watt-hours in 1971 to 1,950 billion in 1980 (Princiotta, p. 2).[1] The EPA recently projected that flue gas desulfurization (FGD) control systems will be installed on 90,000 megawatt (mw) or about 25%, of total estimated coal-fired utility generating capacity by 1980. This would result in an annual production of 131,000,000 tons of throwaway sludge if the limestone slurry process were used.

Disposal costs for the limestone slurry process are high, and the process is wasteful of large quantities of sulfur, a vital economic resource. To the extent that these emissions can be economically recovered, society would be the net beneficiary.

In Japan, several FGD systems that produce abatement gypsum have been developed and are in use, but in the U.S. technology and market conditions have yet to be established. The gypsum is used primarily in the wallboard and cement industries (Ando, Corriyan). The Tennessee Valley Authority (TVA) has also developed an FGD system with a limestone oxidation to gypsum process. This process is not subject to the proprietary restrictions of the processes utilized in Japan.

The purpose of this study is (1) to provide an estimate of the costs that will be incurred in the use of the FGD system developed by TVA, (2) to identify fossil-fired power plants that might produce and sell abatement gypsum in competition with existing sources of crude gypsum and other power plants, and (3) to estimate the reduction in the cost of compliance with SO_2 regulations that would occur as a result of producing and marketing abatement gypsum in lieu of the conventional limestone slurry throwaway FGD system.

II. THE MARKET FOR GYPSUM

It is important to evaluate abatement gypsum FGD systems under U.S. conditions. Abatement gypsum has immediate uses which are alternatives to throwaway systems. Gypsum can be stockpiled for future needs. In the U.S., a demonstration gypsum-producing FGD system on a coal-fired facility is being operated by Gulf Power and Light in cooperation with EPA. Samples of abatement gypsum have been used successfully in wallboard and cement manufacture. Hence, we assume that abatement gypsum can be substituted for gypsum in the wallboard and cement industries (Ando, Bucy, Lankard).[2]

While gypsum reserves are extensive both in the world and the U.S., with the exception of one producing area in southwest Virginia, no economic reserves are located in the southeastern portion of the U.S. Transportation costs are a large proportion of the value of the product (Appleyard, U.S. Bureau of Mines, Minerals Yearbook).

Gypsum use in the U.S. is estimated at 15 to 20 million tons annually, of which about one-third is imported. Seventy-three percent of all gypsum goes into calcined materials such as wallboard manufacture, cement used 20%, and 7% goes into agricultural uses (Reed, 1973). Despite the close dependence on the construction industry, gypsum demand does not have a significant seasonal pattern. In terms of value of product sold, the gypsum industry is highly integrated from mining through calcining and sale of manufactured products (Federal Supplement 326, Appleyard). However, wallboard products are sold to independent building supply dealers or building contractors. Increasingly, byproduct gypsum from fertilizer manufacturing operations is replacing gypsum for agricultural uses.

The industry is highly concentrated. From 1947 to 1972, the leading four firms accounted for approximately 80% or more of value of industry shipments in every year. The eight-year ratio has consistently been above 90% (U.S. Bureau of Census, Bain), and the costs of entry are very high.

Gypsum consumption has been growing at an average rate of 2% per year through 1976 (Reed). Based on the projections of the Bureau of Mines, consumption is expected to reach 20.6 million tons in 1978 of which 14.6 million tons will be used in calcining plants, 4.1 million in cement use, and 1.4 million in agriculture (U.S. Bureau of Mines Preprint and Ransom).

III. AN AGGREGATE ECONOMETRIC MODEL

An econometric model of the gypsum industry was postulated in this study. The model was designed to be used as a mechanism for estimating the elasticities of demand for gypsum. Information with respect to demand elasticities for gypsum is essential in order to assess the impacts of potential new supplies of abatement gypsum on the market. If the elasticity of demand is relatively small in absolute value, new supplies of abatement gypsum could have a substantive price-depressing effect on the gypsum market. An elasticity of demand large in absolute value would suggest that new supplies would have minimal impact on the price of gypsum. The model considers the demand and supply of gypsum on both the domestic and import side.

Domestic Demand and Supply

The demand for domestic gypsum (Equation 1, Table 1) is determined primarily by the levels of residential, business and industrial construction. The wallboard industry uses 73% of the gypsum, and cement accounts for another 20%. The three exogenous variables in the demand equation are the price of wallboard (W_t), the amount of total new construction (NC_t), and the percentage of new construction that is residential.

The supply of domestic gypsum (Equation 2) is a function of the quantity of gypsum provided by the industry ($\hat{Q}_t$), the level of stocks at the beginning of the year ($\hat{ST}_t$), the index of mining productivity (MIP_t), which is a measure of industry costs, and an index of the energy efficiency of industries which use gypsum (EIX). The cement and wallboard industries are very energy intensive, and energy costs comprise more than 40% of the direct costs of production (U.S. Bureau of Mines).

Gypsum Imports and Stocks

Two equations are used to determine the price and supply of imported gypsum (Equations 3 and 4). The price of imported gypsum (PM_t) is functionally related to the domestic demand levels ($\hat{Q}_t$), the quantity of gypsum imported ($\hat{M}_t$), and the input price lagged one year (PM_{t-1}).

The demand for imported gypsum is a function of the price of imports ($\hat{PM}_t$), the domestic demand ($\hat{Q}_t$), and prior year imports (M_{t-1}). Stringent environmental regulations have been imposed on the domestic cement producing industry since 1969, and there has been an increased reliance on imported cement since then (Brown, p. 15).

