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Tennessee Valley Authority Office of Power	Energy Demonstrations and Technology Muscle Shoals AL 35660	TVA/OP/EDT-83/15
United States Environmental Protection Agency	Industrial Environmental Research Laboratory Research Triangle Park NC 27711	EPA-600/7-84-019 February 1984

Marketing of Byproduct Gypsum from Flue Gas Desulfurization

Interagency Energy/Environment R&D Program Report

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EPA-600/7-84-019
TVA/OP/EDT-83/15
February 1984

Marketing of Byproduct Gypsum from Flue Gas Desulfurization

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EPA Interagency Agreement No. 79-D-X0511

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U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

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ABSTRACT

The 1985 marketing potential of byproduct gypsum from utility flue gas desulfurization (FGD) was evaluated for the area east of the Rocky Mountains using the calculated gypsum production rates of 14 selected power plants. The 114 cement plants and 52 wallboard plants in the area were assumed to be the potential market for FGD gypsum sales. Assuming use of an in-loop forced-oxidation limestone FGD process, the results showed that producing a marketable gypsum was less expensive than disposal by fixation and landfill for many power plants in the area--including all those used in the study. With this savings to offset freight costs, the power plants could market 4.35 million ton/yr of gypsum (92% of their production), filling 63% of the cement plant requirements and 20% of the wallboard plant requirements. Cement plants are a geographically dispersed market available to most power plants, but able to absorb the production of only a few power plants; wallboard plants are a larger market but power plant location is a more important marketing factor. Other variations of the marketing model indicated that: (1) drying and briquetting had little effect on the marketing potential, (2) sales were reduced 25% when the savings in FGD cost were not used to offset freight costs, and (3) relocation of wallboard plants to sources of byproduct gypsum appeared economically feasible in some cases.

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ABBREVIATIONS AND CONVERSION FACTORS

ABBREVIATIONS

aft3/min	actual cubic feet per minute
Btu	British thermal unit
°F	degrees Fahrenheit
dia	diameter
FGD	flue gas desulfurization
ft	feet
ft^2	square feet
ft^3	cubic feet
gal	gallon
gpm	gallons per minute
gr	grain
hp	horsepower
hr	hour
in.	inch
k	thousand
kW	kilowatt
kWh	kilowatthour
lb	pound
L/G	liquid-to-gas ratio in gallons per thousand actual cubic feet of gas at outlet conditions
M	million
mi	mile
mo	month
MW	megawatt
ppm	parts per million
psig	pounds per square inch (gauge)
rpm	revolutions per minute
sec	second
sft3/min	standard cubic feet per minute (60°F)
SS	stainless steel
yr	year

CONVERSION FACTORS

EPA policy is to express all measurements in Agency documents in metric units. Values in this report are given in British units for the convenience of engineers and other scientists accustomed to using the British systems. The following conversion factors may be used to provide metric equivalents.

To convert British		Multiply by	To obtain Metric	
ac	acre	0.405	hectare	ha
Btu	British thermal unit	0.252	kilocalories	kcal
°F	degrees Fahrenheit minus 32	0.5556	degrees Celsius	°C
ft	feet	30.48	centimeters	cm
ft^2	square feet	0.0929	square meters	m^2
ft^3	cubic feet	0.02832	cubic meters	m^3
ft/min	feet per minute	0.508	centimeters per second	cm/s
ft^3/min	cubic feet per minute	0.000472	cubic meters per second	m^3/s
gal	gallons (U.S.)	3.785	liters	L
gpm	gallons per minute	0.06308	liters per second	L/s
gr	grains	0.0648	grams	g
gr/ft^3	grains per cubic foot	2.288	grams per cubic meter	g/m^3
hp	horsepower	0.746	kilowatts	kW
in.	inches	2.54	centimeters	cm
lb	pounds	0.4536	kilograms	kg
lb/ft^3	pounds per cubic foot	16.02	kilograms per cubic meter	kg/m^3
lb/hr	pounds per hour	0.126	grams per second	g/s
psi	pounds per square inch	6895	pascals (newton per square meter)	Pa (N/m^2)
mi	miles	1609	meters	m
rpm	revolutions per minute	0.1047	radians per second	rad/s
sft^3/min	standard cubic feet per minute (60°F)	1.6077	normal cubic meters per hour (0°C)	m^3/hr (0°C)
ton	tons (short)	0.9072	metric tons	tonne
ton/hr	tons per hour	0.252	kilograms per second	kg/s

ACKNOWLEDGMENTS

Studies of this type depend upon information whose special nature or necessary timeliness makes it difficult or impossible to obtain from conventional published sources. We were fortunate during this study to have the assistance of many people who gave freely of their time to provide us with this information. In particular, we are indebted to the generosity and patience of the following for sharing their knowledge and experience with us.

Jean W. Pressler, S. T. Absalom, and James T. Dikeou of the U.S. Bureau of Mines; Julian W. Jones and Norman Kaplan of the EPA Industrial Environmental Research Laboratory; Gerald Lappan of the EPA Compliance Data Systems; Editha M. Ardiente, Keith D. Colamarino, Richard S. Du Bose, Peter W. Schaul, Dave Schulz, and James T. Wilburn of the EPA Air and Waste Management Division; Clair Fancy and Hamilton Oven of the State of Florida Department of Environmental Regulations; Ralph W. Weggel, Julian J. Boyce, Robert N. Ebersbacher, Thomas E. Bacon, and Martin A. Barone of the Bepex Corporation; E. Robert Kiehl of the Celotex Corporation; John M. D'Alonzo, G. Steven Detwiler, and Louis M. Ruggiano of Conversion Systems, Inc.; A. Victor Abnee of the Gypsum Association; F. MacGregor Miller of Ideal Basic Industries; C. H. Weise of the Portland Cement Association; Mark Richman and Robert E. Byrne of Research-Cottrell, Inc.; Darryl D. Ciliberto and C. Richard Hach of the Tampa Electric Company; Robert J. Wenk of the United States Gypsum Company; and J. R. Black, H. R. Granade, and L. E. Stone of the TVA Office of Economic and Community Development.

MARKETING OF BYPRODUCT GYPSUM FROM FLUE GAS DESULFURIZATION

EXECUTIVE SUMMARY

INTRODUCTION

This study involved investigating the marketing of byproduct gypsum as a more economical means of operating flue gas desulfurization (FGD) processes at utility power plants. In the past few years, the prospects for marketing FGD gypsum have improved. Simple and effective variations on low-cost limestone FGD processes that incorporate forced oxidation to produce gypsum have been developed and have become economically competitive with the more conventional limestone processes that have increasingly expensive waste treatment costs. Forced-oxidation processes are now offered by several vendors and are being adopted by utilities seeking to reduce waste treatment and handling problems, or in some cases, to produce a marketable gypsum.

This study is based on published information available through 1982 on the type of coal used by utility power plants and the emission control regulations to which they are subject. This and the general geographic locations provide a representative gypsum production model. Actual site-specific conditions and existing or planned emission control and waste disposal practices that would affect the economics of gypsum marketing at specific power plants are not considered because the study is an assessment of FGD gypsum marketing in general.

Rapidly increasing transportation costs have also improved the prospects for FGD gypsum because of the nonuniform distribution of natural gypsum, which sometimes requires the shipment of natural gypsum or gypsum products over long distances. FGD gypsum is one of the better candidates among byproduct gypsums for replacement of natural gypsum because of its chemical and physical properties. Wallboard is produced from FGD gypsum in Japan and West Germany. It has been evaluated in several wallboard manufacturing tests in the United States that were reportedly successful--an important factor since wallboard manufacture has the most stringent quality requirements and is the largest use of gypsum. The manufacture of portland cement, which contains a small percentage of gypsum, is the only other market that utilizes sufficient gypsum to support the marketing of FGD gypsum.

In 1981, about 19 million tons of gypsum was used in the United States, 3.6 million tons for the manufacture of portland cement, 1.5 million tons in agriculture, and most of the remainder to manufacture wallboard and plaster products. About 11.5 million tons was produced at 70 mines in 22 states; the remainder was imported.

The unusually large import trade is largely the result of a lack of gypsum deposits in the eastern United States. It is more economical to import gypsum by sea from Canada and Mexico than to ship it overland from domestic mines, a situation with important implications for marketing byproduct gypsum in the eastern states.

In the 37 states east of the Rocky Mountains, the study area of this investigation, gypsum deposits occur in the inland coastal plains from Arkansas to eastern Texas, in a broad belt from western Texas into Iowa and in the area around the lower Great Lakes. Except for a mine in southwestern Virginia, there are no gypsum mines east of the Mississippi River and south of the Ohio River. In 1981, an estimated 8 million tons of gypsum was produced at 36 mines in 12 of the 37 states. An additional 6.2 million tons was imported through 13 ports of entry on the Eastern Seaboard and Gulf Coast.

MARKETING MODEL

The marketing model used in this study was based on the premises that utilities who have chosen to use FGD to meet SO_2 emission control requirements would adopt FGD gypsum production and marketing if this were the lowest cost FGD option, and that cement and wallboard manufacture would use the byproduct gypsum if it cost less than their natural gypsum supply. The study area was limited to the 37 states east of the Rocky Mountains and sales were limited to cement and wallboard plants. All of the costs, quantities, power plant conditions, and marketing structures were projected to 1985 using information available through mid-1982.

Gypsum Market

The cement plant market consisted of 114 cement plants projected to be in operation in 1985. The geographic distribution of the plants is quite uniform and bears little relationship to natural gypsum sources, as shown in Figure S-1. The total cement plant gypsum requirements were projected to be 3.42 million ton/yr. The requirements of most individual plants ranged from 10,000 to 60,000 ton/yr and the average for all of the plants was 30,000 ton/yr.

The wallboard plant market consisted of the 52 wallboard plants projected to be in operation in 1985. The geographic distribution of the plants is almost entirely related to source of gypsum, either mines or import points, as shown in Figure S-2. The total wallboard plant gypsum requirements were projected to be 10.4 million ton/yr. Most wallboard plants have requirements

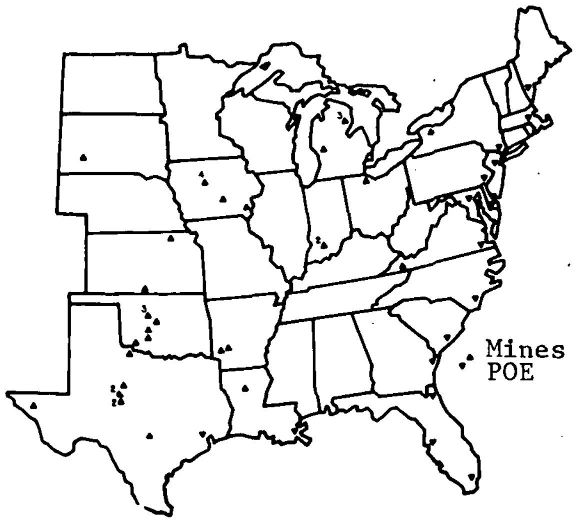

Figure S-1. Location of gypsum mines and ports of entry.

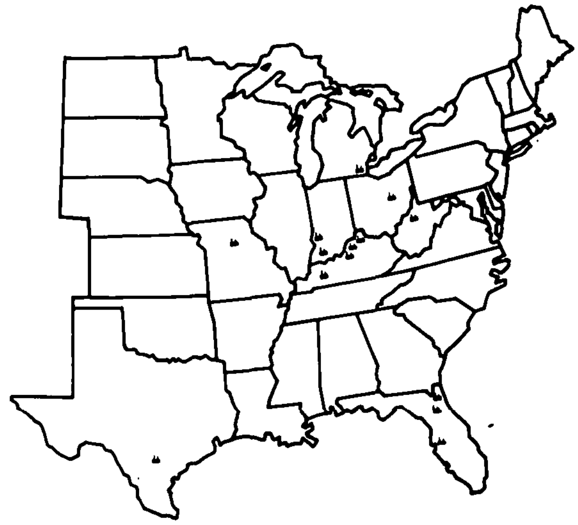

Figure S-2. Location of power plants used in the study.

Figure S-3. Location of cement plants.

Figure S-4. Location of wallboard plants.

of 100,000 to 500,000 ton/yr, with an average of about 250,000 ton/yr. Individual wallboard plant requirements are proprietary information and the requirements used in this study were determined and verified by indirect methods.

Power Plants

To provide an accurate representation of the production of FGD gypsum by utilities, the fuel, operating conditions, and emission regulations of 14 power plants were used to determine the gypsum production rates and FGD costs used in the marketing model. Their locations, relative to cement plants and wallboard plants, are shown in Figures S-3 and S-4, respectively. These were screened from all coal-fired power plants in the study area with boilers over 100 MW in size that were, or are scheduled to be, started up between 1960 and 1985 (104 power plants). The 14 power plants selected were among those best suited economically for use of gypsum-producing FGD strategy. All 14 power plants were calculated to have lower FGD costs for a gypsum-producing FGD process than for a waste-producing FGD process. The screening process consisted of comparing computer-generated costs of two limestone FGD systems based on the individual power plant fuel, boiler design, and emission regulations. One FGD system was a conventional limestone process producing a high-sulfite waste that was fixed with fly ash and lime and disposed of in a landfill. The other was an adipic-acid-enhanced limestone process incorporating in-loop forced oxidation in which the gypsum produced was washed and filtered to 90% solids. The process included stockpiling and loading facilities for 85% of the gypsum produced. Costs for landfill disposal of the remaining gypsum (representing off-quality production) and all of the fly ash (to make disposal costs comparable with the waste-producing process) were included. The cost differences, expressed as an "incremental cost" in $/ton of gypsum, were used in most of the evaluation as an important economic factor in the marketability of the FGD gypsum. The incremental cost was negative (that is, the gypsum process was less expensive) for all the power plants used in this study.

Gypsum Costs

Almost without exception, wallboard manufacturers control the source of their gypsum (rather than purchase from independent producers) whether it is domestic or foreign. The cost of gypsum is regarded as an operating cost passed on as a portion of the total manufacturing costs. Consequently, the cost of gypsum used in wallboard manufacture is low. Cement plants more commonly purchase gypsum from suppliers at a higher cost. The 1985 cost of domestic gypsum at the mine was projected to be 8.20 $/ton for wallboard plants and 15.60 $/ton for cement plants. The 1985 cost of imported gypsum for wallboard was projected to average 15.15 $/ton at the port of entry and ranged from 10.50 to 18.00 $/ton for individual ports. The same port of entry cost for cement plant gypsum, increased by estimated brokerage fees, was projected to average 19.71 $/ton and ranged from 18.00 to 21.00 $/ton.

Freight Costs

Freight costs for both natural gypsum and FGD gypsum are based on shipments by truck for distances up to 250 miles and shipments by railroad for distances greater than 150 miles. A truck freight rate of 1.30 $/ton was used for all distances up to 10 miles and 0.13 $/ton-mile for distances beyond 10 miles, based on a 23-ton load. Beyond short distances, truck freight rates do not differ greatly in terms of ton-miles so no adjustment for the distance shipped was made. Railroad freight rates decrease with distance, however. The railroad freight rates used varied from 0.13 to 0.10 $/ton-mile between 250 and 500 miles.

In contrast to bulk gypsum, the freight rates for wallboard differ considerably among the six railroad rate territories in the study area. For the evaluation of wallboard shipments, therefore, freight rates based on rates developed by TVA for the various intra- and interterritory shipments were used. These differ by a maximum of 125%, depending on the source and destination of the shipments.

Marketing Evaluations

The primary evaluation consisted of a determination of the extent to which the FGD gypsum could be marketed to cement and wallboard plants as a lower cost replacement of their natural gypsum supplies. A delivered cost of natural gypsum was established for each cement and wallboard plant. This served as the basis for an "allowable cost" for delivered FGD gypsum. If the FGD gypsum could be delivered at a cost less than the allowable cost, it was regarded as successfully replacing the natural gypsum supply. Several variations of this model were evaluated. In most of them, the delivered cost of the FGD gypsum was based on the premise that the objective of producing and marketing FGD gypsum was to reduce FGD costs and that the savings in using the gypsum-producing FGD process could be used in part to ensure sale of the gypsum, thus making use of the lower cost process practical.

The variations of this model evaluated are summarized below. Also listed is a different evaluation in which an aspect of the economic feasibility of manufacturing wallboard at sources of FGD gypsum was examined.

- Marketing of as-produced gypsum containing 10% water, with the incremental cost offsetting the freight costs and an allowable cost equal to 90% of the cost of the natural gypsum supply (to account for possible resistance to the water content). The individual marketing potential of each power plant without competition from other FGD gypsum and the marketing potential of all 14 power plants when marketing simultaneously were evaluated for three marketing conditions: sales only to cement plants, sales only to wallboard plants, and sales to both cement and wallboard plants.

- Marketing under all of the conditions above but without the incremental cost offsetting freight costs. This assumed that the gypsum-producing FGD process had no cost advantage over the waste-producing process. In this case, freight costs alone determined the delivered cost of the FGD gypsum.

- Marketing of gypsum dried to a water content of 2.5%, with the incremental cost offsetting the freight costs and an allowable cost equal to the cost of the natural gypsum supply. The cost of drying was added to the FGD costs, reducing the incremental costs by 4 to 6 $/ton, depending on the quantity dried. Only the marketing potential of all 14 power plants marketing simultaneously to both cement and wallboard plants was evaluated.

- Marketing of dried gypsum as above but with the portion of the gypsum sold to cement plants pressed into briquettes (to simulate natural lump gypsum). The briquetting costs were added to the FGD costs, further reducing the incremental costs.

- A different marketing model in which a stochastic array of distribution centers representing wallboard marketing areas was used to represent wallboard marketing in the study area. The freight costs of wallboard from existing wallboard plants and from the power plant locations were compared to examine the economics of locating wallboard plants at sources of FGD gypsum.

DISCUSSION OF RESULTS

In contrast to most byproduct FGD processes, the gypsum process used in this study was less expensive than the alternative waste-producing process for many power plants, a result of advances in forced-oxidation limestone FGD technology, the improved handling properties of gypsum, and the reduced disposal costs resulting from marketing the gypsum. The lower costs of the gypsum process greatly enhanced the marketability of the gypsum. Conditions that favored the adoption of a gypsum marketing strategy were a high flue gas SO_2 content and high SO_2 removal rates--typified by boilers with stringent emission limits that burn high-sulfur coal. FGD processes incorporating fixation and landfill were generally more economical for boilers with less stringent emission limits or that burned lower sulfur coal.

Market Characteristics

The cost of gypsum to cement plants averaged about twice the cost of gypsum to wallboard plants. There were also wide differences in gypsum costs among different geographical areas. These differences were an important factor in the marketability of the FGD gypsum. The inland trans-Mississippi and Great Lakes areas had the lowest gypsum costs, the Eastern Seaboard and Gulf Coast had higher costs, and the Appalachian area had the highest costs. In general, using incremental cost to offset freight costs, gypsum could be marketed to cement plants at distances up to 500 miles, with little difference in marketability between power plants in different areas. Gypsum could be marketed to wallboard plants under the same conditions at distances up to 250 miles, with the longer distances representing power plants with access to wallboard plants with higher gypsum costs.

Marketing Model Results

A summary of the gypsum marketing model and the results is shown in Table S-1. Without competition, each of the power plants could market all of its product to cement plants. Together, all of the plants could reach almost the entire cement plant market. However, the cement plant market has a limited capacity to absorb FGD gypsum; 10 power plants typical of those used in this study could supply the entire cement plant market. This is evident in the marketing model of the 14 power plants marketing simultaneously; gypsum was marketed to 95 cement plants, supplying 83% of the total cement plant requirement, but only 4 power plants could market all of their production, 2 had no sales, and only 60% of the total power plant production was marketed.

Without competition, all of the power plants also had sales to wallboard plants but only 11 could market all of their production. In contrast to the cement plant market, only a portion of the wallboard plant market could be reached; the power plants could market to only 20 of the 52 wallboard plants in the study area because of the shorter economical transportation distance. With the 14 power plants marketing simultaneously to wallboard plants, 12 power plants had sales to 17 wallboard plants, and 6 were to market all of their production. Competition was less important in limiting sales but location was more important than in the cement plant market.

With incremental cost offsetting freight costs and the 14 power plants marketing simultaneously to both cement and wallboard plants, the results were largely additive as compared with the individual markets; 4.35 million ton/yr of gypsum was marketed to 79 cement plants and 14 wallboard plants at a savings of 110 million $/yr. Twelve plants marketed all of their production and only one had insignificant sales. The sales met 63% of the cement plant requirements and 20% of the wallboard plant requirements, with both volume and savings divided almost equally between the markets.

Without the incremental cost to offset freight costs, sales to distant cement plants and wallboard plants were substantially reduced. Without competition, only about one-half of the power plants was able to market all of their production to either the cement plant market alone or the wallboard plant market alone. In the combined market, 3.23 million ton/yr of gypsum was marketed to 52 cement plants and 10 wallboard plants at a savings of 30 million $/yr. All power plants had sales and seven marketed all of their production. The primary effect of the elimination of incremental cost was to eliminate the more distant markets, particularly in the cement plant market. Location became much more important in marketing success since proximity to a wallboard plant was necessary to market all of the production of most of the power plants.