The stocks equation (Equation 5) completes the model. Stocks are assumed to be a function of the price of gypsum ($\hat{P}_t$), the quantity of domestic gypsum demand during the year (Q_t), and imports from the prior year (M_{t-1}).

Results

Prices and quantities in the model were simultaneously determined. Time series data for the period 1955 to 1974 were used as the basis for the estimation of the model. The model was estimated via two-stage and three-stage least squares. The three-stage least squares method was more efficient, hence, three-stage least squares results are presented in Table 1.

The parameter estimate on the gypsum price coefficient reveals the elasticity of demand for gypsum in the aggregate model to be near unity (1.0049).[3] This suggests that a new supply of abatement gypsum may not have as heavy a price-depressing effect on the industry as had been thought.

IV. A DISAGGREGATED ECONOMETRIC MODEL

A second model was used to break the demand for gypsum into its component demands for the wallboard, cement and agricultural industries (Table 2).

Specification

The demand for gypsum by the wallboard industry is a function of the price of gypsum for wallboard (PN_t), the total value of newly built structures (VST_t), the percentage of the total value of newly built structures that is residential ($RESP_t$), and the price of wallboard (W_t). The supply of gypsum to the wallboard industry is determined by the quantity of gypsum used in wallboard production (DW_t), the index of energy used in gypsum manufacturing (EIX_t), the mining index of productivity (MIP_t), and the stocks of gypsum (ST_t).

The demand for gypsum to the cement industry (DC) is determined by the price of gypsum to the cement industry (PC_t), the price of the substitute road oil asphalt ($PROA_t$), the total value of construction (NC_t), and the price of portland cement (C_t). The price (supply) of gypsum to the cement industry (PC_t) is a function of the quantity of gypsum for cement (DC_t), the mining index of productivity (MIP_t), the energy index (EIX_t), and gypsum stocks (ST_t).

The demand for gypsum to agriculture (DA_t) is a function of the price of gypsum to agriculture (PA_t), the price index of vegetable crops (PVC_t), and thousands of irrigated acres planted in peanuts (VA_t). The price (supply) of gypsum in agriculture (PA_t) is determined by the quantity of gypsum for agriculture (DA_t), the mining index of productivity (MIP_t), the energy index (EIX_t), and gypsum stocks (ST_t).

Imports of gypsum (M_t) are determined by the price of imports (PM_t), the quantity of imports in the previous time period (M_{t-1}), and the price of wallboard (PM_t). The price (supply) of imported gypsum (PM_t) is determined by the quantity of imports (M_t), the prices of imports in the previous time period (PM_{t-1}), prices for wallboard (PW_t) and cement (PC_t), and the energy index (EIX_t).

Results

Prices and quantities in this model were also simultaneously determined. This model was also estimated using three-stage least squares. Results are presented in Table 2.

The price coefficient of demand for gypsum by the wallboard industry was nonsignificant. This is because of the integration between wallboard producers and gypsum production. The elasticity of demand for gypsum by the cement industry was found to be -.22. This suggests that there are few substitutes for gypsum in cement production. The elasticity of demand for gypsum in agricultural use was -1.276. This suggests that supplies of abatement gypsum for agricultural use would have the least price-depressing effect on the natural gypsum industry as a whole.

Owing to the relative inelasticity of the demand for gypsum by the cement industry it would be expected that no appreciable quantity effect would take place due to the competition of new abatement gypsum. This analysis, therefore, will proceed under the assumption that abatement gypsum produced and distributed by the utilities will be replacing natural gypsum in the specific use.

V. COSTS AND SUPPLY OF ABATEMENT GYPSUM

The study is based on the premise that all utilities currently out of compliance comply by 1978 by choosing one of the following alternatives: (1) scrub by limestone slurry process, (2) scrub by gypsum-producing process,

(3) use low-sulfur fuel (clean fuel), or (4) use combinations of one or two with alternative three.[4]

Estimates of abatement gypsum supplies were developed from the Emission Control Development staff of TVA. The supply of abatement gypsum was determined on a plant-by-plant basis for 1978.[5] The analysis is based on projections of fuel use and other operating characteristics as reported by the utilities themselves to the federal power commission.

The limestone oxidation to gypsum process was used for comparing gypsum production costs with the scrub limestone throwaway process. Costs were calculated by summing the cost of scrubbing on a boiler-by-boiler basis to the plant level. The appropriate air quality regulation for the plant was determined and translated in to the allowable SO_2 admission. The Clean Air Act as amended allows states and air quality regions to establish implementation regulations and standards for meeting local needs. Substantial variation exists between districts as to standards and how they are to be applied. Regulations may apply at each specific boiler, or they may apply at a stack or plant level. When regulations apply at the boiler level, each boiler out of compliance must scrub. When regulations apply at the stack of plant level, only a sufficient number of boilers must scrub to bring total SO_2 emissions into compliance with the point source standard.[6]

The next step was to determine if the plant would be in or out of compliance in 1978 if operated as projected. Emissions were calculated based on the projected quantity of fuel to be burned in each boiler and its sulfur content. If calculated SO_2 emissions exceeded calculated allowable

SO_2 emissions by 10% or more, the plant (or boiler) was determined to be out of compliance for purposes of this study.

Industry costs were summarized and the supply of abatement gypsum determined. The study considered all fossil-fired utilities in the U.S. According to data available from the federal power commission, a total of 800 plants with 3,382 boilers having total capacity of 411,404 megawatts were expected to be in operation in 1978.

A total of 187 plants were expected to be out of compliance in 1978. These plants are shown in Figure 1. These plants would have to remove a total of 4,440,000 tons of sulfur to meet compliance regulations. This is more than twice the quantity of sulfur imported into the U.S. in 1974 and equal to 38% of domestically mined sulfur in 1974. If this amount of sulfur were to be abated in the conventional limestone slurry FGD systems, a total of 25,393.0 thousand tons of calcium solids would be made and have to be ponded in the first year. Total investment would be 6.89 billion dollars if all sulfur were to be abated by the limestone slurry system (Ransom).

The $0.70 per million Btu heat input clean fuel screen was applied to reduce to those plants that might realistically be considered candidates to install some form of FGD system.[7] When the screen was applied, 106 plants in total and ten additional plants had one or more boilers that might conceivably employ some FGD system. These plants are shown in Figure 2. These 116 plants would abate a total of 4,109,000 tons of sulfur. The 331,000 remaining tons would be "abated" by use of clean fuel. At $0.70 per million Btu heat input, the cost would amount to an extra 267.3 million dollars for the clean fuel. First-year limestone slurry FGD cost would amount to 2,037.2 million dollars, making a total first-year cost of 2,350.7

million dollars. Total investment in the throwaway FGD system under this assumption would be 545 million dollars. Table 3 summarized cost at different levels of clean-fuel cost. The table illustrates the importance of cost and availability of clean fuels in reducing overall costs of meeting current emission regulations.

At the $0.70 clean-fuel level, 116 plants were found to be candidates to install some form of FGD system. These plants would produce about 27.4 million tons of gypsum with an average cost of 61.3 dollars per ton and an incremental cost, compared with the throwaway system, of 7 dollars per ton. If clean-fuel cost were $0.50, potential gypsum production would decline to 6 million tons. The revenue requirements for the first year operation of the average plant would be 13.0 million dollars if the throwaway process is used and 14.7 million dollars if the gypsum producing process is used. Revenue requirements over the life time (30 years) of the plant are 243.9 million dollars for the throwaway process and 274.5 dollars for the gypsum producing process (Ransom).

Cost variability occurs in only a few cases, and only a small volume of required sulfur removal is involved (from a -13 dollars to a +20 dollars per ton). The base estimate indicated an incremental cost of 7 dollars per ton for a new 500-megawatts plant. Results of the cost model when applied to all plants out of compliance indicated a 7 dollar per ton incremental cost on 13% of total potential gypsum production. Two-thirds of total potential production would occur within a range of $3.50 to $10.50 per ton incremental cost. Only 10% of total potential abatement gypsum production would occur at or below estimated cost of mining.

VI. MARKETING POTENTIAL OF ABATEMENT GYPSUM

To determine the market potential for abatement gypsum, consumption was projected at each demand point, and the delivered price of crude gypsum was calculated at each demand point. To calculate the delivered cost of crude gypsum, the current rail rate for gypsum was escalated by 15% to reflect estimated 1978 rates. Rates were calculated to select appropriate tariff and to calculate miles from supply point to each demand point. Rate-per-ton mile was multipled by miles to each point to obtain transportation cost which was added to f.o.b. price of supply points. This assured that the lowest delivered cost of gypsum to each demand point was calculated (Ransom).

The mathematical statement of the objective function to be minimized can be stated as:

$$TIC = \sum_{i=1}^{n} C_i d_i + \sum_{j=1}^{m} TSL_j - \max_{X_{ij}} NR(X_{ij})$$

Where:

$$NR(X_{ij}) = \sum_{j=1}^{m} \{\Sigma(C_i - T_{ij})X_{ij} - (TG_j - TLS_j)X_{oj}\}$$

Subject to:

$$\sum_{j=1}^{m} X_{ij} - S_j \quad (X_{oj}) = 0 \qquad X_{oj} = \{^0_1\}$$

$$\sum_{j=1}^{m} X_{ij} \leq d_i \quad (i=1,2,\ldots,N).$$

$$X_{ij} \geq 0.$$

Where:

TIC = total gypsum industry cost

C_i = delivered cost crude gypsum to the i^{th} demand point

d_i = quantity of gypsum demanded by the i^{th} point

X_{ij} = abatement gypsum shipped from the j^{th} steam plant to the i^{th} demand point

T_{ij} = transportation cost from the j^{th} steam plant to the i^{th} demand point

TG_j = total cost gypsum process

TLS_j = total cost throwaway process

X_{oj} = a zero or one variable

S_j = abatement gypsum production by the j^{th} steam plant

Total cost of the gypsum-using industries (wallboard and cement) to purchase crude gypsum and total cost to the utilities industry to meet compliance by the limestone slurry FGD system are represented on the left-hand side of the equation. The sum of the two costs represents total cost to both industries. Cost to the utilities industry to meet compliance by the gypsum-producing FGD process has also been established. All costs are established on a point-by-point basis, and industry cost represents the sum of each cost at demand points or supply points. The transportation portion of the model solves for the maximum potential revenue to each utility (supply point) on a plant-by-plant basis. If total gypsum revenue $\Sigma(C_i-T_{ij})(x_{ij})$ minus total incremental gypsum production cost (TG_j-TLS_j) is positive on a plant basis, there is a basis for production and sale of abatement gypsum by the utility, and cost to both the utilities industry and gypsum users is reduced. If total revenue minus total incremental cost to the utility is zero, there is still a basis for production and sale of abatement gypsum since the utility avoids the problems associated with ponding slurry and the cost to the gypsum users is reduced. If total revenue minus total incremental cost is negative, there may still be a potential savings to the two industries. It would not be realized, however, because the utility would have to produce gypsum at a net cost and would not do so without outside funding.