TABLE S-1. SUMMARY OF GYPSUM MARKETING RESULTS

Power plant County, State	Incremental cost, $/ton	Sales with incremental cost, kton/yr: Cement plants only	Wallboard plants only	Cement and wallboard plants: Cement	Wallboard	Total	Dried[a]	Dried and briquetted[b]	Sales without incremental cost, kton/yr: Cement plants only	Wallboard plants only	Cement and wallboard plants: Cement	Wallboard	Total
Pleasants, W. Va. (307 kton/yr)	-19	292	None	307	None	307	307	307	108	None	108	None	108
Coshocton, Ohio (483 kton/yr)	-20	483	128	355	128	483	483	483	162	128	162	128	290
Monroe, Mich. (700 kton/yr)	-18	357	700	156	544	700	700	700	156	452	156	452	608
Boone, Ky. (197 kton/yr)	-13	None	None	29	None	29	None	None	32	None	32	None	32
Trimble, Ky. (166 kton/yr)	-23	53	85	81	85	166	166	166	51	None	51	None	51
Jefferson, Ky. (577 kton/yr)	-24	206	163	334	243	577	577	577	53	None	53	None	53
Muhlenberg, Ky. (544 kton/yr)	-18	165	170	186	170	356	444	356	243	170	271	170	441
Pike, Ind. (254 kton/yr)	-20	None	254	None	254	254	254	254	32	254	32	222	254
Sullivan, Ind. (282 kton/yr)	-21	235	282	80	202	282	282	282	100	282	54	228	282
Randolph, Mo. (363 kton/yr)	-16	363	170	302	61	363	363	363	273	None	273	None	273
Atascosa, Tex. (222 kton/yr)	-22	222	153	222	None	222	222	222	222	None	222	None	222
Hillsborough, Fla. (160 kton/yr)	-20	160	160	89	71	160	160	160	89	160	89	71	160
Putnam, Fla. (271 kton/yr)	-26	242	271	28	243	271	271	271	None	271	None	271	271
Duval, Fla. (182 kton/yr)	-22	60	182	None	182	182	182	182	63	182	None	182	182
(4,708 kton/yr)		2,838	2,718	2,169	2,183	4,352	4,411	4,323	1,584	1,899	1,503	1,724	3,227
% of total market		83	25	63	20	31	31	30	46	18	44	16	23

Note: All gypsum quantities are dry weight, 100% gypsum. Except as noted, all sales are as-produced gypsum containing 10% water and the allowable cost is 90% of the cost of the natural gypsum supply.

a. Sales of gypsum dried to 2.5% water to cement and wallboard plants with an allowable cost equal to the cost of the natural gypsum supply.
b. Sales of gypsum dried to 2.5% water to wallboard plants and dried and briquetted gypsum to cement plants with an allowable cost equal to the cost of the natural gypsum supply.

Drying the gypsum produced had little effect on sales or total savings. Drying reduced freight costs, which for the more distant markets, sometimes offset the drying costs. Similarly, briquetting the dried gypsum sold to cement plants had little effect on sales volume although it reduced the savings.

Location of Wallboard Plants at Power Plant Gypsum Sources

The possibility of locating wallboard plants at power plant sources of gypsum is an appreciably more complicated and hypothetical question than the marketing of gypsum in the conventional marketing structure evaluated in the foregoing studies. It depends, for example, not only on the economics of the gypsum supply but on the economics of marketing the finished product, which need not be a part of a gypsum marketing study. Only one aspect of the potential for relocation of wallboard plants to power plant gypsum sources was investigated in this study: the freight costs for wallboard from power plants to marketing areas were compared with the freight costs from existing wallboard plant locations to the same marketing areas. This was accomplished by developing a model using the 14 power plants and a system of 43 hypothetical regional wallboard distribution centers, shown in Figure S-5.

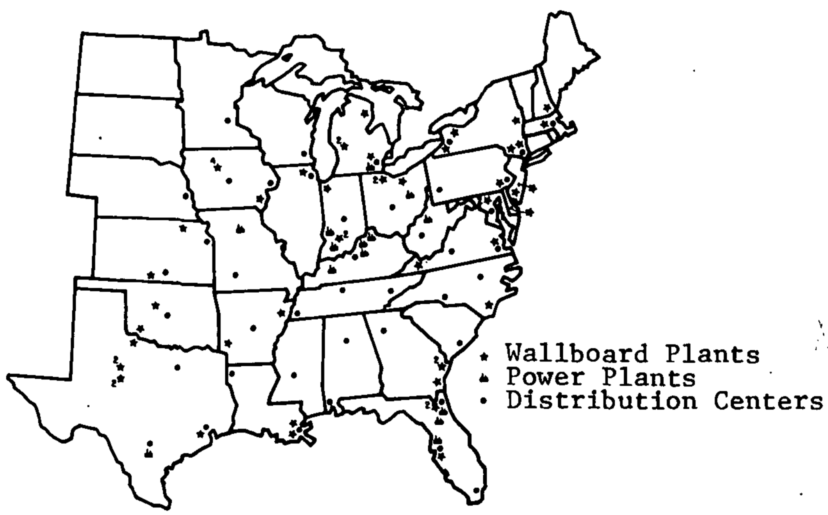

Figure S-5. Locations of wallboard plants, power plants, and hypothetical distribution centers.

The model results, shown in Table S-2, indicate that in some cases the manufacture of wallboard at power plant locations has the potential for substantial reductions in freight costs. About one-half of the total power plant production could be used to manufacture wallboard competitive with wallboard from existing wallboard plant locations. In most cases, the power plant wallboard replaced wallboard from distant wallboard plants, either because there were no wallboard plants in the marketing area or because the local supply was inadequate. The results appear to indicate a moderate economic potential for the relocation of wallboard plants but it is apparent that they were influenced by the power plant locations--which in some cases were not particularly well suited to serve as gypsum sources in areas without natural gypsum deposits (note, in Figure S-4, the absence of gypsum-producing power plants in the inland Southeast). Nor do the results indicate the full potential for wallboard plant relocation since they do not reflect the possible additional advantages of a more economical gypsum supply.

CONCLUSIONS

Advanced limestone FGD gypsum-producing processes are economically competitive with processes that produce a fixed waste. These processes have enhanced the prospects for marketing FGD gypsum since the gypsum process does not necessarily require sales revenue to make it economically competitive with other FGD processes in cases in which waste disposal is difficult and expensive. The sales revenue--and savings from the use of the gypsum process itself in some cases--can be an added economic inducement to gypsum marketing or used in part to offset marketing costs.

The only gypsum markets capable of supporting a general production of FGD gypsum are the portland cement and wallboard industries. The 114 cement plants east of the Rocky Mountains could consume the production of about 10 power plants typical of those used in this study and the 52 wallboard plants in the same area could consume the production of about 32 similar power plants. With the FGD cost savings offsetting freight costs, gypsum could be marketed to cement plants within a radius of about 500 miles and to wallboard plants within a radius of about 250 miles.

All of the marketing model evaluations in this study can be regarded as successful. With the FGD cost savings offsetting freight costs and without direct competition, all of the power plants could market all of their production. With all power plants marketing simultaneously, all but two of the power plants were able to market all of their production in spite of extensive competition. Drying and briquetting had little effect on the marketability of the gypsum. Without FGD cost savings offsetting freight costs, total sales were reduced by about one-fourth and savings by about three-fourths but seven power plants were able to market all of their production. As an alternate to marketing to existing wallboard plants, relocation of wallboard plants to sources of power plant gypsum would, in some cases, reduce the costs of shipping wallboard to marketing areas.

TABLE S-2. POWER PLANT WALLBOARD SUPPLY TO REGIONAL DISTRIBUTION CENTERS

Power plant county, state	Gypsum equivalent shipped kton/yr	Distribution center	Freight savings, k$/yr
Pleasants, W. Va. (307 kton/yr)	203	Pittsburgh, Pa. Roanoke, Va. Charleston, S.C.	2,415
Coshocton, Ohio (483 kton/yr)	483	Pittsburgh, Pa. Columbus, Ohio	4,629
Monroe, Mich. (700 kton/yr)	94	Detroit, Mich.	489
Boone, Ky. (197 kton/yr)	None		
Trimble, Ky. (166 kton/yr)	None		
Jefferson, Ky. (577 kton/yr)	135	Louisville, Ky. Knoxville, Ky.	1,020
Muhlenberg, Ky. (544 kton/yr)	207	Nashville, Tenn. Birmingham, Ala.	3,748
Pike, Ind. (254 kton/yr)	None		
Sullivan, Ind. (282 kton/yr)	148	Chicago, Ill.	385
Randolph, Mo. (363 kton/yr)	275	St. Louis, Mo. Springfield, Mo.	1,926
Atascosa, Tex. (222 kton/yr)	222	San Antonio, Tex.	5,484
Hillsborough, Fla. (160 kton/yr)	160	Tampa, Fla.	3,536
Putnam, Fla. (271 kton/yr)	271	Tampa, Fla. Miami, Fla.	884
Duval, Fla. (182 kton/yr)	None		
(4,708 kton/yr)	2,198		24,516

Without competition from other power plants, most of the power plants in the study area for which a gypsum process is more economical than a waste-producing process could successfully market to cement plants, regardless of the power plant location, and some could market successfully to wallboard plants, although power plant location would be a factor in marketing to wallboard plants.

In a competitive situation with several power plants marketing FGD gypsum, competition would limit sales in some cases. The cement plant marketing structure would be quite fluid, subject to the activities of other, often distant, power plants. Competition in the wallboard plant market would be more localized and, in some cases, less severe because of the large gypsum requirements of wallboard plants and the tendency in some cases for wallboard plants to be clustered at sources of gypsum, creating very large localized gypsum requirements. The evaluation excludes site-specific situations that could have large effects on the comparative economics of the processes, however, and does not substitute for a site-specific study in individual situations.

FGD gypsum marketing differs from the marketing of other FGD byproducts such as sulfur and sulfuric acid. For example, gypsum-producing FGD processes are not dependent on sales revenue for their economic justification. In many cases, simple removal of the gypsum at no cost is sufficient to justify adoption of the process and, in some cases, the savings in FGD costs by adopting a gypsum-producing process could be used to supplement freight costs, thus enhancing the marketability of the gypsum. On the other hand, other FGD byproduct processes usually involve much higher costs, to the point that sales revenue is an integral and important factor in their economics, making them more vulnerable to market conditions. However, even widespread adoption of byproduct processes that produce sulfur and sulfuric acid would supply only a small portion of the market requirements. This is in contrast to the situation which could exist by a similar adoption of gypsum processes. In this case, the FGD gypsum supply would saturate the market (exceed the market requirements) and would result in intense competition.

RECOMMENDATIONS

The site-specific nature of power plant waste disposal economics has been widely and frequently commented upon; the situation is familiar to those who have evaluated these economics and has been well illustrated by the many studies that have been published. This general study--which excludes or uses representative averages for the many such site-specific situations that cannot be readily quantified or which would detract from a general overview--suggests that corresponding site-specific studies for specific situations should be performed for those faced with the necessity of disposing of FGD products.

Some of the specific conditions that should be included in such studies (which in this study have been assigned average values or which are assumed to be unnecessary in a general study) are: the actual production rates based on projected capacity and unit lives; land costs and availabilities; retrofit factors for existing units; actual allowable disposal practices, which differ among states; and other necessary costs, such as upgrading of existing equipment. All of these factors could have important effects on the costs of gypsum production and marketing versus production of a waste. In addition, this study has shown that both location and the potential of competition are important considerations. These factors too should be considerations in a site-specific study.

There is also a factor of industry acceptance that is difficult to quantify on economic or technical bases: the apparent reluctance--or inertia--of potential users to abandon traditional sources of raw materials without inducements other than a lower cost (which at best is all that FGD gypsum could offer either wallboard or cement plant operators). If this cannot be quantified, neither should it be ignored in any assessment of FGD gypsum marketing prospects.

INTRODUCTION

This is an Environmental Protection Agency (EPA) sponsored study to evaluate the potential for the production and sale of flue gas desulfurization (FGD) byproduct gypsum as an option for utility power plants in the 37 eastern states. It was prompted by recent changes in FGD technology and practices and in the major gypsum-using industries that suggest an increased potential for the use of FGD byproduct gypsum. Power plants in the 37 eastern states were screened to identify those whose emission regulations, fuel, and operating conditions make forced-oxidation limestone FGD processes producing gypsum economically competitive with other emission control options. The potential for sale of the gypsum to wallboard and cement plants as a lower cost substitute for their existing supplies was then determined. The study is based on conditions projected to 1985 to provide information more useful for planning emission control strategies.

This study is based on published information available through 1982 on the type of coal used by utility power plants and the emission control regulations to which they are subject. This and the general geographic locations provide a representative gypsum production model. Actual site-specific conditions and existing or planned emission control and waste disposal practices that would affect the economics of gypsum marketing at specific power plants are not considered because the study is an assessment of FGD gypsum marketing in general.

For the past several years, the Tennessee Valley Authority (TVA) has conducted similar studies for EPA to evaluate the potential of various byproduct-producing FGD processes. The studies were modeled on actual power plant and marketing conditions, and predicated on the assumption that the power plants have several options for meeting SO_2 emission control regulations. Usually the options considered were the use of a higher cost low-sulfur coal, a waste-producing limestone FGD system, and a FGD system producing a byproduct in which the revenue from the byproduct compensated for some of the FGD costs. The general model consisted of a comparison of the costs of the FGD options based on the actual power plant emission limitations, coal used, and operating conditions. The revenue from the byproduct sales was determined using transportation cost models and potential use of the byproduct by existing consumers as a lower cost substitute for their existing supply. The extent to which markets for the byproduct could be found, and the extent to which the byproduct-producing process was the lowest cost option, represented the potential for use of the byproduct-producing process as a practical SO_2 emission control option.

Several byproduct marketing studies have been made for sulfuric acid, historically an objective of much FGD development effort, and the byproduct that attracted the most interest in the early and middle 1970s. The last byproduct marketing study, a projection to 1985 (1), also included byproduct sulfur as interest in sulfur-producing processes increased in the late 1970s. Only one FGD gypsum marketing study was made (2), reflecting the low regard for the potential of FGD gypsum in competition with low-cost, natural gypsum (particularly in the closely controlled, vertically integrated wallboard industry, which consumes most of the gypsum produced) and the lack of simple and economical gypsum-producing FGD processes. In this 1978 study, the prospects for FGD gypsum sales appeared poor in comparison with other FGD byproducts. A similar byproduct sulfuric acid study, also projected to 1978 and using the same modeling procedures, projected sales of over three times as much sulfuric acid, for example (3).

In recent years a somewhat different perspective has emerged, one which suggests that FGD gypsum may play a role in the gypsum industry. The composite mine value of natural gypsum has increased appreciably, from 4.58 $/ton in 1975 to 8.66 $/ton in 1981 (4). Also, gypsum users, particularly wallboard manufacturers, now regard FGD gypsum with more interest (5). Several wallboard manufacturing tests with FGD gypsum have been made with favorable results; FGD gypsum is considered one of the most promising byproduct gypsums for wallboard manufacture (6).

Gypsum-producing FGD technology has also developed substantially. Generic limestone processes that incorporate forced oxidation in existing designs with only marginal increases in cost have been developed and several have been demonstrated (7). In comparison with other byproduct-producing processes, including the many two-stage gypsum processes in foreign use, these processes are much less expensive. Most FGD vendors now offer forced-oxidation versions of their basic processes and several systems have been, or are being, installed in utility applications (8). In at least two cases, the forced-oxidation processes were selected with the intention of marketing the gypsum produced.

The potential for FGD byproduct marketing has also been affected by the development of environmental regulations. The revised new source performance standards (NSPS) promulgated in 1979 require a reduction of 70% to 90% in SO_2 emissions for all power units upon which construction began, or begins, after September 1978, regardless of the sulfur content of the coal used (9). The 1979 NSPS essentially preclude low-sulfur coal as an emission control option for these plants and, in many cases, make FGD mandatory since it is the only practical method for attaining emission reductions of these magnitudes with most U.S. steam coals. The influence of solid waste regulations stemming from the Resource Conservation and Recovery Act of 1976 (Public Law 94-580) is less well defined. Utility wastes such as fly ash and FGD waste are presently excluded from hazardous waste regulations pending the development of additional data upon which to base regulations (10). Anticipated environmental restrictions, as well as the practical difficulties of high-sulfite sludge disposal, have, however, led to increasing use of sludge fixation processes or forced oxidation and decreasing use of low-cost pond disposal of untreated wastes (11). With pond disposal limited, gypsum-producing processes are economically competitive with processes that produce a high-sulfite waste (12).

This byproduct marketing study incorporates these developments. The SO_2 emission control options used are a generic limestone FGD process with in-loop forced oxidation and a similar limestone process without forced oxidation using fixation and landfill waste disposal. The selection of power plants began with a screening, using computer-generated FGD costs, of all coal-fired power plants over 100 MW in size that were scheduled to be in operation in the 37 eastern states, and less than 25 years old, in 1985. About 50 power plants had a combination of emission regulations, fuel, and boiler characteristics that made a gypsum-producing process the most economical FGD system, excluding site-specific factors. Further screening (elimination of plants with commitments to emission control strategies incompatible with FGD or using simultaneous collection of fly ash and SO_2, for example) produced the 14 power plants in 8 states used in the study. All had lower calculated FGD costs for gypsum-producing processes than for processes using fixation and landfill waste disposal.

In recognition of the growing importance of transportation costs, two paradigms were used. The first, which constitutes the major portion of this study, was based on the shipment of gypsum to wallboard and cement plants at their existing locations. The second was a limited conceptual analysis based on a relocation of wallboard plants to the power plant source of the byproduct gypsum, with shipment of the wallboard to hypothetical regional sales distribution centers in the marketing areas. It is essentially an analysis of a partial change from a wallboard manufacturing industry structure centered on mines and import points to a structure centered on byproduct sources. This is conceivable since the wallboard industry is already strongly influenced by the source of raw materials and the cost of bringing a new mine into production can be a major cost in developing a new wallboard plant (13). In addition, the production rate of a gypsum-producing utility FGD installation is frequently in the range of the consumption of a typical wallboard plant.

The marketability of the gypsum produced by each of the power plants to consumers at existing locations was based on the ability to supply gypsum to a consumer at a cost lower than that of his existing supply and with a FGD cost to the power plant less than the FGD cost of the alternative fixation and landfill process. The basic evaluation assumed sale of crystalline as-produced gypsum containing 10% water. The effect of drying the crystalline gypsum for both markets and drying and briquetting the gypsum for cement plants was also evaluated.

The potential market was limited to wallboard and cement plants expected to be in operation in 1985. These can be readily identified by location and consumption so that transportation costs can be accurately determined. Since they account for well over 90% of all gypsum consumption, the exclusion of the many dispersed low-volume users does not materially affect the results of the study. Transportation costs were based on actual truck and rail freight rates for the areas involved, obtained from published information or developed by TVA.

BACKGROUND

Gypsum, $CaSO_4 \cdot 2H_2O$, the dihydrate, is the stable form of calcium sulfate under the normal conditions found at the surface of the earth. It has the useful property of readily giving up some of its combined water when heated to a moderate temperature, and of quickly reverting to the dihydrate form when mixed with water at a lower temperature to form a hard, consolidated mass. This, and the widespread occurrence of natural gypsum, have made it a major construction material throughout recorded human history.

A gypsum molecule loses 1-1/2 molecules of water at 262°F at standard conditions, forming the hemihydrate:

$$CaSO_4 \cdot 2H_2O \longrightarrow CaSO_4 \cdot 1/2H_2O + 1\text{-}1/2H_2O$$

The hemihydrate thus produced by calcination is called stucco or calcine in industrial terminology and has the common name, plaster of paris. Two forms are recognized (14), the alpha form, which is produced when gypsum is heated in water or a steam atmosphere, and the beta form, which is produced when gypsum is heated under conditions that maintain an atmosphere that is low in water. The alpha form requires less water to slurry and forms a denser, stronger cast. Most commercial processes produce stucco containing some proportion of the beta form but there are several processes that produce only the alpha form for special uses.

Further heating to 325°F at standard conditions produces the anhydrite:

$$CaSO_4 \cdot 1/2H_2O \longrightarrow CaSO_4 + 1/2H_2O$$

A "soluble anhydrite" is produced below about 392°F. It is a powerful desiccant and is widely used as a drying agent. It also readily forms the dihydrate when mixed with water but it has no significant advantages over stucco for most industrial uses. A "dead burned" anhydrite is produced by heating to about 1,600°F. It is used to produce some plasters and also as a whitening agent and filler in some manufacturing processes.

Uncalcined natural gypsum was used in earliest recorded history (15) as a construction material and as a medium for carvings and decorations. The Egyptians invented a crude form of calcining and used gypsum to produce stucco as well as for a construction material. Stucco was used as mortar in the Great Pyramid of Cheops and the exterior was sheathed with alabaster, an aesthetically pleasing crystalline form of gypsum (16). By the 18th century, gypsum was also being used in Europe as a soil conditioner called land plaster. The use of stucco for construction was limited by its rapid (25 to 30 minute) setting rate. A better understanding of gypsum chemistry in the 18th century led to the production of set retarding agents and gypsum-based plaster quickly became a standard wall surfacing (17). These developments originated in France, where there are vast gypsum deposits in the Paris Basin, hence the name, plaster of paris, for the hemihydrate. In the early 20th century, technology to cast gypsum into sheets was developed and gypsum wallboard replaced plaster as the predominate wall covering in the 1930s (18). Wallboard is now used almost universally for wall surfacing and accounts for most of the gypsum consumption in the world. The development of portland cement also created another need for gypsum, which is required in small amounts to modulate the setting rate of the cement. These uses, and minor agricultural uses, account for almost all of the gypsum consumed. The demand is met by mined gypsum and, in some cases, by byproduct gypsum from manufacturing processes.