In terms of the model, the mixed integer variable X_{oj} would take on a value of one when total revenue minus total incremental cost is equal to or greater than zero. When total revenue minus total incremental cost is less than zero, the variable X_{oj} takes on a value of zero. When $X_{oj}=1$, the constraint $\Sigma X_{ij}-Sy(1)=0$ holds and the supply is at its maximum. When $X_{oj}=0$, the constraint $\Sigma X_{ij}-Sy(0)=0$ also holds and supply is zero.

The market analysis was limited to the industry east of the Rocky Mountains after it was determined that only three plants were out of compliance in the western states. These three plants are located in Nevada and Wyoming and, because of their location, would have limited opportunity to market abatement gypsum. In the study area an assumed 15,043,301 tons of gypsum will be used in 1978 by the wallboard and cement industries at 187 demand points. The total cost to market that crude gypsum under the study assumptions will amount to 124.4 million dollars. Approximately 58% of the total cost is for transportation. Calcining plants are located either at domestic mine sites or at deepwater ports to utilize imported gypsum; therefore, the major portion of transportation costs is borne by the cement industry.

Fifty-five demand points are calcining plants. These plants are assumed to use 11,855,910 tons of gypsum in 1978. Estimated consumption per plant ranges from a low of 58,260 tons to a high of more than 500,000 tons. Average consumption per plant is estimated at 215,562 tons. Delivered cost to calcining plants is based on estimated domestic variable mining costs of 3 dollars per ton and 2 dollars per ton for imported gypsum. Imported gypsum (mainly from Canada) is transported to coastal calcining plants at rates ranging from 3 dollars to 5 dollars per ton. All interior calcining plants but three are located at or near mine sites. In these cases a flat 1 dollar per ton is assumed to cover costs of moving the material from mine to plant. Rail rates are calculated from company-owned mines to calcining plants for the plants located away from mine sites. Projected use by size and delivered costs to wallboard plants are summarized in Table 4.

Imports are assumed at more than 5.9 million tons (in the study area) in 1978. Under the study assumptions, 66 demand points will use imported crude gypsum. Forty-three are cement plants which use an estimated 1.164 million tons. This gypsum is imported to the calcining plant and then shipped to the cement plant. Rail rates are calculated in each point. Twenty-three calcining plants will directly use 4.777 million tons of imported gypsum.

One hundred and thirty-two demand points are cement plants. The cement industry is projected to use a total of 3.187 million tons of gypsum in 1978 (Mineral Industry Surveys). This is based on each plant in the industry operating at 85% of rated capacity and each plant using a finished cement containing 5% gypsum. Use per plant ranges from a low of 2,550 tons to a high of 65,875 tons. Average use per plant will amount to 24,147 tons. Delivered prices are based on a conservative average f.o.b. price of 6 dollars per ton from nearest supply points. Rail transportation is assumed in each case, and minimum delivered cost of crude gypsum is calculated to each cement demand point. Delivered costs range from a low of $12.43 per ton to a high of $21.18. The majority of tonnage used will have a delivered cost of between $15 and $18 per ton. Projected use by size and delivered cost to cement plants are summarized in Table 5.

The 30 steam plants in the final solution, their location, production, and incremental cost per ton of gypsum are shown in Table 6. The over-all results of the analysis are summarized in Table 6. The analysis indicates that abatement gypsum would be used by only one existing wallboard manufacturing plant. This is a result of more profitable markets in the cement industry. For example, two plants in Florida are located near wallboard manufacturing plants. If cement markets were not available, these two plants could partially supply the needs of the wallboard plants on a mutually profitable basis.

The major potential for abatement gypsum marketing is to supply the cement industry. In the analysis, 2.132 million tons were calculated to be supplied to 92 plants in the cement industry. This tonnage represents 67% of the projected 1978 consumption of gypsum by the cement industry in the eastern U.S. Plants calculated to produce gypsum are smaller than plants that would use the limestone slurry throwaway process. On the average, the annual output of sulfur is only about one-fourth as much as for limestone systems. In general, the gypsum-producing plants are newer plants; 29% of them are between zero to 5 years old compared with 11% for limestone systems. The sulfur content of fuel by type is lower. In addition, the percentage of Btu heat input from oil and gas is higher than in plants predicted to install the limestone slurry throwaway system.

The results of the market analysis summarized in Table 7 indicate a limited potential for abatement gypsum production and marketing to significantly contribute to solving major FGD problems faced by the nation's utilities. Abatement gypsum was supplied by small abatement producers that could supply requirements of cement plants located near the utility. Fifteen of the thirty utilities in the final solution actually were calculated to have lower cost gypsum production than for the limestone slurry throwaway product. An additional seven plants had an incremental cost of less than 1 dollar per ton of gypsum. The average annual production at these steam plants was 65,377 tons.

When average savings per ton to the gypsum-using industry were calculated to be only 86 cents per ton, the economics of using abatement gypsum by the existing industry are questionable. However, the steam plants could pass additional savings to the gypsum-using industry to compensate for added costs of using abatement gypsum. For example, if these costs amounted to 2 dollars per ton, 27 steam plants would continue to produce. At a 3-dollar-per-ton price reduction, 24 plants would continue to produce and market abatement gypsum to the cement industry. The analysis, furthermore, indicates that 74% of imported material used by the cement industry would be replaced.

VII. CONCLUSIONS

Gypsum is a low-value product used in substantial quantities by wallboard and cement manufacturing plants. The cost of SO_2 removal by the gypsum producing process is higher than for the limestone slurry throwaway process. The only exceptions are some small plants, in terms of SO_2 removal, which have a cost advantage to produce gypsum. This works to the disadvantage of the gypsum process to supply the existing wallboard industry. The analysis was based on conservative estimates of gypsum mining costs, but in all other respects the analysis was based on premises favorable to abatement gypsum.

Production and marketing of abatement gypsum to the cement industry seems to offer an opportunity for steam plants with low annual volumes of sulfur removal to lower cost of compliance. By the same token, there seems to be little opportunity to lower compliance cost by marketing abatement gypsum to the existing wallboard products industry. The gypsum-producing alternative seems to offer only a limited potential to solve the larger problems of sulfur conservation and disposal of calcium solids. However, in terms of a total program of byproduct marketing, the gypsum-production alternative may fill a specific role in that it seemingly meets the needs of small plants when other byproducts may be better suited to larger plants. If that proves to be the case, the gypsum process seems to be of more total importance than the analysis indicates.

FOOTNOTES

[1] A 500-megawatt (MW) per unit, burning coal of 3.5% sulfur constant, will produce approximately 20,500 pounds SO_2 per hour. A more recent estimate (Devitt, T.W., et al.) indicates that 109 FGD systems with an equivalent rating of 42,128 MW are either operational, under construction or planned.

[2] Two specific disadvantages for abatement gypsum were identified as: The product has 20% free moisture, and it may present mechanical handling problems. Extra cost to the industry using gypsum to overcome these disadvantages could not be quantified; but to the extent that they present real costs to the gypsum using industry, the added costs must be discounted from value attributed to abatement gypsum.

[3] The elasticity of demand for gypsum was calculated on the basis of the regression coefficient on gypsum price (Equation 1, Table 1).

[4] Compliance refers to the achievement of the existing SO_2 air quality regulations at each plant, in affect June 30, 1976.

[5] See Ransom and future EPA Report for the cost calculations and McGlanery, et. al.

[6] Any FGD system installed is assumed to remove 90 percent of SO_2 emissions.

[7] It is assumed that any plant out of compliance can purchase and use low-sulfur fuel to meet compliance at a premium cost of 70 cents per million or Btu heat input.

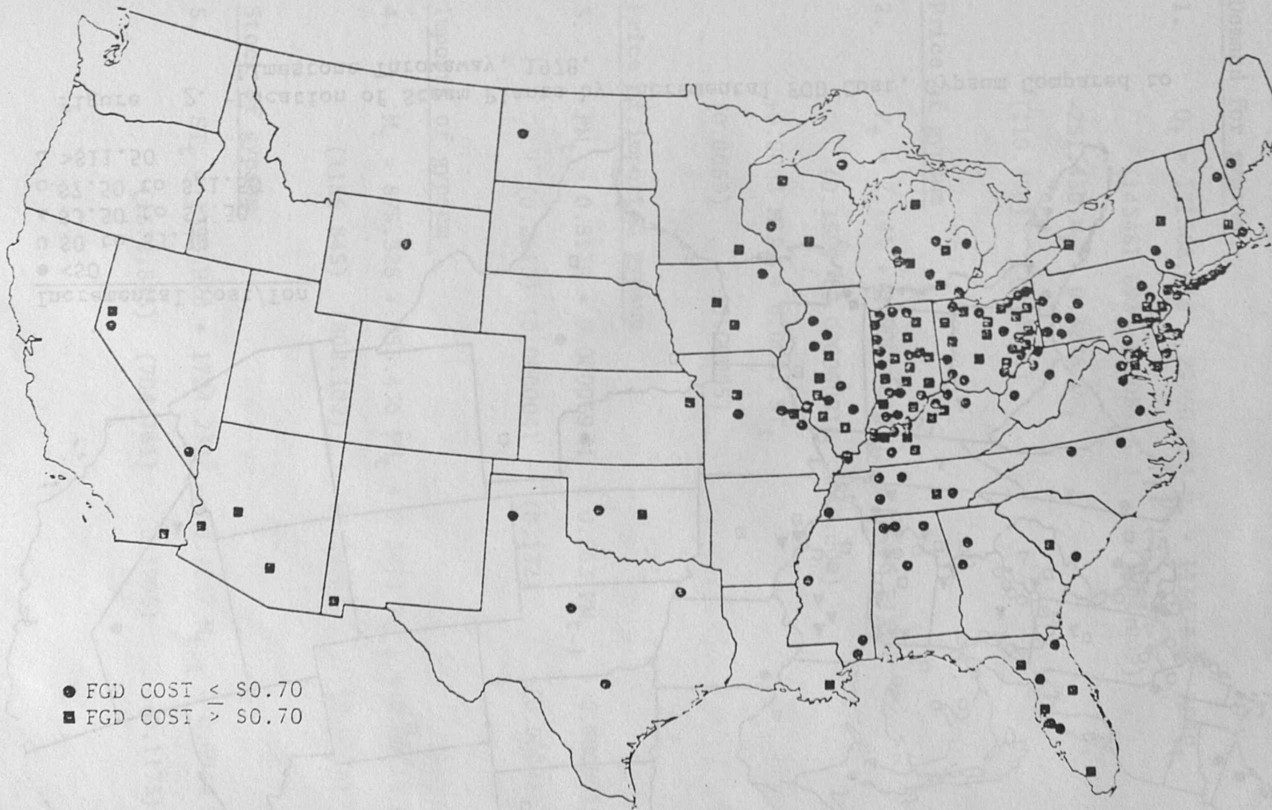

Figure 1. -Steam Plant Locations Calculated to Exceed Compliance Regulations, 1973.