NATURAL GYPSUM

Natural gypsum is an evaporite mineral selectively precipitated when seawater is concentrated by evaporation in restricted basins. This is not an uncommon geological occurrence, the nature of which tends to produce thick beds of high-grade gypsum that often extend over wide areas. Beds over 30 feet thick, containing over 80% gypsum, and extending over dozens or hundreds of square miles are common in many parts of the world. The world reserves of gypsum, including those of the United States, are regarded as virtually inexhaustible (19). The reserve base--"that part of an identified resource that meets specified minimum...criteria related to current mining and production practices..." (20)--in the United States, Canada, and the world, in tons, is:

United States	700,000,000
Canada	410,000,000
World	2,400,000,000

In the United States, commercial gypsum deposits occur in most parts of the country (19) with the exception of the Southeast and Eastern Seaboard. The main deposits occur in the Great Lakes region, associated with the Michigan Basin and Silurian Basin; in the Gulf Coast embayment area of inland south Texas, Louisiana, and Arkansas; in the Permian Basin area of New Mexico, north Texas, Oklahoma, and Kansas (where gypsum deposits extend for 200 miles from Texas into Kansas); in Iowa (where 70 square miles of Webster County is underlain by gypsum deposits 30 feet thick); in southern Indiana; and in several basins in the Rocky Mountains and Great Basin. The 11 western states, not included in this study, produced 30% of the 11.5 million tons of gypsum mined in the United States in 1981. California accounted for about 40% of this production but gypsum was mined in all of the 11 western states except Oregon. Gypsum was mined in 12 of the 37 eastern states included in this study, as shown in Figure 1. In addition to California, which ranked second in national production, the leading states were Texas (which ranked first), Iowa, Oklahoma, and Michigan.

Figure 1. Gypsum mines in the 37 eastern states.

Nationwide in 1981, 45 companies produced gypsum at 70 mines in 22 states (21). The leading companies were United States Gypsum Co. (12 mines), National Gypsum Co. (6 mines), Georgia-Pacific Corp. (6 mines), Celotex Division of Jim Walter Corp. (3 mines), Genstar Building Materials Co. (3 mines), and Weyerhaeuser Co. (1 mine). These companies produced 78% of the gypsum mined. Almost all of the remaining mines produced and sold only uncalcined gypsum for portland cement or agricultural use and thus accounted for only a small portion of the total gypsum mined.

BYPRODUCT GYPSUM

Enormous quantities of byproduct gypsum--also called chemical gypsum to differentiate it from natural gypsum--are produced in various manufacturing processes. Most of it is produced by the phosphate fertilizer industry as a byproduct of phosphoric acid manufacture. About 30 million tons of waste gypsum called phosphogypsum is produced each year by the phosphate fertilizer industry in Florida alone, where over 300 million tons of phosphogypsum has been discarded in stacks (22). Byproduct gypsum is also produced in the manufacture of titanium dioxide and several industrial acids (6). In general, byproduct gypsum has found very limited use in countries with abundant natural gypsum such as the United States and Canada (23). The indifference of gypsum consumers to byproduct gypsum has led many byproduct gypsum producers to regard it as a waste and make little effort to improve its quality.

Extensive efforts have been made, particularly by the phosphate fertilizer industry, to find uses for this gypsum, but with little success. Most of the byproduct gypsum used in the United States is used for agricultural applications which do not require high-quality gypsum. Large-scale use of phosphogypsum for wallboard and cement manufacture faces formidable obstacles because of its chemical and physical properties. The phosphoric acid manufacturing processes used by the phosphate fertilizer industry in the United States are designed for economic acid production without regard to the quality of gypsum produced. Consequently, the gypsum has several undesirable properties, including a poor crystal morphology, a low pH, a high phosphorous content, and a high concentration of radionuclides (6). It is not regarded as suitable for manufacturing purposes unless it is reprocessed. In contrast, FGD gypsum has been evaluated by several wallboard manufacturers and found to be equal or superior to natural gypsum for their purposes, if produced with the intent of marketing (24).

In countries with little natural gypsum, however, byproduct gypsum has been readily adopted by gypsum-consuming industries. In Japan, which has only scarce, low-grade gypsum deposits, byproduct gypsum is routinely used for wallboard and cement manufacture. The Japanese phosphate fertilizer industry uses processes designed to produce high-quality gypsum and its byproduct gypsum has been used in manufacturing since 1931. The Japanese FGD industry has been, from its beginnings, also directed toward production of high-quality gypsum. In 1979, the total production of byproduct gypsum in Japan was 6.4 million tons, including 2.2 million tons of FGD gypsum and 4.1 million tons of phosphogypsum and other byproduct gypsum. This, with stockpiles and 36,000 tons of imported gypsum, met the consumption of about 6.6 million tons. As a result of increased byproduct gypsum supplies, production of natural gypsum in Japan declined steadily from about 0.6 million tons in 1970 and ceased in 1977 (25).

USES OF GYPSUM

Gypsum has two major uses: the production of stucco, from which plasters and prefabricated construction materials are made, and as a minor ingredient in portland cement to retard the setting rate. Together these uses account for over 90% of the gypsum consumed. Most of the remaining gypsum consumed is used as a soil amendment and conditioner for some types of crops and certain soils. Normally in the United States about 70% of the gypsum consumption is used to produce stucco. About 20% is used in portland cement and 7% is used in agriculture (26).

The apparent consumption of crude gypsum in the United States in 1981 (27) was about 19 million tons, 14% of the world consumption. About 5.3 million tons, including 3.6 million tons used in portland cement and 1.5 million tons used in agriculture, was not calcined. The remainder was calcined to stucco, about 90% of which was used to manufacture wallboard. This consumption was met by the domestic mine production of 11.5 million tons, imports of about 7.6 million tons, and 0.7 million tons of byproduct gypsum from the chemical industry that was used in agriculture. These quantities represent a significant decrease in consumption since the late 1970s because of a decrease in construction activity. In the period from 1978 to 1980, for example, the apparent consumption was 24 million to 21 million ton/yr (26).

There is little international trade in gypsum because of its widespread occurrence and low cost, which makes transportation of gypsum over long distances uneconomical, particularly by land. The absence of gypsum deposits on the Eastern Seaboard and Gulf Coast, both areas of large consumption, has created an extensive import trade in the United States, however. Gypsum transported by sea from Canadian mines on the Atlantic and Mexican mines on the Gulf of Mexico is more economical in these areas than gypsum from inland domestic mines. This trade has made the United States the leading importer and Canada the leading exporter in the world (14). Figure 2 shows the major import points for this gypsum.

The importance of transportation costs of both the raw materials and the products has shaped the structure of both the wallboard and portland cement industries. Although a few companies account for most of the production, the manufacturing facilities are geographically dispersed, as shown in Figures 3 and 4, to minimize transportation costs. Wallboard plants usually have gypsum consumptions of 100,000 to 500,000 ton/yr and the average consumption is about 250,000 ton/yr. Typically they are located at the source of the gypsum, either a mine or an import point, as shown in Figure 5. In 1981 (27), 14 companies calcined gypsum at 72 plants in 30 states. Nationwide, the leading

Figure 2. Gypsum import points in the 37 eastern states.

Figure 3. Locations of wallboard plants in the 37 eastern states.

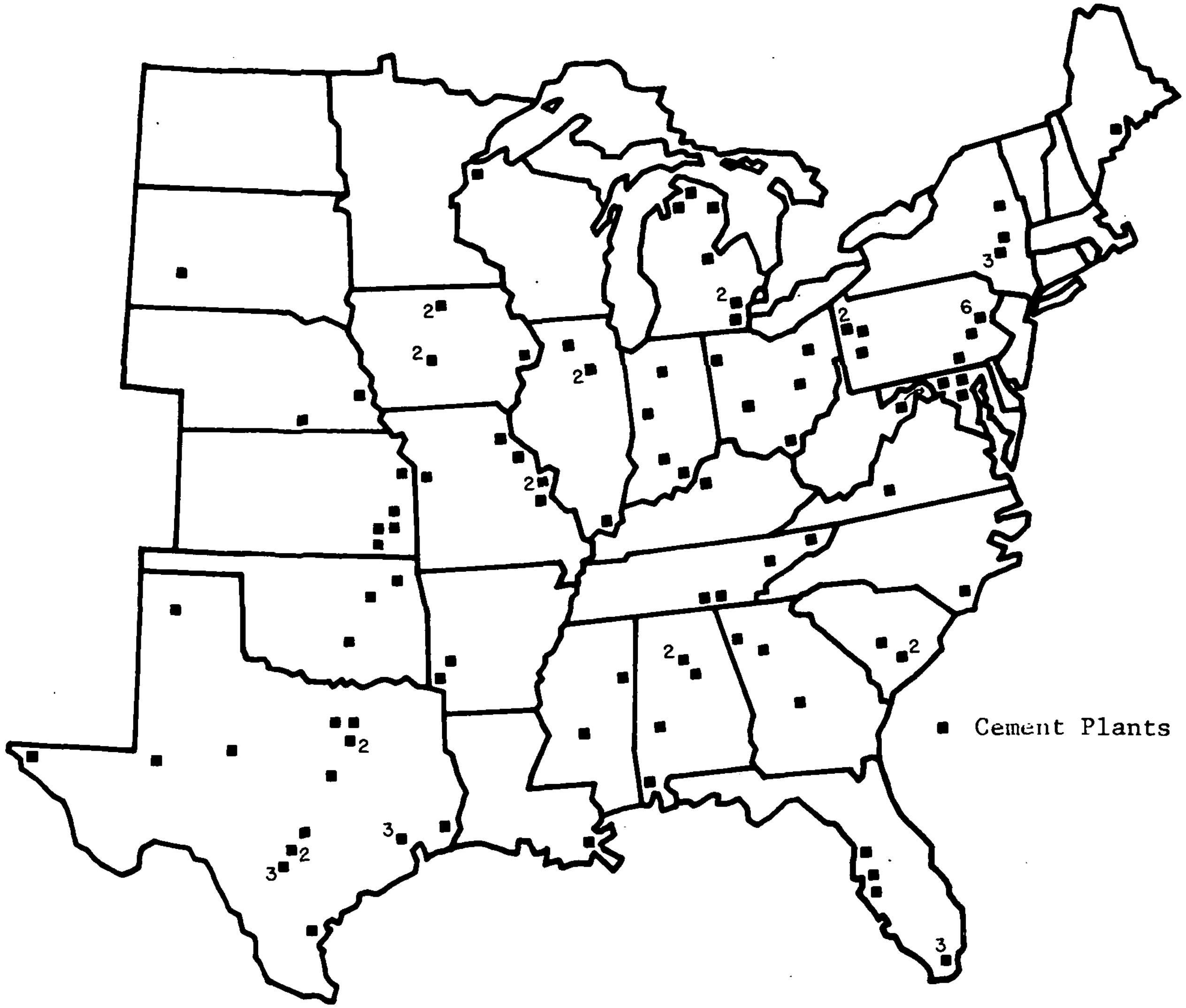

Figure 4. Locations of cement plants in the 37 eastern states.

Figure 5. Locations of gypsum mines, gypsum import points, and wallboard plants in the eastern 37 states.

companies were United States Gypsum Co. (22 plants), National Gypsum Co. (19 plants), Georgia-Pacific Co. (9 plants), Genstar Building Materials Co. (6 plants), and Celotex Division of Jim Walter Corp. (4 plants). These companies accounted for 85% of the calcined gypsum produced. In almost every case, the companies calcining gypsum also controlled the source of the gypsum, whether nearby or remote.

Cement plants are usually located at the source of the major raw materials such as limestone and shale since it is more economical to transport the relatively small quantities of gypsum used. In 1979, the last year for which nationwide data are available, 153 plants operated by 50 companies produced about 75 million tons of clinker, from which about 82 million tons of portland cement and 3.8 million tons of masonry cement were manufactured (28). Cement was produced in 39 states, with California, Texas, Pennsylvania, Michigan, Missouri, and Florida accounting for almost one-half of the production. No company served a national market and the largest plant had only 7% of the total production capacity, but the 10 largest companies accounted for over 70% of the production capacity. In 1981, there were 114 operating cement plants in the 37 eastern states. In addition to serving a local market, some plants shipped bulk cement by barge and rail to distant distribution centers (29).

Cement plants are much more uniformly distributed geographically than wallboard plants, reflecting the wider distribution of the major raw materials. Cement plants are also found far from sources of gypsum, as is evident in Figure 6 showing the locations of gypsum sources and cement plants. A number of plants are located in the inland Southeast and Appalachian area, for example, where only one source of gypsum and one wallboard plant are located.

Gypsum Wallboard Manufacture

Gypsum wallboard is widely used as an interior wall and ceiling surfacing material in the construction industry. It consists of a uniform gypsum plaster core with a special paper facing and backing that can be economically installed in sheets and the joints finished to form a smooth surface suitable for paint or wall covering. It has largely replaced gypsum plasters once used for the same purpose. The primary advantages are its low cost, ease of installation, light weight, dimensional stability, and fire resistance. Gypsum wallboard is commonly produced in 4- by 8-foot sheets from 3/8 to 5/8 inches in thickness but other sizes and thicknesses and special shapes are common. In 1981, the U.S. manufacturing capacity was 19 billion square feet at about 70 wallboard plants. About 14 billion square feet of wallboard was produced (27). Little literature on wallboard manufacturing technology other than general discussions (18) and patents exists. The basic manufacturing process consists of casting a slurry of stucco between moving strips of paper as the papers converge and pass through forming rolls. The continuous length of board is supported on a moving belt for 4 to 6 minutes until it sets. It is then cut into the desired lengths and the individual sheets are dried,

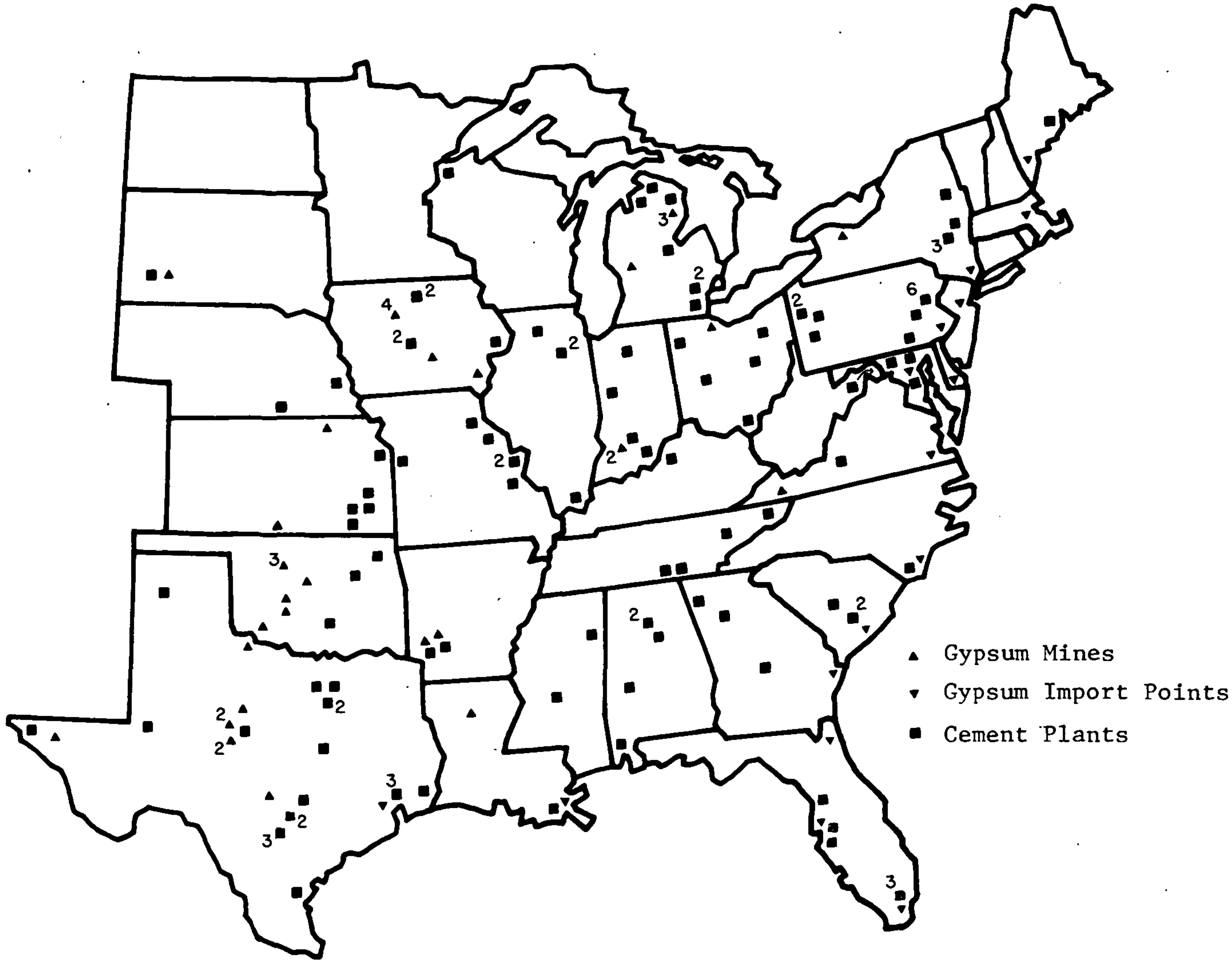

Figure 6. Locations of gypsum mines, gypsum import points, and cement plants in the 37 eastern states.

after which they are subjected to various finishing and packaging operations. The entire process is continuous and operates at up to 200 ft/min on a 3-shift basis.

Of the three main uses of gypsum, wallboard manufacture makes the most stringent demands on the properties of the gypsum. Factors that affect the properties of the slurry or the finished board must be carefully controlled. Among these are the calcining characteristics that affect slurry properties such as flow characteristics and setting rate and impurities that could cause poor bonding of the paper, reduced strengths, and efflorescence and discoloration. Among these are the particle size, which determines the slurrying properties, and soluble salts, even at low levels. Typical specifications for gypsum used for wallboard manufacture are shown in Table 1. Wallboard manufacturers control raw gypsum properties to some extent by selective mining and blending. They also have extensive experience in the use of additives to modify the effects of gypsum properties.

TABLE 1. WALLBOARD MANUFACTURER GYPSUM SPECIFICATIONS

	A		B		C	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
$CaSO_4 \cdot 2H_2O$, %			94		90	
$CaSO_3$, %	43					
CaO, %	30	33				
pH	6.5	8.0	6	8	3	9
Soluble Na, ppm						
Soluble Mg, ppm						
Soluble Cl, ppm						
Combined water, %	19.4				18.5	
Free water, %		16		20		10

Note: Particle size is variously specified by mean dimension (30 to 50 micrometers), area and aspect ratio (2,000 or more square micrometers, obtained by multiplying the x and y axes, with $x/y < 10$), or by Blaine fineness (3,000 or less). FGD gypsum crystals are usually 50 to 250 micrometers long, with an average of 130 micrometers and 40 to 60 micrometers wide and have aspect ratios of about 3 (30). Some companies also specify limitations on other constituents such as organic carbon (less than 1,000 ppm), fluorine (less than 200 ppm), fly ash (less than 3%), and soluble PO_4^{3-} (less than 200 ppm). A, B, and C represent different wallboard manufacturers. (Adopted from information provided by D. D. Clasen, Chiyoda International Corp., to R. L. Torstrick, TVA, in March 1981.)

A flow diagram of a generalized wallboard plant is shown in Figure 7. The basic operation consists of drying and pulverizing the gypsum rock, calcining the pulverized gypsum to stucco, preparing a slurry of the stucco and other additives, and the wallboard manufacturing process itself. In the example shown, run-of-mine gypsum in sizes up to 5 inches is crushed to about 1-1/2 to 3/4 inches and dried to about 5% free moisture at 400°F to 500°F in a rotary drier. The dried gypsum is then pulverized so that about 65% will pass 325 mesh. The pulverized gypsum is called land plaster because it is the type used in agriculture. The pulverized gypsum is calcined in a continuous calciner in the example shown because this type of calciner is replacing the older kettle-type calciners. The calciner consists of tiers of horizontal vessels each containing an oil-heated screw conveyor. The pulverized gypsum is added to the top tier and moves progressively, back and forth, downward until it emerges from the bottom at about 300°F to 320°F as stucco. The stucco consists of about 87% hemihydrate; the remainder is uncalcined gypsum or overcalcined anhydrite.

Many plants still use batch-type kettle calciners. These consist of steel vessels with agitators, mounted on a firebox. Batches of pulverized gypsum are added and heated under agitation. A boil occurs at about 250°F as the water of hydration is evolved. Heating is continued to about 320°F and the batch is dumped and cooled.

The stucco is mixed with various additives and continuously slurried with water. The additives may consist of fillers, foaming agents, accelerators, reinforcing fibers, and bonding agents. Their main purpose is to produce a strong, lightweight board with a firmly bonded paper, and to control properties such as the slurry flow characteristics and setting rate that affect the manufacturing process.

The casting operation is straightforward but requires careful control of the slurry properties and operating conditions. Continuous strips of specially made face and back paper are fed to the casting machine, usually at about 150 ft/min. The slurry is injected between the two papers as they converge and is spread to a uniform thickness. The edges of the paper are folded and glued and the sheet passes between final forming rollers. The still-plastic sheet is supported on a moving belt or rollers for 4 to 6 minutes until the slurry sets. It is then cut into the desired lengths, turned face-side up, and passed through a dryer. The dryer typically contains several decks and has four sections with separate controls to facilitate control of the drying process. The temperature of the first section is 500°F to 600°F and the temperature of each succeeding section decreases to 150°F to 200°F in the final section so that the board remains at about 200°F throughout the drying process. The dried boards are cooled; trimmed; formed into books; and taped, labeled, and stacked.