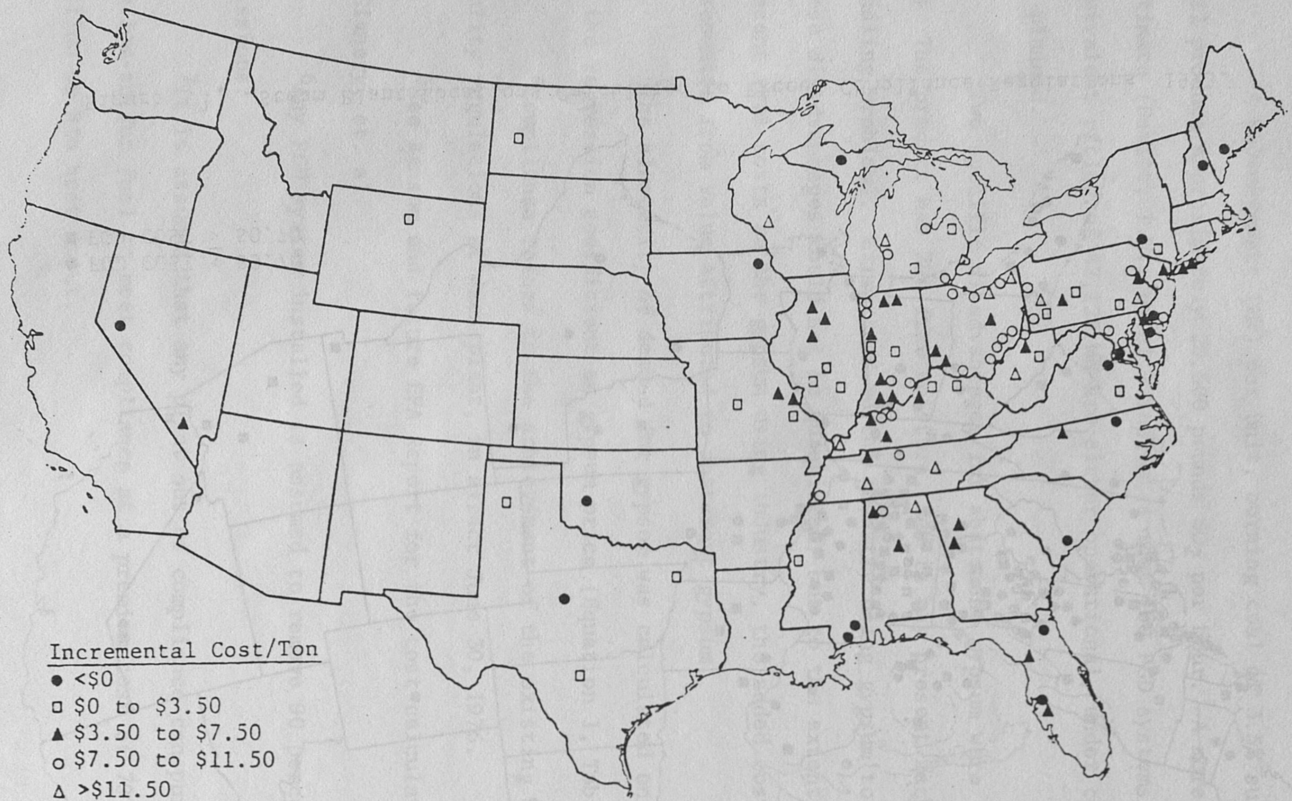

Figure 2. -Location of Steam Plants by Incremental FGD Cost, Gypsum Compared to Limestone Throwaway, 1978.

Table 1. Three-stage least squares estimates of the market for gypsum.

Demand for gypsum

1. $$Q_t = 171568.918 - 29760.204\ \hat{P}_t + 1136.338\ RESP_t$$

(143481.893) (22051.313) (1004.009)

$$-251.450\ W_t + 0.3276\ NC_t$$

(110.450) (0.4455)

Price of gypsum

2. $$P_t = 2.141 + 0.00000003\ \hat{Q}_t - 0.006\ EIX_t$$

(0.159) (0.00000001) (0.001)

$$+0.0063\ MIP_t + 0.0001\ \hat{ST}_t$$

(0.0059) (0.00005)

Price of imported gypsum

3. $$PM_t = 0.5179 + 0.000069\ M_t + 0.563\ PM_{t-1} + 0.0000013\ Q_t$$

(0.2613) (0.000004) (0.132) (0.000011)

Imports of gypsum

4. $$M_t = 875.328 + 855.436\ \hat{PM}_t + 0.5471\ M_{t-1} + 0.00016\ \hat{Q}_t$$

(1186.845) (802.102) (0.1905) (0.0006)

Stock of gypsum

5. $$ST_t = 1399.920 + 1724.233\hat{P}_t + 0.4897\ M_{t-1} - 0.6944\ \hat{Q}_t$$

(1372.845) (704.761) (0.1905) (0.1173)

Table 1. - Continued.