<u>Portland Cement Manufacture</u>

About 95% of the hydraulic cement produced in the United States is portland cement. Portland cement is also a component of masonry cement, which

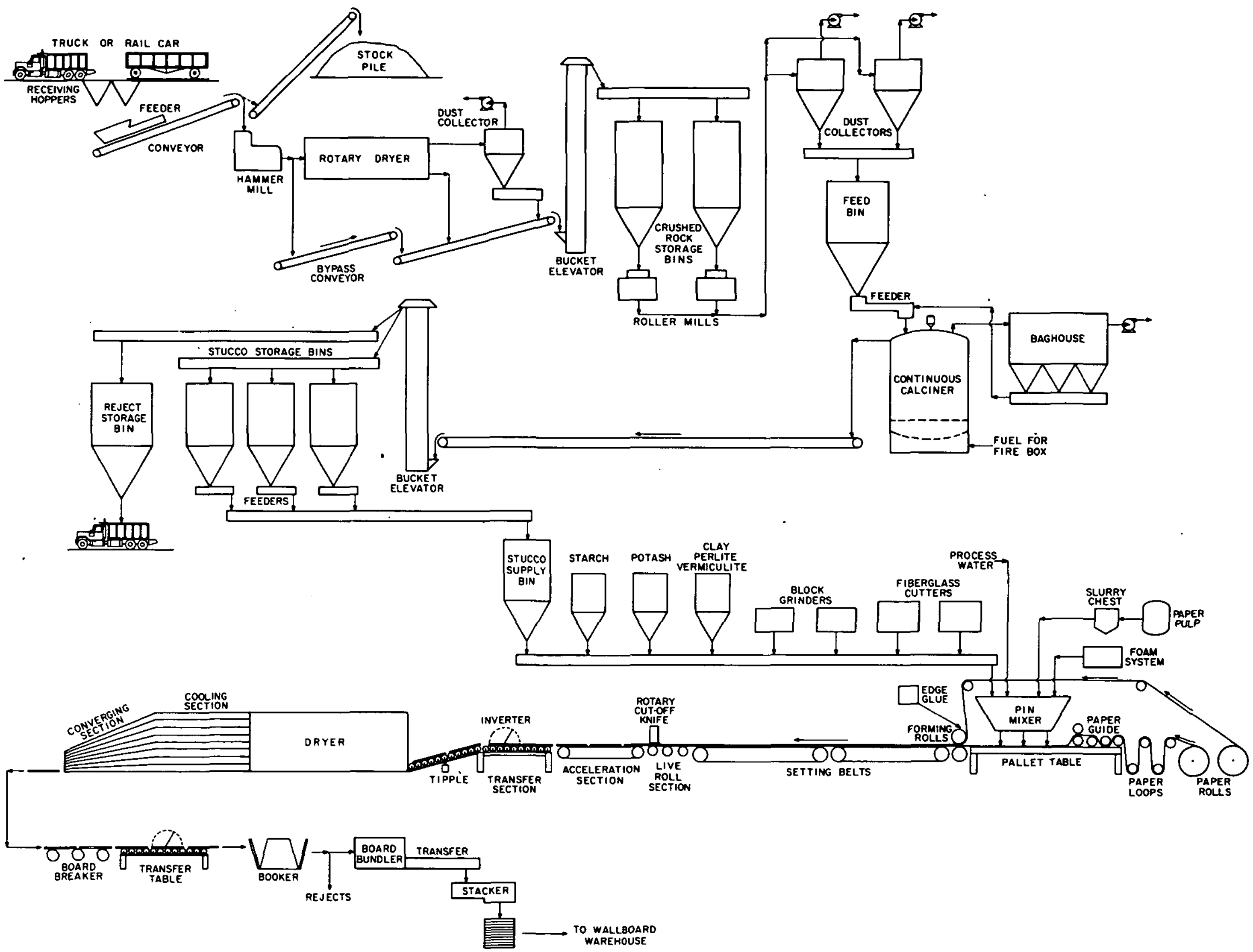

Figure 7. Wallboard plant flow diagram.

accounts for most of the remaining production. Portland cement is produced in several types, defined by exacting chemical and physical specifications, by grinding a pyrogenic agglomerate of synthetic minerals called clinker with a small amount (3% to 6%) of gypsum. Clinker is composed of minerals formed when a finely ground mixture composed primarily of calcium carbonate, alumina, and silica is heated to partial fusion under carefully controlled conditions. The manufacture of portland cement is largely the manufacture of clinker. This phase of the process consumes over 95% of the raw materials and almost all of the energy used. The manufacture of the cement itself is a simple grinding operation.

About 1.7 tons of raw materials is needed to produce 1 ton of clinker (29). The weight loss is primarily due to the decomposition of $CaCO_3$ to CaO and the evolution of CO_2, which is vented to the atmosphere. In 1979, about 130 million tons of raw materials was consumed (28), mostly calcareous rocks (114 million tons), clay and shale (11 million tons), and sand and sandstone (3 million tons). In addition, about 4 million tons of gypsum was used with the clinker to produce portland cement.

Many raw materials can be used as kiln feed for clinker production. The primary requirements (31) are that the proper proportions of calcium carbonate, silica, alumina, and usually iron oxide are obtained, that excessive quantities of impurities such as magnesium are not present, and that the fusing characteristics of the blended raw material are adequate. In some cases, these requirements can be met by a rare, naturally occurring carbonate rock called cement rock. Usually, however, different natural and manmade materials must be combined. The calcium carbonate can be provided by limestone rock, marble, shell deposits, carbonate sands, or calcium-rich slags. Numerous materials such as shale, clay, slag, fly ash, and mill tailings can supply the silica, alumina, and iron oxides. This flexibility in raw material selection must, however, be weighed against complex considerations of cost, availability, and the effects they have on the design and operation of the clinker plant.

In contrast to the flexibility in kiln feed materials, gypsum in some quantity is necessary for blending with the clinker before it is ground to form portland cement. Gypsum is necessary to control the setting rate of the cement. Some sulfate in the proper form may be supplied by the clinker but additional gypsum or anhydrite, usually 3% to 6% of the clinker weight, is necessary. No suitable substitute is available for gypsum as a set retarder in the manufacture of portland cement. No general quality specifications are available but gypsum suitable for wallboard manufacture is regarded as suitable for cement manufacture.

Clinker manufacture involves blending the raw materials in carefully controlled proportions, grinding the mixture to a very fine particle size, and heating the ground mixture to partial fusion in a large rotary kiln. The clinker produced consists of ball-like, sand- to walnut-sized particles that have both a specific chemical and mineral composition, determined by the chemical and mineral composition and physical properties of the kiln feed and the rate and degree of the heating in the kiln. These properties of the clinker determine the properties of the resulting cement and must be carefully controlled.

Blending plays an important role throughout the process. This begins during raw material acquisition with careful sampling and selective mining, and sometimes with beneficiation such as washing and screening. The raw materials are usually stored separately at the grinding mill to provide opportunity for further blending. Additional argillaceous, siliceous, and ferriferous materials may be used to modify the composition of the primary raw materials. Further blending takes place after grinding.

Both the mineralogy of the clinker and efficiency of the kiln are affected by the particle size of the feed. The optimum fineness is usually particle sizes in the range of 75% to 90% to pass 200 mesh. Both wet and dry grinding processes are used. Wet grinding was adopted because raw material drying equipment is not needed and there is more opportunity for blending. In wet grinding processes, the ground kiln feed is added to the kiln as a slurry and dried in the kiln. There is less opportunity for waste heat recovery, however, and with rising fuel costs, which are an important factor in clinker manufacture, dry grinding has again become the favored method.

In wet grinding processes, the raw materials are ground in water in ball or rod mills to form a slurry of 55% to 70% solids. The slurry is stored in tanks where further blending can be accomplished. The slurry is fed directly to the kiln. In dry grinding processes, the raw materials are dried to about 1% moisture, preferably with waste heat, before being ground. Roll and ball-race mills are sometimes used instead of ball and rod mills. Dry ground materials are more difficult to blend effectively but feed preheaters using waste kiln heat and precalciners can be used, both of which reduce kiln fuel requirements.

Pyroprocessing, called burning, is the most important phase of the clinker process. Large, refractory-lined kilns, up to 750 feet long and 25 feet in diameter, are used. The kilns are slightly inclined and rotate at 1 to 3 rpm. They are fired at the lower end with coal, oil, or gas burners. The raw material is introduced at the upper end and progresses through the kiln in a period of several hours. Progressively they are dried (if wet), the carbonates are calcined and volatile materials are vaporized, and finally in the burning zone at a temperature of 2,700°F to 2,900°F, the materials are partially fused, allowing the complex reactions that form the cement minerals to take place. The clinker leaving the kiln is quenched with air to recover the heat and solidify the fused materials.

Wet process kilns have sufficient length to dry the slurry as well as calcine and burn the feed. Dry process kilns may also be extended to improve the energy efficiency. Increasingly, however, suspension preheaters, consisting of a series of cyclone separators, are used to heat the kiln feed with kiln gases or quenching air. Highly efficient suspension preheaters may heat the feed to 1,400°F to 1,600°F, at which it is partially calcined. In large installations, they may reduce the heat requirements to as low as 2.8 MBtu/ton of clinker (32). The alkali content of the clinker is a possible limitation to the use of suspension preheaters. Alkali and alkali-earth metals are vaporized in the kiln and carried out in the kiln gas. If suspension preheaters are used, some of these metals are deposited on the feed and returned to the kiln, increasing the alkali content of the clinker. The low alkali limits in U.S. portland cement specifications sometimes limit the percentage of kiln gas that can be used for preheating.

Precalciners, called flash furnaces, are also used, particularly in Japan and Europe where alkali specifications are less restrictive. These consist of vessels similar to the suspension preheaters in which some of the kiln fuel is burned to complete the calcining that normally takes place in the kiln, permitting the use of a shorter kiln. Quenching air is used for combustion air in the precalciner. The gas from the precalciner passes through a succession of suspension preheaters in the same manner as the kiln gas in systems with only suspension preheaters. Systems with precalciners and suspension preheaters have about the same energy efficiency as systems with only suspension preheaters, but they reduce the energy losses in cases in which bypass of kiln gas is necessary to control alkali levels since less than half of the total fuel is burned in the kiln (31). Precalciners are now coming into use in the United States (33).

Figure 8 illustrates a modern dry process portland cement plant with a precalciner and suspension preheaters. The major raw materials are limestone and shale obtained from an adjacent quarry. The quarried materials are reduced in size by crushing equipment and placed in separate storage along with other raw materials. From storage, the raw materials are conveyed to bins from which they are fed to the grinder by proportioning feeders. In this case, a roller mill is used to simultaneously grind and dry the mix using hot gases from the clinker quencher. This process is similar to the pulverizing mills used in pulverized-coal-fired power plants. Steel rolls on stationary shafts ride on a rotating grinding table. The feed is introduced so that it falls between the rolls onto the grinding table. The hot gas is introduced around the periphery of the grinding table and carries the particles upward, simultaneously drying them. Coarser particles fall back to the grinding table. The classifier in the upper portion of the mill removes additional coarse particles and the remaining fine particles are carried out in the air to collection equipment. The ground mixture is blended and stored in silos.

The feed to the kiln passes through a suspension preheater consisting of a series of cyclone separators. Kiln gases pass through the cyclones in the opposite direction, preheating the feed. The feed then passes through a precalciner or flash furnace containing a secondary burner that calcines the feed so that only the burning portion of the processing is carried out in the kiln. The calcined feed enters the kiln at about 1,500°F and is heated to about 2,700°F to 2,900°F, depending on the particular composition of the feed, at which a partial fusion of the minerals occurs, allowing the reactions to occur that form the cement minerals. The clinker leaving the kiln is quenched to stop these reactions at the desired point. The quenching air is

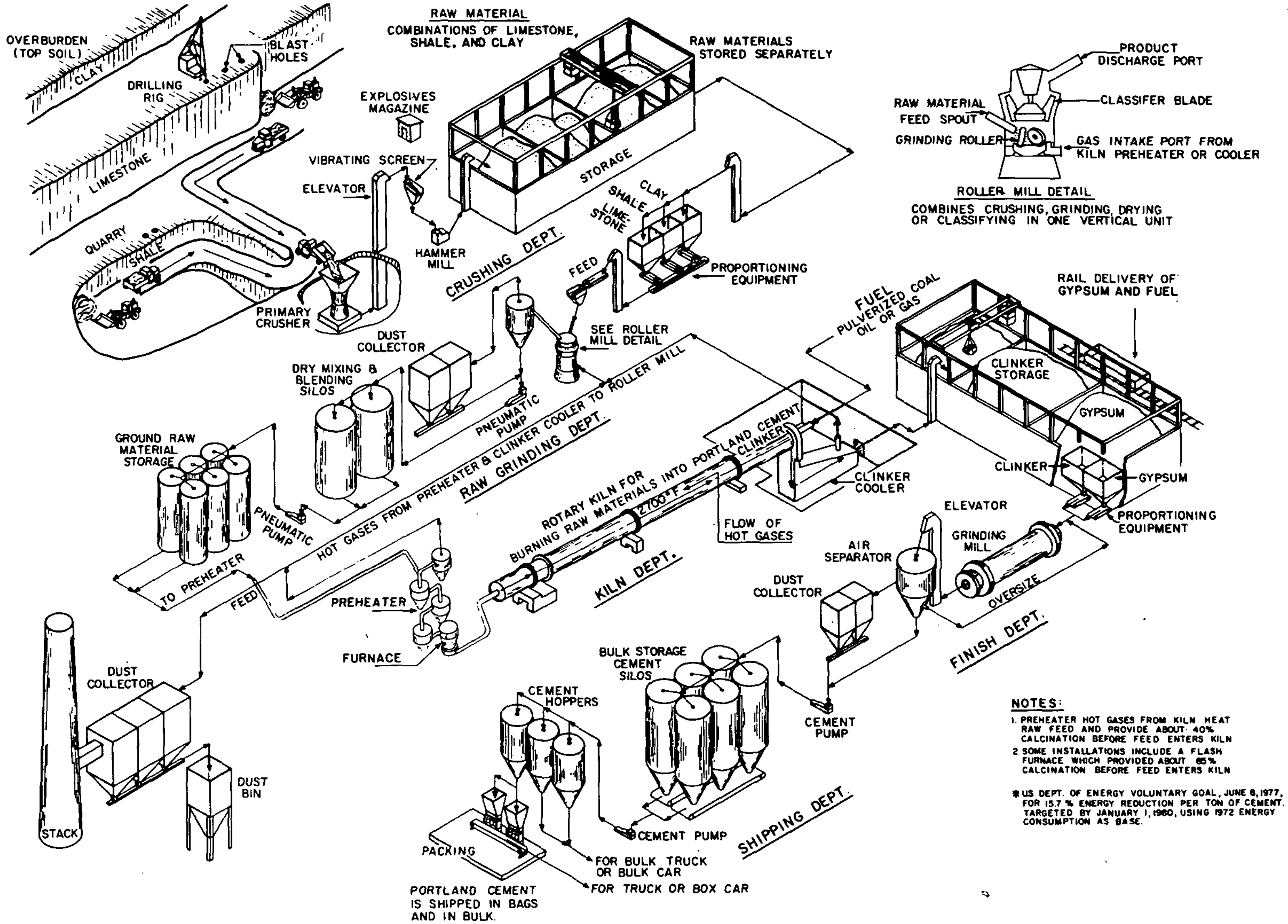

Figure 8. Dry process cement plant.

used as secondary air to the kiln burners and in the grinding mills. The clinker is blended with gypsum and ground to a specified size range in ball or roller mills to form portland cement. It is bagged in 94-lb bags or shipped in bulk by truck, rail, or barge. Some large bulk shipments are made by barge and rail to distant distribution points.

Figure 9 illustrates an older plant as it would appear for both a dry process and a wet process without suspension preheaters or a precalciner. The raw material acquisition remains the same. For the dry process, however, a separate raw materials drying system and a combination vertical grinder and tube mill are used to grind the feed. For the wet process, the raw materials are proportioned to a combination ball mill and tube mill grinding system without drying. In it they are ground to a slurry with a solids content of about 60%, which is blended to adjust the composition and stored in tanks. The feed is fed directly to the kiln as a powder in the case of the dry process and as a slurry in the case of the wet process. The kiln is long enough to preheat the dry feed or to dry and preheat the feed in the case of the wet process. Normally the kiln contains chains or other recuperative heat recovery devices to increase its efficiency. The clinkers produced by either process, and by the modern plant shown in Figure 8, are identical, as is the overall gypsum and clinker blending and grinding process. In Figure 9, however, an older two-stage grinding process using a ball mill and tube mill is shown.

The portland cement industry has a very high ratio of energy costs to raw material costs and the industry is making extensive efforts to reduce the energy costs. Energy, most of it in the form of kiln fuel, is the largest direct production cost in portland cement manufacture (29). In 1979 (28), fuel requirements averaged 5.6 MBtu/ton of clinker produced and ranged from 2.3 to 12.5 MBtu/ton of clinker produced. Electrical consumption, mostly for grinding, averaged 139 kWh/ton of cement, or 0.5 MBtu/ton of cement. The primary efforts to reduce energy costs have been in conversion to coal, the use of dry processes, and the incorporation of suspension preheaters and precalciners. The percentage of fuel requirements filled by coal has increased from about 40% in 1972 to about 70% in 1979. The use of dry processes contributes substantially to reductions in energy requirements. In 1979, the average fuel requirements for wet processes were 6.1 MBtu/ton of clinker and for dry processes it was 4.9 MBtu/ton of clinker. Those without suspension preheaters averaged 5.8 MBtu/ton of clinker, while those with suspension preheaters averaged 4.8 MBtu/ton of clinker.

The adoption of dry processes and suspension preheaters, along with the retirement of older plants and other energy conservation measures, has led to substantial reductions in the amount of energy used in portland cement production. The reduction has not, however, been as much as expected. A voluntary goal of a 15.7% reduction in overall energy consumption per ton of cement, as compared with 1972, was established by the U.S. Department of Energy in 1977. By 1979, a reduction of 8.2% had been achieved.

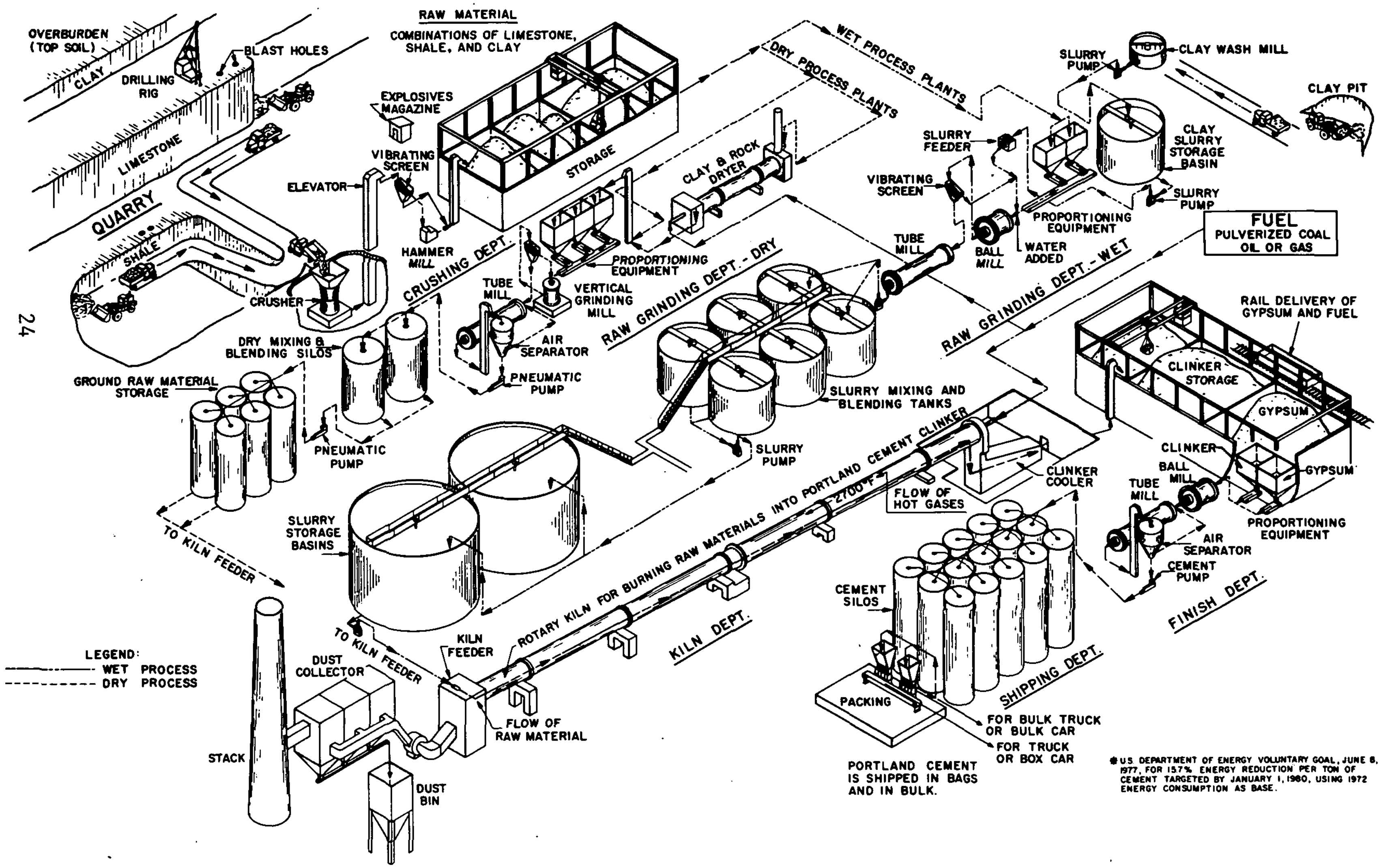

Figure 9. Wet process type cement plant.

FORCED-OXIDATION FGD PROCESSES

Oxidizing high-sulfite sludge FGD waste to gypsum by sparging air into it was proposed in England in the 1930s as a solution to waste disposal problems (34). As the use of FGD in England declined, however, these problems became less urgent and the idea did not mature. In Japan, where a rapid growth in FGD technology began in the 1960s, a byproduct-producing technology in which gypsum played the central role was followed from the beginning.

Many companies in Japan, often without FGD experience, undertook development of gypsum-producing FGD processes, usually following their own philosophies of the best means of attaining both adequate SO_2 removal and high oxidation in the same system. The result was a profusion of rather complex processes, often differing widely in concept and design. These have been widely described in FGD literature, notably by Ando in a series of papers at FGD symposiums (35). In general, the development of gypsum-producing FGD processes in Japan was both swift and successful. Of some two-dozen FGD processes being operated or constructed in 1973, over one-half was gypsum-producing processes; only one was a high-sulfite waste-producing process. In 1979, over two-thirds of the FGD capacity in Japan, which consisted of some 500 systems equivalent to about 30,000 MW, produced gypsum. That year, Japan's gypsum consumption of 6.6 million tons was largely supplied by 4.1 million tons of industrial byproduct gypsum and 2.2 million tons of FGD gypsum (25).

These gypsum-producing processes have been followed with interest but they have evoked little additional response in the United States. None have been adopted for commercial use by utilities although several are marketed here under license. Three Japanese processes have been evaluated at a prototype scale, supported in part by institutional funding as demonstration units. The Chiyoda Thoroughbred 101 and Thoroughbred 121 processes, developed by the Chiyoda Chemical Engineering and Construction Co. and marketed in the United States by Chiyoda International Corp., were evaluated at the Gulf Power Company's Scholz Power Station from 1975 through 1979. The Dowa process, developed by the Dowa Mining Co. and marketed in the United States by UOP, Inc., was evaluated at the Shawnee test facility in 1979. All of the evaluations have been reported by the Electric Power Research Institute (EPRI) (36). SO_2 removals of 90% or more and essentially complete oxidation to gypsum were attained. By the nature of the processes, essentially complete limestone utilization is achieved with the Chiyoda 101 and Dowa processes. The Chiyoda 121 process also operates at a relatively low pH (for limestone slurry processes) and it also has a high limestone utilization rate. All of the gypsums could be dewatered to 80% solids or more with vacuum filters.

Interest in gypsum-producing FGD processes was slow to develop in the United States. There was little incentive to produce gypsum for manufacturing use, the prospects for which were persistently regarded as poor, and while the superior dewatering properties of gypsum were recognized, ponding of high-sulfite sludge was at least a temporary practicality. In addition, almost all FGD development efforts were directed toward complicated sulfuric acid and sulfur-producing processes or direct limestone or lime slurry scrubbing. For the latter, there was little technical basis that supported or encouraged the incorporation of forced oxidation without reverting to the Japanese-style two-stage processes. Various operating problems with these processes as they existed occupied much of the technical efforts devoted to them. One of the more serious problems, the rapid accumulation of gypsum scale in the absorbers, also sometimes casts doubt on the wisdom of deliberately inducing the formation of gypsum (37).

As the chemistry of the scaling mechanisms became better known, however, effective control measures were developed. Among these was the provision of abundant gypsum crystals in the slurry, upon which gypsum in solution would preferentially precipitate instead of nucleating on the absorber surfaces to form scale (37). Forced-oxidation systems to provide gypsum seed crystals were incorporated into FGD systems on units 1 and 2 at the Northern States Power Company's Sherburne County Generating Plant, which were started up in 1976 and 1977 (38). Similar forced-oxidation systems were installed on units 4 and 5 at the Kansas Power and Light Company's Lawrence Energy Center when the units were modified and on unit 1 at their Jeffery Energy Center. The systems were placed in operation in 1977 and 1978 (39). More recently, FGD systems installed on units 1 and 2 of the Hoosier Energy Rural Electric Cooperatives's Merom Generating Station were designed with partial forced oxidation for scale control (40).

By the mid-1970s, interest in essentially complete oxidation to gypsum for waste disposal purposes was growing. Forced-oxidation studies were begun at the EPA Industrial Environmental Research Laboratory (IERL) in 1975 (41). The tests were generally successful in demonstrating effective oxidation rates by sparging air into limestone slurry absorbent in the circulating liquid loop. These tests were continued at the Shawnee test facility from 1976 through 1979 (42), during which several design and operating configurations were evaluated and numerous relationships quantified. The published results of these tests are one of the most detailed and extensive records of primary experimentation in limestone and lime forced-oxidation FGD processes.

During the same period, most vendors of lime and limestone FGD systems developed forced-oxidation versions of their processes. These developments and their testing and application are not well documented. Forced oxidation is easily adapted to various sizes of test equipment and to portions of multi-train full-sized systems. Unless institutional funding supporting publication of detailed results was involved, the results of most of these tests remain only generally reported, if at all. There are no comprehensive surveys of utility applications of forced oxidation, particularly of installations in the construction stage or in the advanced design stage in which forced oxidation may be incorporated or which is an option still under consideration. Several utilities are reported to be planning or considering forced-oxidation limestone systems but the extent to which forced oxidation will be adopted remains undefined. Table 2 is a listing of limestone forced oxidation at utility power plants that have been described or otherwise reported in the literature.

TABLE 2. LIMESTONE FORCED OXIDATION AT UTILITY POWER PLANTS

Unit	Size, MW	Utility	Purpose[a]	Disposal	Vendor	Startup
MSCPA 1	55	MSCPA	Disposal	Landfill	B&W	1982
Sherburne 1	740	NSP	Scale	Pond	C-E	1976
Sherburne 2	740	NSP	Scale	Pond	C-E	1977
Lawrence 4	125	KP&L	Scale[b]	Pond	C-E	1977
Lawrence 5	420	KP&L	Scale	Pond	C-E	1978
Jeffery 1	540	KP&L	Scale	Pond	C-E	1978
Laramie River 1	570	BE	Disposal	Landfill	R-C	1980
Laramie River 2	570	BE	Disposal	Landfill	R-C	1981
Dallman 3	350	SWL&P	Disposal	Landfill	R-C	1980
Southwest 1	195	SCU	Test		UOP	1981
Martin Lake		TU	Test[b]		R-C	1978
Scholz		GP	Test[b]		Chiyoda	1975-1979
Widows Creek		TVA	Test		C-E	1979
Paradise 1	704	TVA	Disposal	Landfill	Chemico	1982
Paradise 2	704	TVA	Disposal	Landfill	Chemico	1982
Montecello		TU	Test		Pilot	
Shawnee		TVA	Test		Pilot	1976-1980
Thomas Hill 3	730	AEC	Disposal	Landfill	P-K	1982
Merom 1	490	HE	Scale	Landfill	MIC	1982
Merom 2	490	HE	Scale	Landfill	MIC	1982
Muscatine 9	160	MP&W	Sale		R-C	1982
Big Bend 4	475	TE	Sale		R-C	1985
Apache		AEC	Test[b]		R-C	1979
Sandow 4	380	TP			C-E	1980
Twin Oaks 1	750	TP	Disposal	Landfill	GE	1987
Twin Oaks 2	750	TP	Disposal	Landfill	GE	1987
J. B. Sims 3	65	GHB	Disposal	Landfill	B&W	1983
Seminole 1	600	SE	Disposal	Landfill	P	1983
Seminole 2	600	SE	Disposal	Landfill	P	1985
Hancock 1	700	KU	Disposal	Landfill	B&W	1987

NSP	Northern States Power Co.
KP&L	Kansas Power & Light Co.
AEC	Associated Electric Cooperative, Inc.
SWL&P	Springfield (Illinois) Water, Light, and Power Dept.
SCU	Springfield (Missouri) City Utilities
TU	Texas Utilities Generating Co.
BE	Basin Electric Power Cooperative
HE	Hoosier Energy Rural Electric Cooperative, Inc.
TE	Tampa Electric
TVA	Tennessee Valley Authority
Chemico	The Envirotech Co.
Chiyoda	Chiyoda International Corp.
C-E	Combustion Engineering, Inc.
MIC	Mitsubishi International Corp.
P-K	Pullman Kellogg (Pullman, Inc.)
R-C	Research-Cottrell, Inc.
UOP	UOP, Inc.
GP	Gulf Power Co.
TP	Texas Power and Light Co.
MSCPA	Michigan South Central Power Association
B&W	Babcock & Wilcox
GHB	Grand Haven (Mich.) Board of Light and Power
P	Peabody Process Systems, Inc.
GE	GE Environmental Services
KU	Kentucky Utilities

a. Stated or apparent purpose: scale control, improved handling in disposal, various test purposes, or sale of the product.

b. Reported production of gypsum evaluated for wallboard manufacture.

Research-Cottrell, Inc., has a forced-oxidation version of their double-loop system. It consists of a quencher, which operates at a low pH to permit efficient oxidation, and an absorber, which operates at a higher pH for efficient SO_2 removal (43). Research-Cottrell has forced-oxidation versions of their double-loop process in use on units 1 and 2 at Basin Electric Power Cooperative's Laramie River Station and on unit 3 of the Springfield (Illinois) Water, Light, and Power Department's Dallman Generation Station, all of which produce gypsum for landfill disposal. Research-Cottrell is also supplying forced-oxidation systems for unit 9 at the Muscatine (Iowa) Power and Water Department's Muscatine Station (44) and unit 4 of Tampa Electric Company's Big Bend Station (45). The Muscatine plant will produce 95% gypsum for agricultural uses. The Big Bend plant will produce gypsum for wallboard manufacture. A Research-Cottrell system also produced gypsum for evaluation in wallboard manufacture in a test at the Texas Utilities' Martin Lake Station (45) and the Arizona Electric Power Cooperative's Apache Station (46) which use their absorbers.

Pullman Kellogg, a division of Pullman, Inc., has a forced-oxidation version of their FGD process, which incorporates a modular horizontal absorber called the Kellogg-Weir scrubber (47). The process is used without forced oxidation in several utility applications. The design is adaptable to forced oxidation because the absorber consists of several separate modules in series, each with its own liquid recirculation system. A magnesium-enhanced limestone forced-oxidation version is scheduled to be started up on unit 3 at the Associated Electric Cooperative's Thomas Hill Energy Center near Moberly, Missouri, in 1982 (48). The unit is rated at 670 MW and burns a local high-ash, high-sulfur coal. In this application, forced oxidation takes place in a bleedstream because of space limitations in the absorber area. This is apparently practical because of the high magnesium content of the waste slurry. Forced oxidation is being used to increase recovery of dissolved magnesium and to improve the properties of the dewatered waste, which will be blended with fly ash and disposed of in a mine.

The forced-oxidation limestone systems being installed on units 1 and 2 at the TVA Paradise Steam Plant were designed by Chemico. The design incorporates a venturi-spray tower absorber and forced oxidation by air sparging in an integral absorber vessel. The flue gas passes downward through a variable-throat venturi into the concentric spray tower, then reverses direction and passes upward around the venturi through an array of spray nozzles. Limestone slurry collects in the bottom of the absorber and is oxidized by sparging air into it. The waste will be dewatered and landfilled.

SCRUBBING COST GENERATOR

The computer model used to compare the FGD process alternatives is the "scrubbing cost generator" portion of the computerized FGD byproduct production and marketing model used in previous TVA byproduct marketing studies (49). It is one of several FGD economic computer models developed by TVA in EPA-supported projects (50).

The scrubbing cost generator calculates the costs of two or more FGD processes based on conceptual designs that represent current utility power plant operating conditions and FGD practices. The input conditions consist of specific power plant data such as boiler size, coal properties, and the applicable emission control regulations. The determinations are made on a boiler-by-boiler basis because of the size, age, and emission control requirement differences among boilers at many power plants. The input data are provided by a computerized data base maintained on all large utility power plants in the eastern 37 states. The data base is compiled from published sources such as the several annual government compilations of regulated utility operating data, EPA reports and regulations, and trade publications.

The scrubbing cost generator calculates the FGD costs based on these data for each of the FGD processes programmed. In this study, the costs of a forced-oxidation limestone process that produced gypsum and a limestone process that produced a waste that was fixed and disposed of in a landfill were determined. The FGD costs are annual revenue requirements, consisting of operating and maintenance costs; overheads; and capital charges, determined following the economic premises discussed below. The FGD costs for each of the processes are compared to produce an "incremental cost," which is the difference between the byproduct-producing process and the waste-producing process.

The incremental cost is a means of quantifying the difference between the byproduct-producing process cost (BP) and the waste-producing process cost (WP) in terms of the quantity of byproduct (P) produced, all in annual terms:

$$(BP - WP)/P = \text{incremental cost in \$/ton of byproduct}$$

If the incremental cost is positive (meaning that the byproduct-producing process is more expensive than the waste-producing process), it is the amount that must be recovered from sales revenue to make the costs of the two processes equal. Since sales revenue must also provide for freight and marketing costs, positive incremental costs reduce the marketing range, and usually the marketability, of the byproduct. If, after deduction of freight and marketing costs, the net sales revenue, in dollars per ton of byproduct, does not exceed the positive incremental cost, the byproduct-producing process will be the more expensive FGD option.

When the incremental cost is negative (meaning that the byproduct-producing process is less expensive to operate than the waste-producing process--provided only that the byproduct can be removed), a different situation prevails. The sales revenue need only provide for freight and marketing costs and even if there is no net sales revenue, the byproduct-producing process remains the less expensive FGD option. In fact, presuming that the only objective of using a byproduct-producing process is to minimize FGD costs, a portion of the incremental cost can be used to subsidize freight and marketing costs. This reduces the total savings from using the byproduct-producing process but it still remains the less expensive FGD option.

A negative or very low positive incremental cost is a critical factor in the marketability of FGD gypsum since the low cost of gypsum provides relatively little sales revenue to provide for freight and marketing costs as well as offset positive incremental costs. In addition, the freight costs are proportionally high compared with other byproducts. To ship each ton of sulfur removed from the flue gas, for example, requires shipping one ton of elemental sulfur and about three tons of sulfuric acid, but over five tons of gypsum. A low-cost gypsum-producing process is thus highly desirable, if not essential, for economic justification of a FGD gypsum marketing strategy.

The nature of the scrubbing cost generator screening process is general although specific power plant data are used. The byproduct marketing evaluation is designed as a general evaluation of byproduct marketing potential for utilities and the identification of conditions that favor adoption of a byproduct marketing strategy, rather than the identification of specific power plants. The use of actual power plant data provides a representative structure (type of coal, unit size and age, emission regulations, geographical distribution) upon which to base the evaluation. The power plant data base is not, in fact, designed to provide an individual plant-by-plant evaluation. Details such as the power plant configuration, land availability, and many other factors that could influence the selection of a particular emission control strategy are not included.

PREVIOUS FGD GYPSUM BYPRODUCT MARKETING STUDY

The previous gypsum byproduct marketing study (2) was published in 1978 based on FGD technology and gypsum industry conditions as they existed in the mid-1970s. The emission control options used were low-sulfur coal (with a 0.70 \$/MBtu additional cost), limestone FGD with pond disposal, and gypsum production using two-stage limestone processes (Chiyoda 101, Dowa, and a generic limestone process in which the bleedstream was acidified and oxidized by sparging air into it). These were compared for 187 power plants that were then out of SO_2 emission compliance based on State Implementation Plan (SIP) emission control requirements. Marketing was based on sales to wallboard plants and cement plants. The study projected that 30 of the 187 plants could most economically meet their SO_2 emission regulations by producing and marketing gypsum. For 71 plants, low-sulfur coal was the most economical option and for the remaining 86, limestone FGD and pond disposal were the most economical. Small power plants were the most favorable producers and cement plants the most favorable consumers. Ninety-six percent of the projected sales were to 92 cement plants; only 1 wallboard plant was a projected consumer. The sale of this gypsum represented about 8% of the projected production of utility FGD waste.

In general, the study projected a moderate potential for small volume FGD gypsum sales to cement plants and little potential for sales to wallboard plants. The controlling factor in most cases was the low production cost assumed for natural gypsum--\$3/ton at the mine--and the proximity of most wallboard plants to captive mines. Transportation costs precluded sales to most wallboard plants except those receiving imported gypsum, to which transportation costs of 1 $/ton or more were assigned. Cement plants, more widely distributed geographically and using more expensive open market gypsum, were thus the more favorable candidates. The study concluded, however, that more detailed and specific costs for domestic and imported gypsum would have enhanced the accuracy of the study. In addition, the FGD processes used, which represented the prevailing technology, tended to favor the limestone FGD process with its low-cost pond disposal over the two-stage gypsum processes, which were 20% more expensive to operate. Under these conditions, the production of FGD byproduct gypsum appeared less attractive than other byproduct marketing courses. A similar byproduct marketing study for sulfuric acid, also based on a projection to 1978 and using the same modeling procedures, projected a market potential of about 6 million tons, for example (3).

This study differs in several respects from the 1978 study. Most notably, a less expensive forced-oxidation limestone FGD process was used instead of the two-stage processes used in the 1978 study, and natural gypsum costs were updated and based on more detailed and specific information. Also, the power plant selection process differed from the 1978 study. There is no longer an extensive body of power plants that can be projected to be out of SO_2 emission control compliance; almost all power plants have completed or are in the process of completing compliance plans, making a selection based on compliance a largely meaningless exercise. Instead, the selection of power plants for this marketing model was a two-stage process. First, all power plants in the study area were screened to select those whose fuel and operating conditions made them most suitable for a gypsum marketing FGD strategy regardless of the compliance plan they were using or committed to. Second, this group was manually screened to eliminate those that would be least adaptable to forced-oxidation limestone FGD strategy--for example, commitment to long-term use of low-sulfur or cleaned coal, lack of upstream particulate control, or commitment to a FGD system obviously not capable of conversion to limestone forced oxidation. The 1978 study was thus a more general analysis of the prospects for successful gypsum marketing only for existing or planned power plants that had not selected a compliance strategy. This study is an analysis of the power plant conditions that favor a FGD gypsum marketing strategy and of the prospects for successful FGD gypsum marketing under various conditions for this type of power plant.

METHODOLOGY

Two models of FGD byproduct gypsum marketing were evaluated in this study: a model based on the structure of existing gypsum sources and existing wallboard and portland cement plant locations in the eastern 37 states, and a model based on the relocation of some wallboard plants to sources of FGD gypsum. The same power plant basis is used for both models. This consists of coal-fired units at 14 power plants, which were selected on the basis of characteristics that make the production of gypsum an economically feasible emission control option as compared with other means of emission control. The emission control options that were compared to select the gypsum-producing candidates were two limestone FGD systems, one designed to produce gypsum and the other designed to produce a fixed waste for disposal in a landfill. Non-FGD emission control options were not included because conditions suitable for these methods (such as the use of a low-sulfur coal) would also be more economically favorable to the use of a waste-producing process than to a gypsum-producing process.

The 14 power plants used in the study were selected by screening all coal-fired utility power units over 100 MW in size that would be in operation and less than 25 years old in 1985, including those under construction and scheduled for startup in 1985 or sooner. The scrubbing cost generator computer model described previously was used to calculate the costs of alternate FGD processes: an additive-enhanced limestone process incorporating forced oxidation with provisions to produce and stockpile a salable gypsum, and a limestone process without forced oxidation incorporating fixation with fly ash and lime followed by onsite landfill. The processes and the premises are described in following sections.

PREMISES

The premises that define the FGD system design criteria and the determination of FGD costs were developed by TVA to make equitable economic comparisons and evaluations of utility FGD processes. The design premises quantify flue gas properties for a typical modern coal-fired utility power unit and specify FGD design criteria representative of current FGD technology. The economic premises define the methods of determining capital investments and annual revenue requirements for FGD systems, based on regulated utility economic practices. The premises have been used in numerous FGD economic studies over a period of several years and have been described in detail in other TVA-EPA publications (50).

Design Premises

The premise power unit is a pulverized-coal-fired boiler burning an eastern bituminous coal with a heat content of 11,700 Btu/lb and containing 15.1% ash (both on an as-fired basis). The power unit is assumed to operate at full load for 5,500 hours each year of its life. The flue gas composition is based on a total air rate (excess air and leakage) of 139% of stoichiometric requirements and emission of 92% of the sulfur and 80% of the ash in the coal. For this study, the cases used were: new (30-year life) and existing (20-year remaining life) 200-, 500-, and 1,000-MW power units, each burning 1.92% and 3.36% sulfur (as fired) coal, a total of 12 conditions that provided a range of power unit sizes and ages and coals typical of the power units included in the study. Heat rates are 9,700 and 9,900 Btu/kWh for the 200-MW new and existing units, 9,500 and 9,700 Btu/kWh for the 500-MW new and existing units, and 9,200 and 9,500 Btu/kWh for the new and existing 1,000-MW units.

The emission control requirements are based on the 1979 NSPS (9) in all cases. These specify a SO_2 emission reduction based on the sulfur content of the raw coal used. The SO_2 removal requirements are 80% (1.92% sulfur coal) and 89% (3.36% sulfur coal) of the SO_2 in the flue gas. Fly ash emission control is based on an emission limit of 0.10 lb/MBtu for the existing units and 0.03 lb/MBtu for the new units. (Fly ash removal costs are not included in the FGD economics.) The 1979 NSPS were used in all cases to provide a uniform standard cost matrix for use in the scrubbing cost generator, which uses actual emission control regulations, coal properties, and unit sizes to calculate actual FGD costs for the specific unit, based on the cost relationship established by the standard costs.

The FGD system includes a plenum into which all of the power unit induced draft (ID) fans discharge. The plenum supplies the number of absorber trains required, which is determined by the flue gas volume. Each absorber train is sized for a maximum of 513,000 ft^3/min (60°F), about 125 MW. At least two operating and one spare trains are provided in all cases; otherwise, a spare capacity of 25% is provided. Emergency bypass ducts from the inlet plenum to the stack plenum for 50% of the flue gas actually scrubbed are provided in all cases. All of the FGD systems are designed for 90% SO_2 removal, regardless of the SO_2 reduction required. If less than 90% removal is required, some of the flue gas is bypassed by incorporating the required bypass capacity into the emergency bypass ducts. This is done because bypassing, which reduces reheat requirements, is more economical than lower efficiency scrubbing with full reheat.

Each absorber train consists of a presaturator, the absorber itself with its liquid recirculation system, an entrainment separator to reduce the scrubbed gas moisture to 0.1%, an indirect steam reheater, and an ID fan that discharges to the stack plenum. An inlet plenum temperature of 300°F, an absorber outlet temperature of 127°F, and a stack inlet temperature of 175°F are assumed. Reheat requirements are determined by the quantity of flue gas bypassed and may range from full to no reheat, depending on the SO_2 removal requirements.