Where:

Q_t	=	Demand for gypsum (million tons), U.S. Bureau of Mines, "Minerals Yearbook."
P_t	=	Price of gypsum (dollars per ton), U.S. Bureau of Mines, "Minerals Yearbook."
$RESP_t$	=	Percent residential construction, Statistical Abstract of the U.S.
W_t	=	Price of wallboard (dollar per ton), U.S. Bureau of Mines, "Minerals Yearbook."
NC_t	=	Total new construction (millions of dollars), Statistical Abstract of the U.S.
MIP_t	=	Mining index productivity, U.S. Bureau of Mines, "Minerals Yearbook."
EIX	=	Energy index in gypsum manufacturing, U.S. Bureau of Mines, "Minerals Yearbook."
ST_t	=	Stocks (million tons), U.S. Bureau of Mines, "Minerals Yearbook."
M_t	=	Imports of gypsum (million tons), U.S. Bureau of Mines, "Minerals Yearbook."

(Values in parenthesis are standard errors.)

Table 2. Three-stage least squares estimates of the disaggregated market for gypsum.

Demand for gypsum by the wallboard industry

1. $$DW_t = 1504.310 + 4{,}395.703\ \hat{PW}_t + 0.0799VST_t$$
$$(1111.875)\quad (25{,}469.051)\quad (0.0038)$$
$$+ 136.846\ RESP_t - 0.7962\ W_t$$
$$(11.940)\quad (6.659)$$

Price of gypsum to the wallboard industry

2. $$\hat{PW}_t = 0.0459 + 0.0000003\ \hat{Dw}_t - 0.000054\ EIX_t$$
$$(0.0024)\quad (0.0000002)\quad (0.000016)$$
$$+ 0.00015\ MIP_t + 0.0000017\ ST_t$$
$$(0.00004)\quad (0.0000005)$$

Demand for gypsum by the cement industry

3. $$\hat{DC}_t = -2389.958 - 0.0000068\ \hat{PC}_t + 646.396\ PROA$$
$$(1235.371)\quad (0.0000016)\quad (619.443)$$
$$+ 0.0243\ NC_t - 4.821\ C_t$$
$$(0.0025)\quad (18.492)$$

Price of gypsum to the cement industry

4. $$\hat{PC}_t = 0.0518 + 0.00000046\ DC_t + 0.000048\ MIP$$
$$(0.0014)\quad (0.00000013)\quad (0.000050)$$
$$-0.000037\ EIX_t + 0.0000012\ ST_t$$
$$(0.000012)\quad (0.0000004)$$

Table 2. Continued.

Demand for gypsum in agriculture

5. $$\hat{DA}_t = 1357.248 - 30136.537\ \hat{PA}_t + 9.673\ PVC_t$$

$$(279.573) \quad (8575.862) \quad (2.809)$$

$$+ 0.00157\ VA_t$$

$$(0.00675)$$

Price of gypsum in agriculture

6. $$\hat{PA}_t = 0.00449 + 0.0000018\ \hat{DA}_t + 0.00842\ EIX_t$$

$$(0.00488) \quad (0.0000002)$$

$$+ 0.00019\ MIP_t + 0.0000003\ ST_t$$

$$(0.00006) \quad (0.0000007)$$

Imports of gypsum

7. $$\hat{M}_t = -6005.653 + 704.479\ \hat{PM}_t - 0.0250\ M_{t-1}$$

$$(1702.220) \quad (604.543) \quad (0.1865)$$

$$+ 2824.770\ \hat{PW}_t$$

$$(596.814)$$

Price of imported gypsum

8. $$\hat{PM} = 0.9571 + 0.000012\ \hat{M}_t + 0.210\ PM_{t-1}$$

$$(0.2629) \quad (0.000071) \quad (0.152)$$

$$- 0.000057\ PW_t + 0.00040\ PC_t - 0.00025\ EIX_t$$

$$(0.000035) \quad (0.00017) \quad (0.00156)$$

Table 2. Continued.

Where:

DW_t = Gypsum to wallboard (million tons), U.S. Bureau of Mines, "Minerals Yearbook."

PW_t = Price of gypsum to wallboard (dollars per ton), U.S. Bureau of Mines, "Minerals Yearbook."

W_t = Price of wallboard (dollars per ton), U.S. Bureau of Mines, "Minerals Yearbook."

VST_t = Value of structure (millions of dollars), Statistical Abstract of the U.S.

$RESP_t$ = Percent of total construction that is residential, Statistical Abstract of the U.S.

EIX_t = Energy Index in gypsum manufacturing, U.S. Bureau of Mines, "Minerals Yearbook."

MIP_t = Mining index of productivity, U.S. Bureau of Mines, "Minerals Yearbook."

ST_t = Stocks (million tons), U.S. Bureau of Mines, "Minerals Yearbook."

DC_t = Gypsum for cement, U.S. Bureau of Mines, "Minerals Yearbook."

PC_t = Price of gypsum for cement, U.S. Bureau of Mines, "Minerals Yearbook."

$PROA_t$ = Price of road oil asphalt (dollars per barrel), U.S. Bureau of Mines, "Minerals Yearbook."

NC_t = Total construction (billions of dollars), Statistical Abstract of the U.S.

C_t = Price of Portland cement (dollars per ton), U.S. Bureau of Mines, "Minerals Yearbook."

DA_t = Gypsum to agriculture (million tons), U.S. Bureau of Mines, "Minerals Yearbook."

PVC_t = Price index vegetable crops, U.S. Department of Agriculture, "Agricultural Prices."

VA_t = Irrigated acres and acres planted in peanuts (thousands of acres), U.S. Department of Agriculture, "Agricultural Statistics."

Table 2. Continued.

M_t	=	Imports of gypsum (million tons), U.S. Bureau of Mines, "Minerals Yearbook."
PM_t	=	Import price of gypsum (dollars per ton), U.S. Bureau of Mines, "Minerals Yearbook."
PA_t	=	Price of gypsum in agriculture (dollars per ton), U.S. Bureau of Mines, "Minerals Yearbook."

(Values in parentheses are standard errors)

Table 3. Relationship Between Assumed Clean-Fuel Cost and Total Cost of Meeting Compliance Regulations.

Clean Fuel Cost ($) P/MM Btu	Sulfur Abated by (1,000 Tons)		Cost ($ million)		Total Cost ($ million)
	Clean Fuel	Limestone FGD	Clean Fuel	Limestone FGD	
Infinite	-	4,440.2	-	2,866.2	2,866.2
0.70	331.2	4,109.0	267.3	2,377.2	2,305.7
0.50	1,337.0	3,103.2	636.3	1,513.2	2,149.5
0.35	3,498.1	942.1	1,225.9	830.6	1,847.7

Table 4. Summary of Projected Use by Wallboard Plants, by Size and by Delivered Cost, 1978 (Eastern U.S.).

Size 1,000 Tons	No. Plants	Delivered Cost/Ton	No. Plants
<10	-	$4	24
100-200	13	5-7	28
200-300	34	8-10	3
300-400	2		
<400	4		

Table 5. Summary of Projected Use by Cement Plants, by Size and by Delivered Cost, 1978 (East of Rocky Mountains).

Size 1,000 Tons	No. Plants	Delivered Cost/Ton	No. Plants
<10	8	<$15	33
10-20	45	$15-18	78
20-30	46	>$22	
30-40	20		
>40	13		

Table 6. Summary of Steam Plants Calculated to Produce and Market Abatement Gypsum and Net Revenue Per Plant.

FPC Number	State	Tons Gypsum Produced	Incremental Cost/Ton ($)	Net Revenue ($)
1385000100	DE	11,288	-12.66	199,063
5250001000	VA	38,520	-5.56	396,425
2345000200	FL	28,677	-3.56	320,266
2770000700	IA	56,278	-2.95	488,383
3945000600	MD	89,101	-2.37	511,865
5430000250	TX	65,887	-1.44	337,968
5440000100	OK	55,371	-1.15	294,934
3080000400	MS	106,933	-0.92	912,828
0805002700	ME	43,895	-0.90	183,935
4050001150	NH	72,128	-0.32	194,889
4740000100	FL	96,176	-0.31	874,427
2920000500	MI	14,520	-0.28	84,715
4480000075	SC	92,238	-0.23	809,931
3080000150	MS	85,829	-0.23	543,275
5235000100	NJ	6,679	-0.03	42,814
4045000800	IN	69,132	0.06	427,859
4785000575	TX	73,647	0.16	331,036
5420000400	PA	15,749	0.29	167,451
1415000150	KY	101,706	0.57	388,260
3590000200	NY	20,977	0.57	146,367
2605000150	MI	58,079	0.59	327,902

Table 6. Continued.

FPC Number	State	Tons Gypsum Produced	Incremental Cost/Ton ($)	Net Revenue ($)
0720000900	NC	76,788	0.68	393,633
3795000350	PA	158,716	0.92	342,920
5250001400	VA	150,519	1.01	328,600
0785000500	IL	170,139	1.60	569,098
2260000100	IN	134,105	2.00	101,735
3085000350	MS	131,672	2.02	205,045
0700000550	NY	164,582	2.46	492,155
4820000700	MI	50,070	3.00	46,109
3840000500	PA	159,690	3.02	612,098

Table 7. Summary of Results of Analysis in Eastern U.S.

Number of plants out of compliance (total)	187
Lowest-cost strategy	
Clean fuel, number of plants	71
Limestone slurry process, number of plants	86
Gypsum production and marketing, number of plants	30
Total gypsum produced (tons)	2,399,081
Average production per steam plant (tons)	79,970
Smallest gypsum supplier (tons)	6,679
Largest gypsum supplier (tons)	170,981
Total gypsum sold (tons)	2,228,100
Total gypsum stockpiled (tons)	170,981
Number plant stockpile part of production	5
Wallboard plants served	1
Cement plants served	92
Sold to wallboard plants (tons)	95,307
Sold to cement plants (tons)	2,132,793
Total net revenue to utilities ($)	11,075,970
Total savings to gypsum industry ($)	1,922,731
Savings to gypsum industry (% of total cost)	1.5
Average savings per ton of gypsum purchased ($)	0.86
Total first-year compliance cost for 113 plants using the limestone slurry process ($)	2,037,721,214
Reduction by marketing gypsum ($)	11,075,970
Cost reduction (%)	0.5
Required sulfur removal (tons)	4,109,000
Sulfur removed by gypsum process (%)	8.7

Table 7. Continued.

Tons imported gypsum displaced	855,992
Tons domestic gypsum displaced	1,372,108
1978 calcining market served with abatement gypsum (%)	0.8
1978 cement market served with abatement by gypsum (%)	67.0

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