The costs for a limestone slurry system are also included. This consists of limestone receiving and storage facilities, crushers, ball mills, and slurry storage tanks.

Byproduct production and waste disposal costs are based on dewatering with thickeners and rotary vacuum filters to 60% solids for the high-sulfite waste and 90% solids for the gypsum. Fly ash handling and metering equipment and fly ash-sludge blending mills are provided for the waste-producing process. Gypsum handling, storage, and loading facilities are provided for the gypsum-producing process. All waste disposal facilities are clay lined, underdrained, and monitored area-type landfills with reclamation costs included. For the waste-producing process, the costs of blending and disposal of all fly ash and FGD waste are included. For the gypsum-producing process, the costs of disposal of all fly ash and 15% of the gypsum produced as noncommercial product in a common landfill are included. Fly ash collection and handling are assumed equal in cost for both processes, and thus are not included.

Economic Premises

A 3-year construction period, from early 1982 to late 1984, with the initial operation in early 1985 is assumed. Mid-1983 costs are used for the capital investment and mid-1985 costs are used for the annual revenue requirements. The costs are projected from cost indexes that appear regularly in *Chemical Engineering* magazine. The indexes are shown in Table 3. Frequently used costs are shown in Table 4. All costs are based on a north-central location.

TABLE 3. COST INDEXES AND PROJECTIONS

Year:	1979	1980	1981[a]	1982[a]	1983[a]	1984[a]
Plant	238.7	261.1	277.1	297.9	320.2	342.6
Material[b]	264.4	292.6	311.2	336.1	363.0	388.4
Labor[c]	194.9	204.3	227.3	245.5	265.2	283.7

a. TVA projections.
b. Same as "equipment, machinery, supports" *Chemical Engineering* index.
c. Same as "construction labor" *Chemical Engineering* index.

The capital investment consists of direct investment, comprising of the installed costs of all process equipment, landfill construction, and landfill equipment; indirect investment, comprising of fees for contracted services, construction expenses, and contingencies; and other capital investment such as allowance for startup and modifications, land, interest, and working capital. The total capital investment of installations on existing power units is increased by 30% because of the greater costs of retrofit installations (51).

TABLE 4. COST FACTORS

1985 Utility Costs	
Electricity	\$0.040/kWh
Steam	\$2.75/klb,
Diesel fuel[a]	\$1.75/gal
Filtered river water	\$0.15/kgal
1985 Labor Costs	
FGD operating labor	\$16.00/man-hr
Waste disposal labor	\$22.00/man-hr
Analysis labor	\$22.00/man-hr
1985 Raw Material Costs	
Limestone	\$9.00/ton (95% $CaCO_3$, dry basis)
Lime	\$81.00/ton (pebble 95% CaO, dry basis)
Adipic acid	\$1,300/ton

a. Cost is based on wholesale price of barge-load quantities at a north-central location. Road taxes are not included.

Annual revenue requirements consist of operating and maintenance costs, overheads, and capital charges. Operating and maintenance costs include raw materials, labor and supervision, utilities, maintenance, and fuel. Raw material and utility costs are determined from material balances; labor and supervision costs are based on process requirements; and maintenance costs are based on the direct capital investment, which reflects the complexity of the process. Overheads are based on the portions of operating and maintenance costs that reflect overhead requirements. Capital charges change from year to year as the capital investment is written off. To provide representative capital charges for comparative purposes, the capital charges used are levelized to account for the cost of money and inflation over the life of the system. The levelized capital charges included in the annual revenue requirements are 14.7% of the total capital investment.

FGD PROCESS DESCRIPTIONS

The two processes used in the model are variations of the widely used limestone-scrubbing process. For the waste disposal process, a limestone-scrubbing process producing a waste slurry consisting primarily of calcium sulfite is used. The slurry is dewatered, mixed with dry fly ash and lime, and disposed of in an onsite landfill. For the gypsum-producing process, a similar limestone process that incorporates forced oxidation in an additional tank in the absorber liquid circulation loop (in-loop forced oxidation) is used. Also, adipic acid additive is used to enhance SO_2 absorption and limestone utilization. The absorber effluent, a slurry consisting of gypsum with little sulfite or limestone, is dewatered and washed to remove chlorides and adipic acid. The gypsum suitable for byproduct use is stacked for removal to trucks or railcars. Nonstandard material is stacked separately and disposed of in a landfill.

The designs are based on EPA-sponsored studies performed at the Shawnee test facility at the TVA Shawnee Steam Plant near Paducah, Kentucky (42), on TVA studies (52), and on current industry practices and trends evident in the early 1980s. Both processes incorporate single-stage spray tower absorbers. Adipic acid as used in the gypsum process has received considerable attention in recent years, following extensive testing by EPA (53) which showed it to be effective in increasing SO_2 removal efficiency and increasing limestone utilization. It is used in the gypsum process to allow use of in-loop forced oxidation while attaining the low-limestone gypsum necessary for byproduct uses.

Both dewatering processes, consisting of thickeners followed by rotary vacuum filters, are based on widely used industry practices (8). The fixation process is based on previous TVA studies and industry information. It is treated as a generic process for costing purposes although it is similar to commercial proprietary processes (8). This particular fixation process is used because it is the most widely used method of FGD landfill disposal (11).

The costs are divided into several process areas to allow scaling by the relative effects of gas volume (power unit size) and equivalent sulfur production (coal sulfur content and emission limitations) on each area.

The processes described below are the 500-MW, 3.36% sulfur coal installations. The general descriptions are also valid for other power unit sizes and the 1.92% sulfur coal cases, which differ in size and in the number of absorber trains used. For example, the 200-MW installations have two operating trains and one spare train, the 500-MW installations have four operating trains and one spare train, and the 1,000-MW installations have eight operating and two spare trains. Installations for the 1.92% sulfur coal cases differ in equipment size in areas whose function is affected by the quantity of sulfur removed such as the limestone preparation, SO_2 removal, and waste handling and disposal areas.

The general design features of both processes include a plenum into which the power unit flue gas ducts discharge downstream of all power unit equipment, including a fly ash removal system. It is assumed that essentially all fly ash is removed upstream of the FGD system and fly ash collection costs are not included in the FGD costs. Fly ash disposal costs are included in the gypsum process costs since fly ash disposal costs are an integral part of the fixation and landfill costs. The plenum supplies the absorber trains. By terms of the 1979 NSPS (54), the spare capacity permits emergency bypass under certain conditions, which is provided for 50% of the flue gas scrubbed. Each absorber train includes, in addition to the absorption equipment, a mist eliminator, indirect steam reheat, and an ID fan sized to compensate for the FGD system pressure drop. The absorber trains discharge into the stack plenum, which is not included in the FGD system costs. A limestone slurry preparation area is provided. The waste and byproduct gypsum dewatering systems consist of conventional thickeners and rotary vacuum filters. The waste is trucked to a landfill one mile from the facility. All of the power unit fly ash is used in the fixation and landfill process. In the gypsum process, it is assumed that 15% of the gypsum is nonstandard. Therefore, landfill disposal of this gypsum and all of the fly ash in a single landfill is included in the gypsum process.

Fixation and Landfill Process

The process is divided into eight process areas which are individually described below. A flow diagram of the FGD system is shown in Figure 10. A flow diagram of the fixation process is shown in Figure 11.

Materials Handling Area--

The materials handling area consists of equipment to unload and store a 30-day supply of 0- x 1-1/2-inch limestone, such as unloading and feed conveyors, bucket elevators, a dust collecting system, feed bins, and a scraper tractor.

Feed Preparation Area--

The feed preparation area consists of crushers, wet ball mills, tanks with agitators and pumps, and a dust collection system. The crushers and ball mills are situated in the limestone storage area, 1,500 feet from the FGD unit. The limestone is first crushed to 0 x 3/4 inch in two parallel gyratory crushers and then wet ball milled as a 60% solids slurry to 90% minus 325 mesh. The minimum size ball mill used is 100 hp and the maximum size is 2,500 hp. Generally two operating mills are used and one spare mill is always provided. The slurry is pumped to a tank located at the FGD unit from which it is pumped to the absorber hold tanks.

Gas Handling Area--

The gas handling area consists of a feed plenum that distributes the flue gas to the individual absorber inlet ducts, the absorber ductwork between the feed plenum and the stack plenum, two emergency bypass ducts (one from each end of the inlet plenum to each end of the stack plenum), and one ID fan per absorber train.

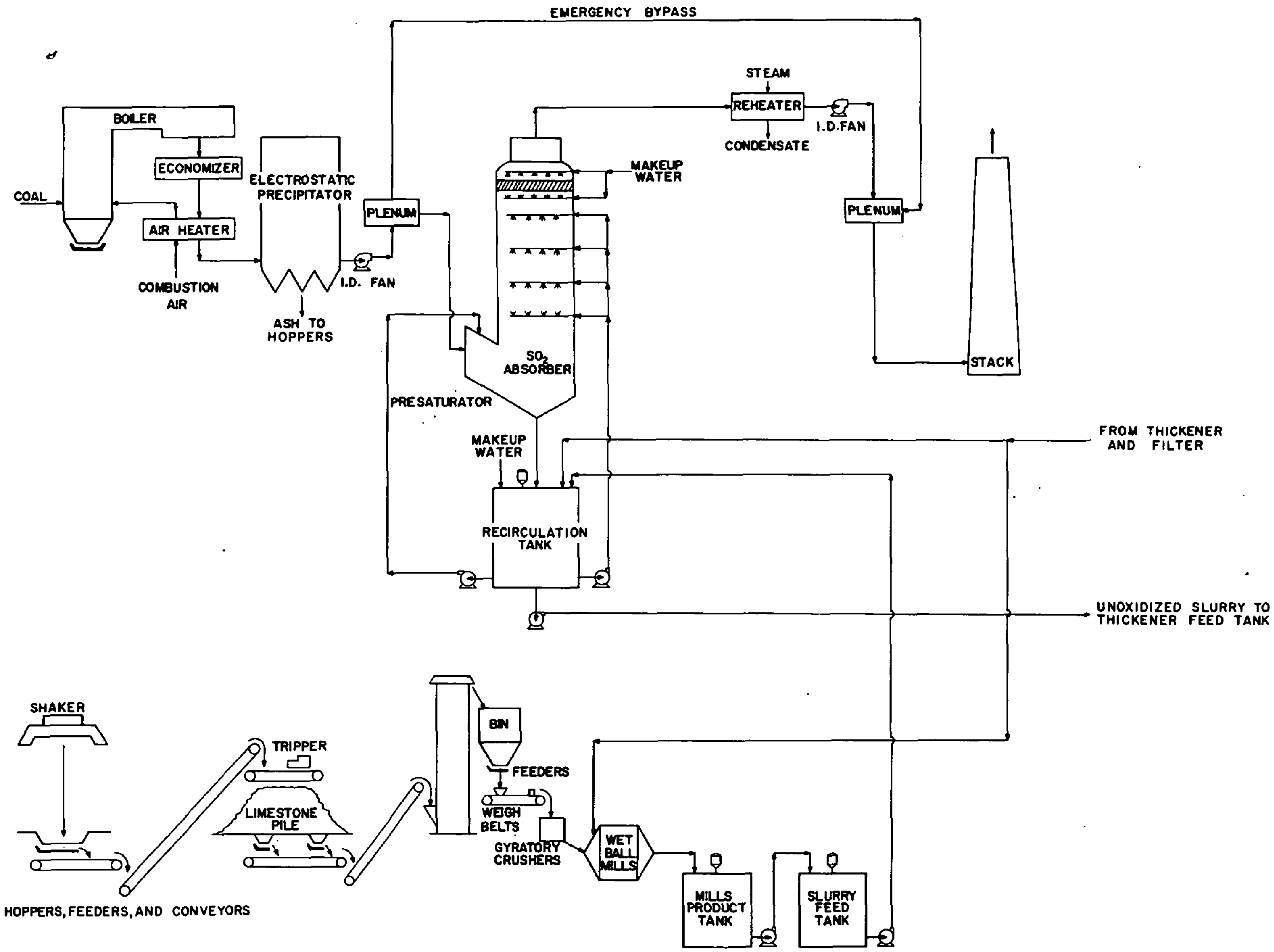

Figure 10. Fixation and landfill FGD process flow diagram.

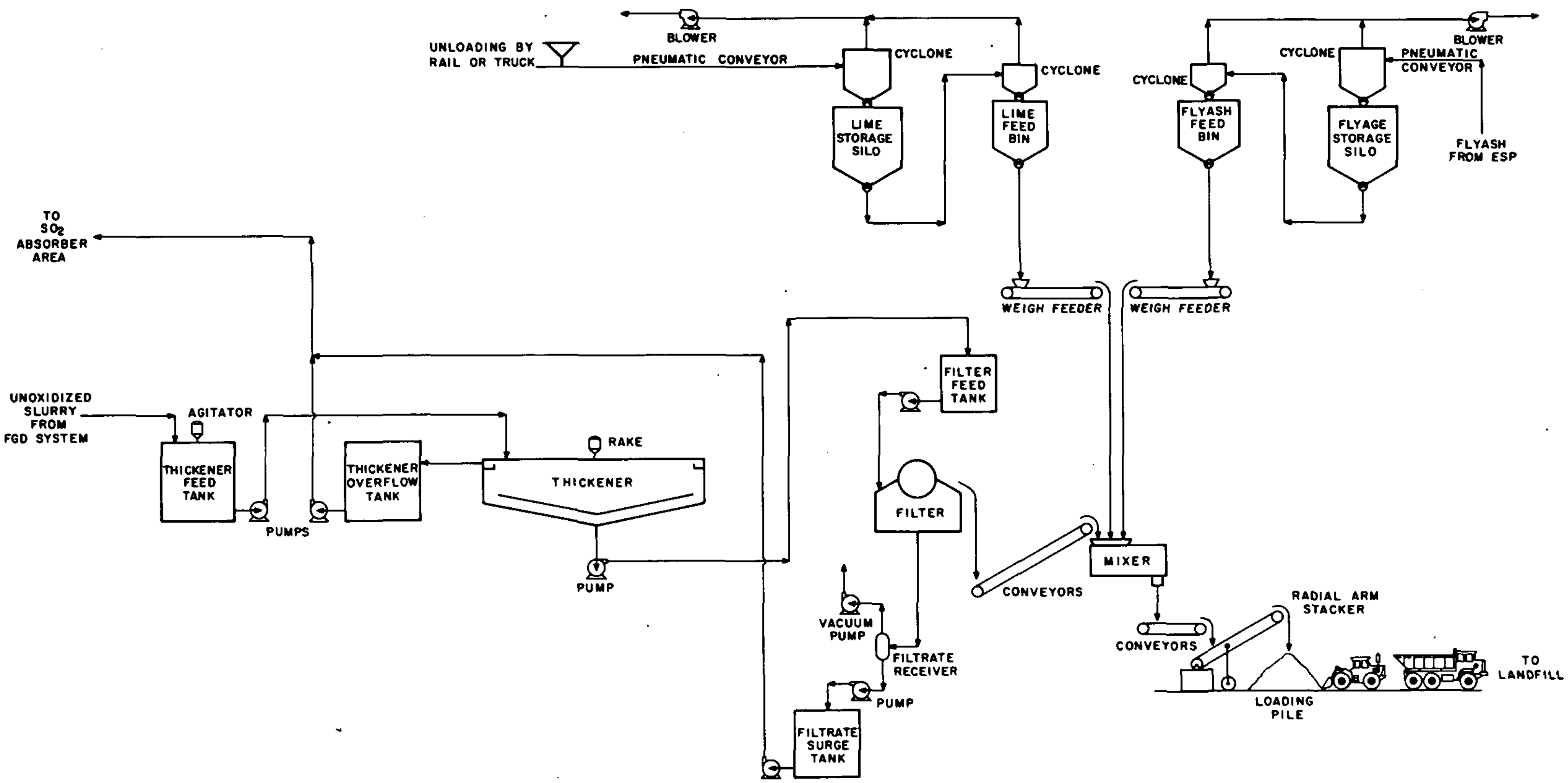

Figure 11. Fixation process flow diagram.

The ductwork upstream of the absorbers is constructed of Cor-Ten steel. The ductwork between the absorbers and the reheaters is constructed of 316 stainless steel. The ductwork between the reheaters and the ID fans is Cor-Ten steel. The ID fans are made of Inconel 625 to provide corrosion protection. The two bypass ducts are constructed of Cor-Ten steel and are designed to handle 50% of the flue gas.

SO_2 Absorption Area--

The spray tower unit is also constructed of neoprene-lined carbon steel. Three 316L stainless steel grids control gas distribution. Four banks of sprays are used for absorbent liquid distribution, one above each of the top three grids spraying downward, and one below the bottom grid spraying upward. The design gas velocity for the spray tower is 10 ft/sec and the liquid-to-gas ratio (L/G) is 90 gal/kaft^3. A chevron-type mist eliminator above the absorbers is provided to reduce the entrained moisture content of the scrubbed gas to a maximum level of 0.1% (by weight) of the flue gas. The mist eliminator is washed on a continuous basis on the underside and on an intermittent basis on the topside with fresh makeup water.

Also included in the SO_2 absorption area is the absorbent liquid recirculation system consisting of tanks, piping, and pumps. The hold tank is a 10-minute-capacity tank beneath the absorber into which the absorbent liquid drains by gravity and from which it is recirculated to the absorber. The hold tank is carbon steel with a glass-flake-filled organic polymer lining and is baffled and agitated. Pumps and pipes are rubber-lined carbon steel. A minimum of two pumps and a spare is provided.

Reheat--

The FGD system is designed for a flue gas temperature of 175°F at the entrance to the stack. The amount of reheat provided by inline steam reheat is calculated by determining the total reheat required and subtracting the quantity of reheat available from ID fan compression. The reheater tubes in contact with the gas up to a temperature of 150°F are constructed of Inconel 625. The remaining tubes are made of Cor-Ten steel. Retractable sootblowers are included with the reheater to keep the tube bundles clean.

Solids Separation Area--

The 15% solids slurry from the SO_2 absorption area is dewatered in this area. The slurry is first thickened to 40% solids in a raked thickener, after which it is filtered in rotary vacuum filters to 60% solids and transferred to the fixation area on a belt conveyor. Thickener overflow and filtrate are returned to the FGD system.

Fixation Area--

Equipment in this area consists of a lime storage and handling system; fly ash storage and handling equipment, which transfers fly ash from the power unit fly ash system; mixing equipment; and a stockpile area from which the waste is removed for landfill disposal. Slaked lime delivered by railcar or truck is pneumatically conveyed to a 7-day-capacity storage silo. Fly ash is pneumatically conveyed from the power unit fly ash silo to an 8-hour-capacity silo. The dewatered FGD sludge is conveyed directly to a pug mill with a belt conveyor. Fly ash is metered to the pug mill with a belt weigh feeder. The ratio of fly ash to dry sludge is approximately 1 to 1 for the 3.5% sulfur coal and 1979 NSPS conditions. For the range of coal properties and emission limits in this study, the ratio is usually over 1 to 1 and does not fall low enough to materially affect handling properties. Lime is also metered to the pug mill with a belt weigh feeder at a rate equal to 3.5% of the combined weight of the fly ash and FGD sludge solids.

The pug mill is 27 inches in diameter, about 12 feet long, and driven with a 60-hp motor. It discharges to a radial stacker that transfers the blended waste to an outdoor stockpile.

Landfill--

The landfill, one mile from the fixation area, has a square configuration with a 20-foot rise and a 6-degree cap. After topsoil removal, the landfill area is lined with 12 inches of clay (assumed available onsite) with a drain system to a sump and 24 inches of bottom ash is placed on the liner. Surface runoff drains into a catchment ditch around the perimeter. The ditch drains into a catchment basin for pH adjustment. Land requirements include the landfill, the catchment basin, an office, equipment storage area, topsoil storage area, and a 50-foot perimeter of undisturbed land. Costs for access roads; a 6-foot security fence around the total landfill area; security lighting; and topsoil stripping, replacement, and revegetation are included. One upstream and three downstream groundwater monitoring wells are also included.

Waste from the fixation area stockpile is loaded into dump trucks with a front loader and transported to the landfill, where it is placed and compacted in lifts of about 2 feet. The landfill is completed in sections, which are covered with 6 inches of clay and 18 inches of soil and revegetated when complete to minimize the area of disturbed land and exposed waste. Costs for all necessary mobile equipment and runoff and sump treatment are included.

Gypsum Process

The byproduct gypsum FGD process is divided into nine process areas. The process is similar in many general aspects to the fixation and landfill process. The same design principles apply and much of the equipment differs only in size or minor design features. A flow diagram of the FGD process is shown in Figure 12. A flow diagram of the dewatering and gypsum handling area is shown in Figure 13.

Materials Handling and Feed Preparation Areas--

The general descriptions of these areas are identical to those of the fixation and landfill process. The only physical differences are slight reductions in equipment size because the gypsum process has a lower stoichiometry (1.05 moles $CaCO_3$/mole SO_2 removed, versus 1.3 for the fixation and landfill process) and requires less limestone.

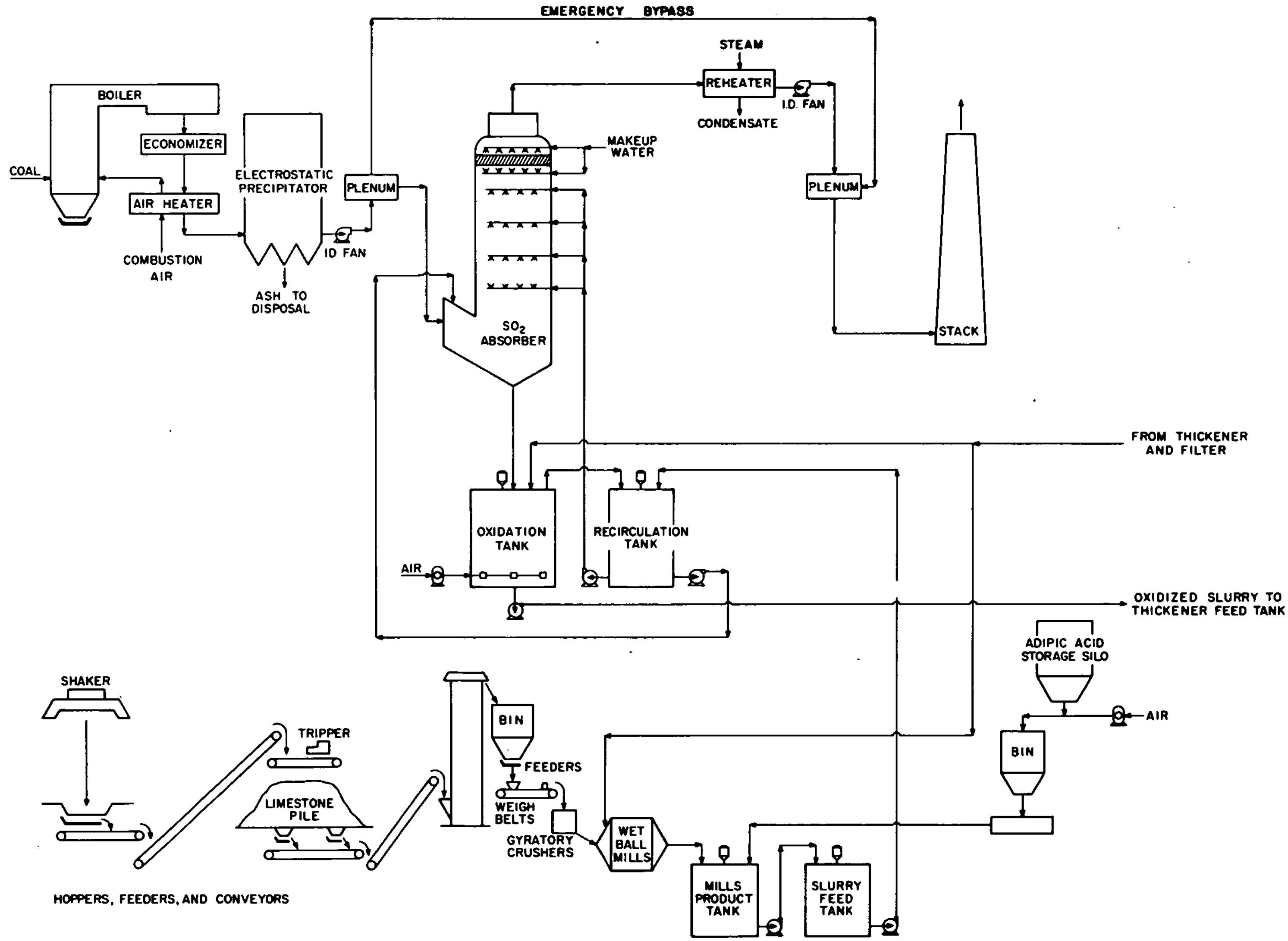

Figure 12. Gypsum-producing process flow diagram.

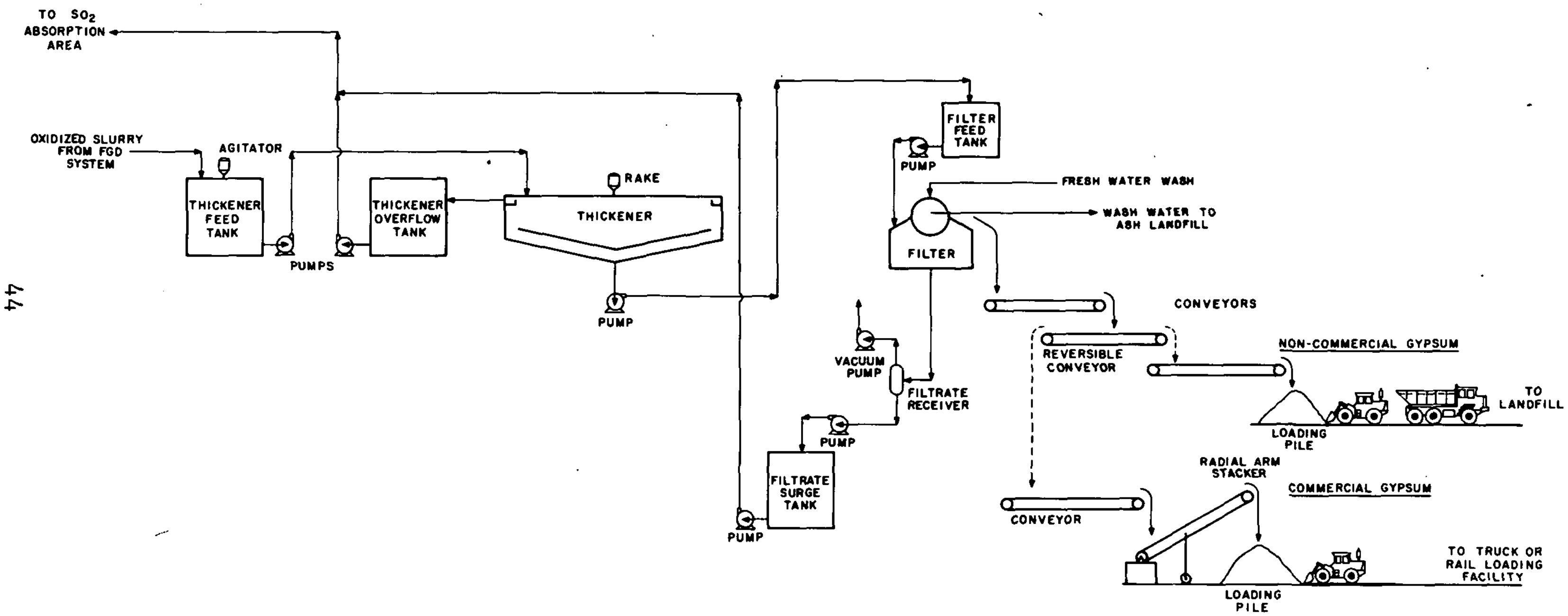

Figure 13. Gypsum dewatering and handling area flow diagram.

In the gypsum process, the adipic acid receiving and handling facilities are also included in these areas. The adipic acid is received as a granular solid and stored in a 30-day-capacity silo. It is conveyed to a feed hopper from which it is metered directly to the limestone slurry feed tank at a rate sufficient to maintain a 1,000 ppm concentration in the absorber loop. The flow rates (a few hundred pounds per hour) are miniscule compared with most of the FGD flow rates and the costs are a minor part of the area costs.

Gas Handling Area--

This area is identical to that of the fixation and landfill process because the same volume of flue gas at the same physical conditions and SO_2 content is handled.

SO_2 Absorption Area--

The absorber description is identical to the absorber description of the fixation and landfill process. Since the same 10 ft/sec flue gas velocity and L/G ratio is used, the size is also identical.

The absorbent liquid recirculation system for the gypsum process has the same pumping and piping system as the landfill process. The hold tank into which the absorber drains is replaced by an oxidation tank, however. (This tank and its equipment are included in the oxidation area rather than the SO_2 absorption area and are discussed below.) A separate 5-minute-capacity hold tank is provided downstream from the oxidation tank. This tank, which is supplied by gravity flow from the oxidation tank, is used to separate the oxidation and makeup slurry addition functions, thus allowing better oxidation conditions and a purer gypsum product. The tank is constructed of polymer-lined carbon steel and is equipped with baffles and an agitator.

Reheat Area--

This area is identical to the reheat area of the fixation and landfill process.

Oxidation Area--

The equipment in this area consists of the oxidation tank beneath the absorber with its agitator and effluent pumps, an air sparger, and the air compressors. The tank has a 15-minute hold time, is agitated, and has internal baffles. It is constructed of lined carbon steel similar in design to the hold tank. A circular air sparging manifold is situated beneath the agitator turbine to supply air at a rate of 2.5 lb atoms O/mole SO_2 absorbed. The air is provided by low-pressure rotary air compressors.

Solid Separation Area--

This area consists of a raked thickener and rotary vacuum filters with an integral spray wash system. The slurry is thickened to a 40% solids slurry and filtered to 90% solids and washed on the vacuum filter. The thickener overflow and filtrate are returned to the FGD system. The wash water filtrate is used for wetting the fly ash to optimum moisture and for dust control in the landfill. The gypsum is transferred by belt conveyor to the conveyor to the waste disposal and gypsum handling areas.

Waste Gypsum and Fly Ash Disposal Area--

Gypsum from the filter conveyor is transferred 1,300 feet to a short reversible conveyor that transfers it either to this area or to the gypsum handling area described below, depending on its quality. The long conveyor allows time for quality assessment and places the waste and gypsum handling areas away from the congested process area. Fifteen percent of the conveyor costs are assigned to this area. A short conveyor carries the gypsum from the transfer conveyor to a dumping area from which it is trucked to the landfill.

Fly ash disposal is also included in this area. The fly ash is transferred from the silos to trucks through conveyor-mixers which add a predetermined quantity of filtrate water to the ash. It is trucked to the same landfill used for the waste gypsum. The landfill description is identical to that for the fixation and landfill process.

Gypsum Handling Area--

A short conveyor carries the byproduct gypsum from the 1,300-foot conveyor described above to a radial stacker that piles the gypsum in an open 90-day stockpile. The gypsum is removed from the stockpile and loaded into trucks or into a railcar loader with a front loader.

GYPSUM PRICES AND PROJECTIONS

Assigning representative average prices to gypsum is complicated by the structure of the industry and the dichotomous nature of the cost structure. Data on individual mines are closely guarded and representative prices are not available from industry sources. In addition, almost all wallboard manufacturers operate captive mines for which the cost of the gypsum is included, without profit, in the overall operating costs of the manufacturing plant (5). The cost assigned to this gypsum is therefore quite low compared with the cost of gypsum sold to cement plants without captive mines and with the cost of imported gypsum. (Most users of imported gypsum also have captive mines but the gypsum costs include freight costs.) As a result, there is a two-tiered price structure in which a representative price for domestic gypsum is lower than the price of imported gypsum and both are substantially lower for wallboard plants than for cement plants.

The U.S. Bureau of Mines publishes summaries of gypsum costs in annual and periodic summaries of the mineral industry. The latest data available in 1982 were summaries of 1980 prices and a 1981 projection (21), which were used to develop average 1981 prices for domestic gypsum to wallboard and cement plants. In addition, the U.S. Bureau of the Census publishes U.S. import statistics, including net quantities and value, which importers are required to file with customs officials. Data for 1980 gypsum imports were used to project 1985 prices for imported gypsum. The prices developed were discussed with several people in the gypsum industry as a general verification of the values.

According to U.S. Bureau of Mines data (19), the "average mine value" (a combination of cost for transfer to wallboard plants and price of sales to nonwallboard markets) of the 12.38 million tons of gypsum produced by domestic mines in 1981 was 8.66 $/ton. The 5.68 million tons of this used in nonwallboard markets had an average mine value of 11.43 $/ton. This left 6.70 million tons for wallboard manufacture at a calculated average mine value of 5.69 $/ton. Adjusted to 1981 average mine value by using the ratio of the 1980 average value to the projected 1981 average value, the average mine value of gypsum for wallboard (cost) was 5.92 $/ton and the average mine value of nonwallboard gypsum (price) was 11.09 $/ton. These values were used to project the average 1985 costs of gypsum to wallboard and cement plants.

The average mine value of domestic gypsum has escalated at an average rate of 14% from 1973 to 1980 (19). For 1981 to 1985, an average annual 9.0% inflation rate was assumed, with 8.5% for wallboard gypsum and 11.5% for cement plant gypsum since the wallboard gypsum rate is based only on cost (inflation) while the cement plant gypsum rate is based on cost, sales expense, and profit (inflation plus profit). The 1985 cost of domestic natural gypsum thus arrived at for use in this study is 8.20 $/ton for wallboard plants and 15.60 $/ton for cement plants.

Imported Natural Gypsum Prices

There are 13 major gypsum ports of entry in the U.S. Custom Code (55). These include 16 major port cities since Philadelphia includes Wilmington, New York includes Newark, and Tampa includes Jacksonville, all of which are important wallboard manufacturing locations. The c.i.f. value of gypsum passing through each of these ports of entry in 1980 was obtained from the Bureau of Customs data (55). The c.i.f. value is the value of the import at the port of entry. It includes the purchase price, all freight, and other charges except U.S. import duties (there are none for crude gypsum) involved in placing the commodity alongside the carrier. These 1980 c.i.f. values were adjusted to 1985 values using an annual inflation rate of 12.5% a year, the average annual inflation for imported gypsum from 1976 to 1980 (26). This 1985 value was used to determine the cost of imported gypsum to wallboard plants since wallboard manufacturers almost always control the foreign source. Defining a representative cost to cement plants is more difficult since these costs involve varying brokerage fees. To establish the cement plant costs, the costs of imported gypsum delivered to cement plants were determined where available and these were used, adjusted for transport distance, to establish a cement plant cost. The differences between imported gypsum costs for wallboard and cement plants also differ because some port of entry c.i.f. values are heavily influenced by single importers whose special conditions reduce the cost of gypsum for wallboard manufacture. The ports of entry, ranked by volume, and the projected 1985 costs are shown in Table 5.

GYPSUM REQUIREMENTS AND PROJECTIONS

The individual cement plant and wallboard plant gypsum requirements for 1985 were calculated using data on 1980 consumption and projected growth rates for the two industries. Actual production rates for cement plants were not available and neither production rates nor capacities of wallboard plants are public information; it was, therefore, necessary to determine and assign 1985 gypsum requirements from other information.

TABLE 5. PORT OF ENTRY GYPSUM COSTS

Volume rank	Port of entry	1985 gypsum cost, $/ton Wallboard	Cement
1	Philadelphia, Pa. (includes Wilmington, Del.)	15.50	19.00
2	New York, N.Y. (includes Newark, N.J.)	15.30	19.00
3	Tampa, Fla. (includes Jacksonville, Fla.)	14.56	21.00
4	Savannah, Ga.	17.89	20.50
5	Baltimore, Md.	11.32	19.00
6	New Orleans, La.	16.00	20.00
7	Norfolk, Va.	15.55	20.50
8	Portland, Me.	15.00	18.12
9	Wilmington, N.C.	14.96	20.50
10	Houston, Tex.	16.00	20.00
11	Miami, Fla.	18.00	21.14
12	Charleston, S.C.	16.50	19.63
13	Wilmington, Del.	15.50	19.00
14	Newark, N.J.	15.30	19.00
15	Jacksonville, Fla.	14.56	21.00
16	Boston, Mass.	10.50	18.00

The total 1980 cement plant capacity in the study area was 77.84 million tons, based on published data for individual cement plants (56). Other sources (57) report that the U.S. cement industry operated at 75.8% of capacity in 1980. Using a gypsum content of 5% for the cement and an annual growth rate of 3% (58), a 1985 gypsum requirement of 3.42 million tons was projected for the cement plants in the study area. The gypsum requirements of the individual plants were determined using the average 75.8% capacity factor and the average 3% growth rate.

The 1980 wallboard shipments by census region were published by the Gypsum Association (59). The projected 1985 wallboard shipments in the seven census regions of the study area were projected to 1985 using a forecast of a 2.3% annual growth rate through 1986 (60). The wallboard was converted to gypsum equivalents using U.S. Bureau of Mines information (61) to produce a projected 1985 wallboard gypsum requirement of 10.78 million tons in the study area. Because individual wallboard plant capacities and productions are proprietary information, the individual wallboard plant requirements were assigned on the basis of regional market volumes. These were compared with actual but unpublished data where available, which indicated that the marketing model thus developed was representative.

TRANSPORTATION COSTS

Transportation costs play an important role in the U.S. economy. In 1979, for example, freight costs were estimated to have accounted for 22% of the gross national product. Freight costs play an even larger role in the costs of low-value bulk materials such as gypsum. Available data show that in 1979 outbound freight alone constituted 22% of the cost of 1/2-inch wallboard, and that at least 45% of the gypsum used in wallboard manufacture also incurred freight costs (5). Since these data are based mainly on ocean freight of imported gypsum and gypsum shipments on the Great Lakes, it is probable that the quantity of gypsum that incurred freight costs in the eastern 37 states is appreciably larger than 45%.

In many cases, these freight costs are well above the intrinsic value of the gypsum itself. Unmined gypsum is regarded to have a value of a few cents per ton at the most, and in many cases it is considered to have no value (5). Like many low-cost abundant minerals, the cost of the gypsum is the cost of opening and operating the mine and of transporting the mined gypsum to the consumer. Increasing freight costs are thus regarded as having a more important effect on gypsum costs and patterns of supply. The gypsum industry recognizes the importance of transportation costs: "...place value which in its simplest terms is the relative freight cost from one source of gypsum as compared to other sources to reach major construction or portland cement market areas, is the most important single economic yardstick in our industry (5)." The rapid increase in these costs may be a factor in the increased interest shown by gypsum-consuming industries in byproduct gypsum. This reversal of attitude from an apparent former indifference has been particularly evident in the past 3 or 4 years.

An extensive deregulation of the trucking and railroad industries, which reduced the control of the Interstate Commerce Commission (ICC) over many operating and pricing practices in these industries (62), is expected to have substantial effects on freight costs in the coming years, but the effects have not been clearly defined and there is no universal agreement on what they will be. In 1980, Congress passed the Motor Carrier Act of 1980 (Public Law 96-296) and the Staggers Rail Act of 1980 (Public Law 96-448). The Motor Carrier Act sharply reduced Federal regulation of the trucking industry, with the intent of promoting competition and efficiency. It was supported by consumer groups, shippers, and agricultural groups, but was strongly opposed by the trucking industry and the Teamsters Union, who feared a ruinous competition and loss of jobs. The act facilitated entry into the industry, reduced routing and commodity restrictions, and greatly relaxed ICC control of rates. The Rail Act, in contrast, was supported by railroad industry and railroad labor groups, but opposed by shippers and consumers, who feared a decline in service and higher rates. The Railroad Revitalization and Regulatory Reform Act of 1976 (Public Law 24-210, the 4-R act) had provided some deregulation of rail rates but they were regarded as insufficient. The 1980 act greatly reduced ICC control of rail rates, created a regulation-free zone within which railroads were free to change rates, and made it easier for shippers to obtain special rates. Both the Motor Carrier Act and the Rail Act also attempted to foster competition by restricting the trucking and railroad industries' ability to set rates collectively through rate bureaus.

Traditionally, rail and truck rates have been established by rate bureaus (groups of carriers that meet to fix rates) who then submitted tariffs (a statement of prices to be charged for specific services) to the ICC for approval. Some rates vary considerably among territories served by bureaus; for example, among the railroad rate territories, which are shown in Figure 14. In this study, a uniform trucking rate for gypsum is used. The rail rate for gypsum also varies little between rate territories and an average rail rate for gypsum is used. For wallboard, however, the rail rates vary appreciably between rate territories, which necessitated a more complex freight cost model for wallboard, as explained below. The effect of deregulation legislation, which removed the exemption from antitrust laws under which rate bureaus had functioned, is difficult to assess. It is assumed for this study that existing patterns will continue to be representative.

Truck Rates

Truck freight rates have risen more rapidly than rail freight rates during the last 10 years. Fuel has been a significant factor in this increase. Highway transport requires an average of 2,400 Btu/ton-mile, as compared with an average of about 750 Btu/ton-mile for rail transport (63). From the post-oil-embargo period in 1973 to 1981, the Hertz Corporation (64) estimates that the cost of truck operation increased 198%. Hertz estimated that at the current inflation rate, truck transportation costs, excluding the driver costs, would rise to 1.33 $/mile (round trip) by 1985. In this study, a slightly lower annual inflation rate of 8.5% was used to project the 1985 trucking costs. A 1985 rate of 0.13 $/ton-mile, including the driver costs and assuming an average load of 23 tons, was used.

Rail Rates

Since 1972, there have been 17 rail rate increases that apply to gypsum, as shown in Table 6. The latest increase, through late 1982, was made on January 1, 1982. Cumulatively, the rate increases represent an increase of 169% in the rail rates for shipment of gypsum as compared with the 1972 rates. The average annual rate increase has been 11.4% over the 10-year period. Since the 4-R act took effect, however, the annual rate of increase has been 13.5%. Based on this and other TVA and industry sources, the annual rate increase of 12% has been projected for 1982 through 1985 for use in this study. The historical and projected rates are shown in Figure 15.

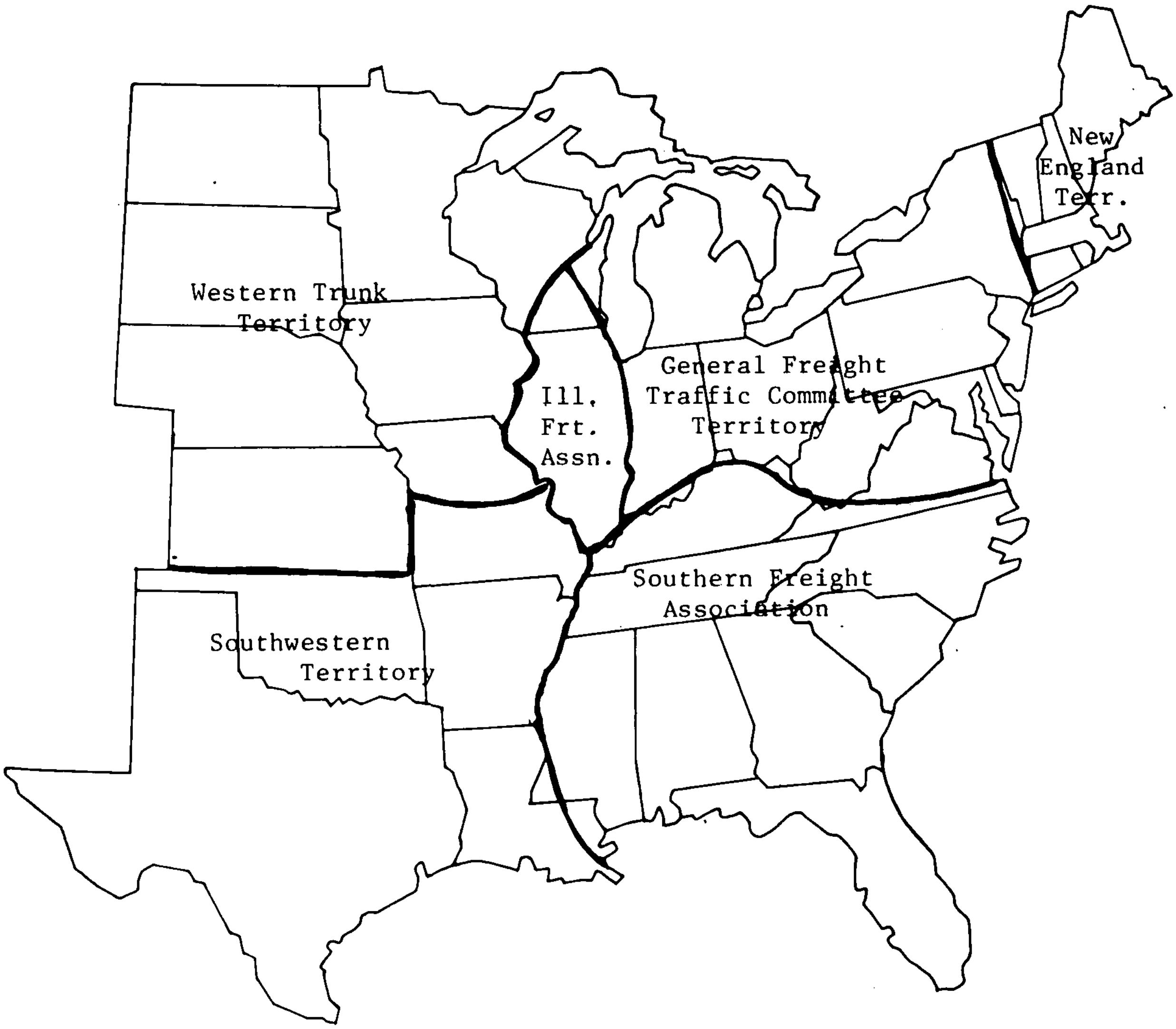

Figure 14. Railroad rate territories.

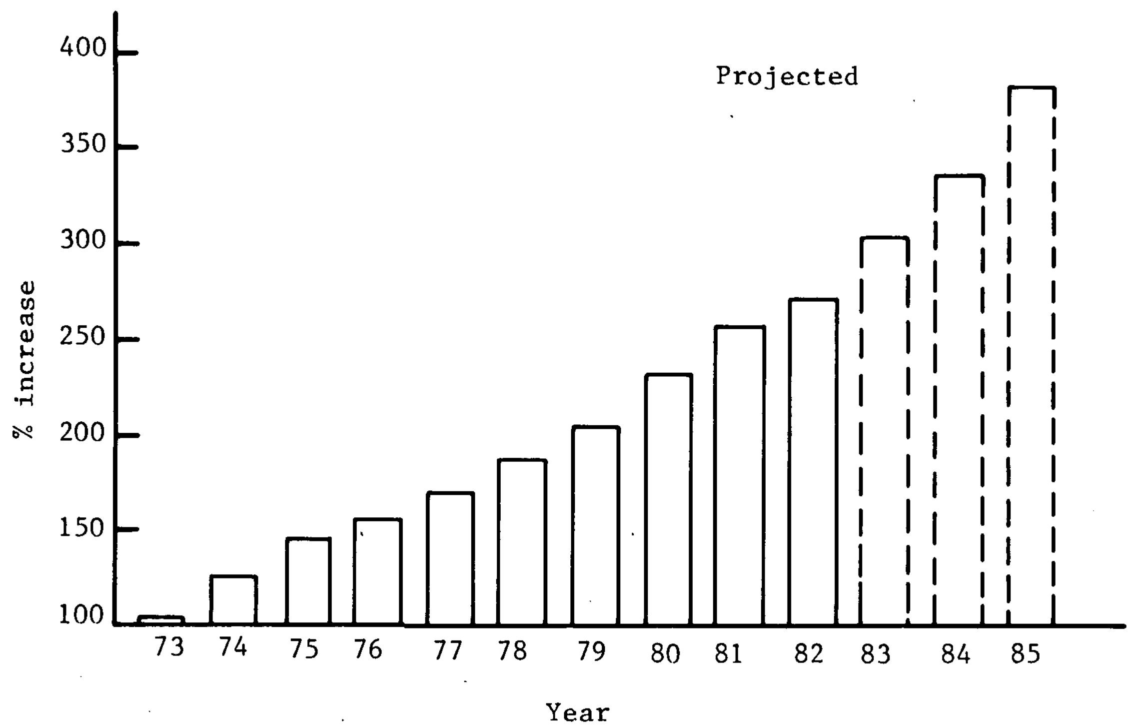

Figure 15. Historical and projected rail rates for gypsum rock.

TABLE 6. RAIL RATE INCREASES FOR GYPSUM ROCK

Tariff	Date applied	Increase, %	Index, basis 1972 = 100
X-295	08/19/73	3.0	103
X-299-B	03/16/74	2.8	
X-303-B	03/19/74	4.0	
X-305-A	06/20/74	3.3 + 10.0	125
X-310-A	04/27/75	7.0	
X-313	06/20/75	5.0 + 2.5	144
X-330	10/07/76	7.0	154
X-336	01/07/77	4.0	
X-343	11/30/77	5.0	160
X-349	06/17/78	2.8	
X-357-A	12/15/78	7.0	184
X-368-A	10/15/79	11.1	204
X-375-C	07/12/80	9.9	
X-386	12/31/80	5.5	237
X-001	06/05/81	4.0	
X-003	10/01/81	2.8 + 1.4	257
X-082	01/01/82	4.7	269

Rail Versus Truck Transportation Costs

The projected 1985 rail and truck freight rates for gypsum are compared in Figure 16 for distances between 40 and 1,100 miles. Truck rates are essentially constant on a ton-mile basis beyond distances of several miles, while rail rates decline rapidly with increasing distance for the first few hundred miles, then more slowly for longer distances. For distances up to about 200 miles, truck rates are lower; beyond 200 miles, the rail rates are lower. For this study, a break-even distance of 250 miles was used. This allowed for the advantages of truck transportation such as lower cost unloading and storage facilities and shorter delivery times. For distances of 250 miles or less, truck transportation at 0.13 $/ton-mile was used; beyond 250 miles, the projected rail transportation rate for the given distance was used. A minimum truck transportation cost of 1.30 $/ton was used for distances under 10 miles to allow for unloading and unloading costs.

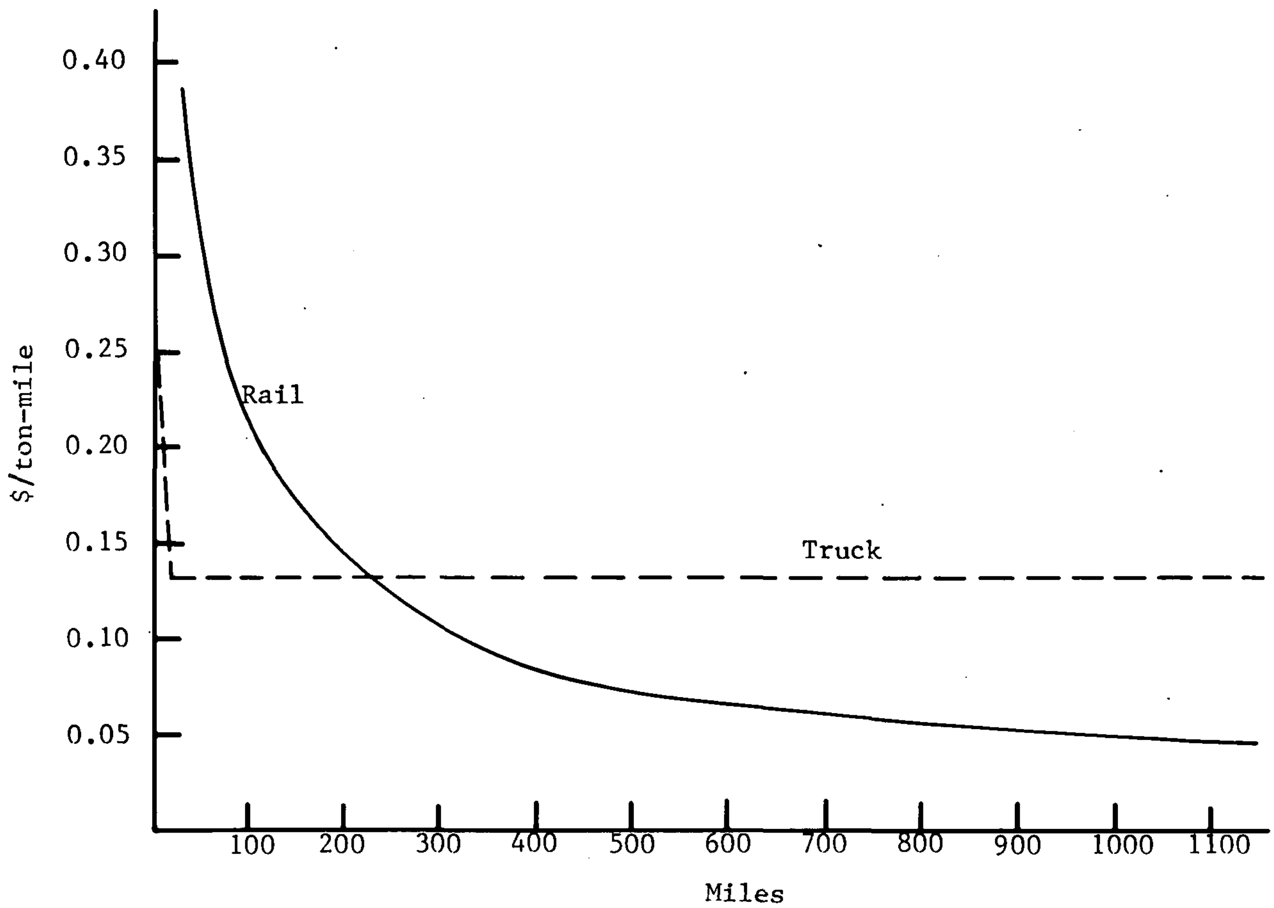

Figure 16. Railroad and truck transportation rates for gypsum.

Wallboard Transportation

Six of the railroad rate territories shown in Figure 11 are in the 37 eastern states included in this study. Only two, the General Freight Traffic Committee territory and the New England territory, have the same rates from and to points within the territories. All of the others have different intraterritory and interterritory rates for many commodities. In the case of wallboard, the difference in freight costs between the lowest and highest territories is 125%. The effect of these differences on wallboard freight costs is shown in Figure 17.

For the portion of this study in which relocation of wallboard plants to sources of FGD gypsum was assumed, with transportation of the wallboard to regional distribution centers, wallboard rail freight costs were developed for each of the intraterritory and interterritory rate possibilities listed in Table 7. These were used to determine the wallboard freight costs from each of the assumed wallboard plants to each of the assumed regional distribution centers.

DISTRIBUTION CENTERS

The second model used in the evaluation consists of a relocation of wallboard plants to sources of power plant gypsum. Forty-three hypothetical distribution centers were established for the 37 eastern states, through which it is assumed that all wallboard was marketed. The freight costs to the distribution centers from existing wallboard plant locations and from wallboard plants at the 14 power plants were compared to illustrate the extent to which such a wallboard plant relocation would be economically feasible. The model was based on U.S. Bureau of the Census regions and wallboard shipment data for 1980 projected to 1985 using census data (65). The projected 1985 wallboard shipments were allocated to the distribution centers to define a demand model by which freight costs could be compared.

The data on wallboard shipments were provided by the Gypsum Association (59), which does not release production data on individual plants or by state. The 1980 wallboard shipments by census region are shown in Table 8. A gypsum equivalent was calculated by assuming that 0.9 tons of gypsum is required to produce 1,000 ft^2 of wallboard (61). In a general sense, wallboard consumption is related to population but the per capita consumption varies widely among census regions, as shown in Table 8, depending on population growth patterns and construction activity.

The wallboard consumption in 1985, expressed in gypsum equivalents, was derived using Census Bureau projections of population growth and the 1980 wallboard consumption data. The projections are also shown in Table 8. The population projection used is the Census Bureau II-B method, which assumes that 1970 to 1975 migration patterns will continue through 1985 (65).

The distribution centers, as shown in Figure 18, were placed in major population centers in each census region, usually so that no point in a census

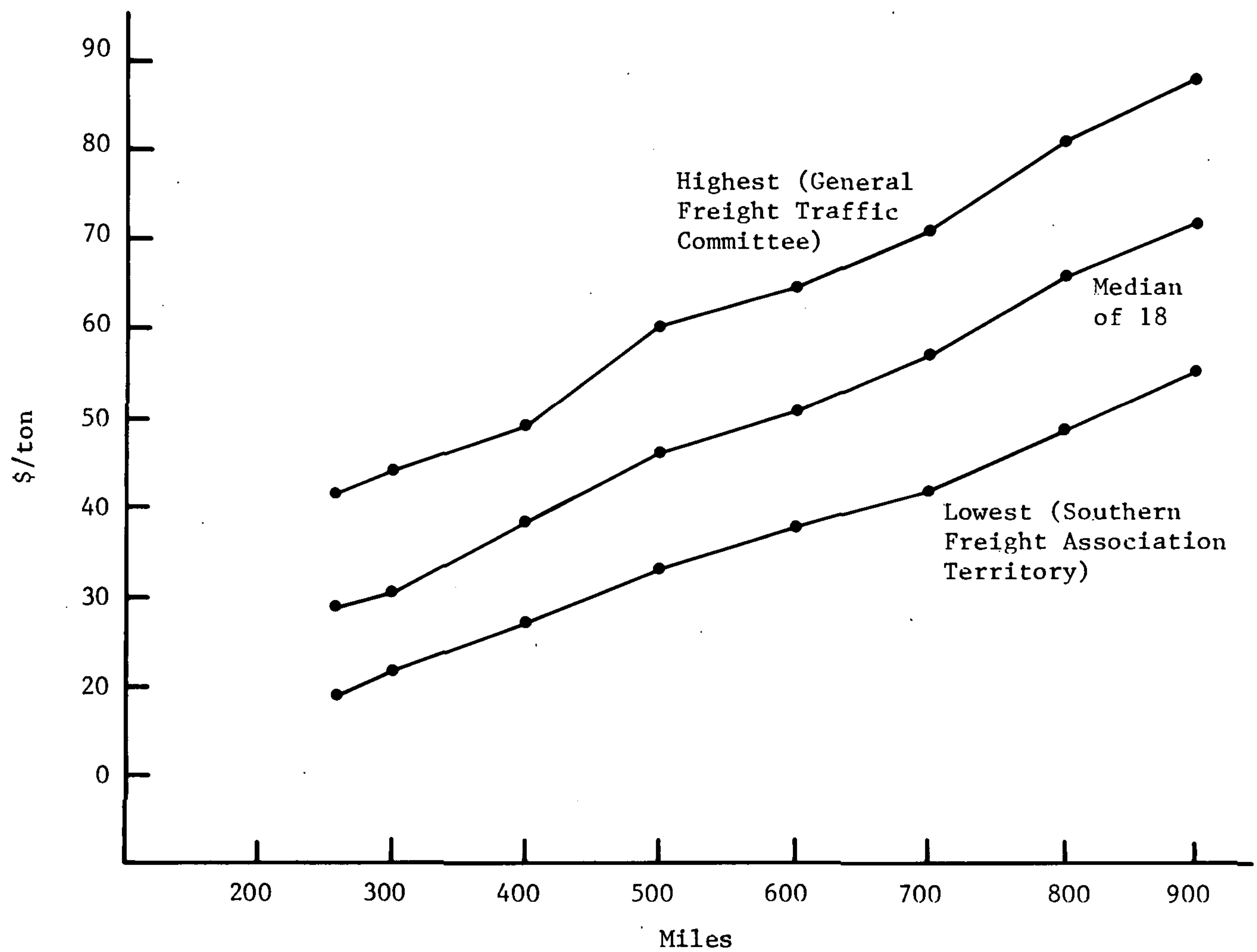

Figure 17. Rail rates for wallboard within and between rail rate bureau territories.

TABLE 7. RAIL RATES WITHIN AND BETWEEN RATE TERRITORIES

Between points in Southern Freight Association Territory
Southern Freight Association Territory to General Freight Traffic Committee Territory
Southern Freight Association Territory to Illinois Freight Association Territory
Southern Freight Association Territory to Southwestern Territory
Southern Freight Association Territory to Western Trunk Line Territory
Between points in General Freight Traffic Committee Territory (also applies between points in General Freight Traffic Committee Territory and points in Illinois Freight Association Territory)
General Freight Traffic Committee Territory to Southern Freight Association Territory
General Freight Traffic Committee Territory to Southwestern Territory
General Freight Traffic Committee Territory to Western Trunk Line Territory
Between points in Illinois Freight Association Territory
Between points in Southwestern Territory
Southwestern Territory to General Freight Traffic Committee Territory
Southwestern Territory to Southern Freight Association Territory
Southwestern Territory to Western Trunk Line Territory (including Illinois Freight Association Territory)
Between points in Western Trunk Line Territory (also applies between points in Western Trunk Line Territory and points in Illinois Freight Association Territory)
Western Trunk Line Territory to General Freight Traffic Committee Territory
Western Trunk Line Territory to Southern Freight Association Territory
Western Trunk Line Territory (including Illinois Freight Association Territory) to Southwestern Territory

TABLE 8. WALLBOARD SHIPMENTS BY CENSUS REGION

Census region	1980 population (in millions)	1985 population (in millions)	Wallboard shipped in 1980: Mft^2	Wallboard shipped in 1980: Gypsum equivalent, ktons	Gypsum eq., tons/1000 population	Projected 1985 gypsum eq., ktons	Regional distribution center	Allocated wallboard in 1985, gypsum equivalent, ktons	
New England	12	13	636	572	46.7	628	Boston, Mass.	460	460
Middle Atlantic	37	38	1,429	1,286	34.7	1,347	New York, N.Y.	560	
							Philadelphia, Pa.	367	
							Pittsburgh, Pa.	321	
							Buffalo, N.Y.	267	1,515
South Atlantic	37	40	2,889	2,600	75.9	3,201	Washington, D.C.	508	
							Norfolk, Va.	236	
							Roanoke, Va.	100	
							Raleigh, N.C.	147	
							Charlotte, N.C.	180	
							Charleston, W. Va.	100	
							Charleston, S.C.	118	
							Atlanta, Ga.	592	
							Jacksonville, Fla.	220	
							Tampa, Fla.	500	
							Miami, Fla.	500	3,201
East North Central	42	42	1,758	1,582	38.5	1,678	Columbus, Ohio	240	
							Detroit, Mich.	344	
							Chicago, Ill.	548	
							Indianapolis, Ind.	240	
							Milwaukee, Wis.	306	1,678
East South Central	15	15	732	659	47.6	727	Louisville, Ky.	110	
							Memphis, Tenn.	110	
							Nashville, Tenn.	102	
							Knoxville, Tenn.	100	
							Birmingham, Ala.	105	
							Mobile, Ala.	100	
							Jackson, Miss.	100	727
West North Central	17	18	1,028	925	54.7	989	Minneapolis-St. Paul, Minn.	175	
							Davenport-Rock Island-Moline, Iowa	100	
							Des Moines, Iowa	100	
							Omaha-Council Bluffs, Neb.	100	
							St. Louis, Mo.	175	
							Kansas City, Kan.	139	
							Wichita, Kan.	100	
							Springfield, Mo.	100	989
West South Central	24	24	2,175	1,958	90.2	2,206	Oklahoma City, Okla.	170	
							Little Rock, Ark.	100	
							Dallas, Tex.	500	
							San Antonio, Tex.	386	
							Houston, Tex.	700	
							New Orleans, La.	250	
							Shreveport, La.	100	2,206
			TOTAL	9,582	TOTAL	10,776	GRAND TOTAL		10,776

Figure 18. Regional distribution centers for wallboard sales.

region was more than 150 miles from a distribution center, although exceptions were made for large areas with low populations. The locations selected are population centers with rail and highway transportation. The portion of the projected 1985 demand assigned to each distribution center is shown in Table 8. The quantity was determined by the population served and the geographical relationships to other distribution centers. A portion of the New England demand was assigned to the New York distribution center because of its proximity to lower New England. The quantity assigned to low-growth regions (New York, Washington, D.C., Detroit, and Chicago) was reduced to 70% of the projected demand and the remaining 30% was allocated to other distribution centers. In addition, a minimum of 100,000 tons was used for distribution centers in less populated areas.

DRYING AND BRIQUETTING

The moisture content of the FGD gypsum can be regarded as a marketing liability, both because of the increased freight costs and because of the possible resistance to its use by users who might find the moisture a handicap. The possible resistance of users is difficult to assess, depending as it does on their particular equipment, processes, and experiences. The tangible economic factors can, however, be quantitied by incorporating the costs of drying into the FGD costs and evaluating the market potential using these FGD costs and revised freight costs. The drying costs for this evaluation were obtained from industrial sources with experience in drying chemical gypsum. The dryer is a pneumatic flash dryer in which the gypsum is entrained in a high-velocity stream of high-temperature air for a short time, during which the surface moisture is rapidly evaporated but the gypsum is not calcined. The drying costs were based on the quantity of gypsum dried and ranged from 4 to 6 $/ton. A final moisture content of 2.5% water was used.

The granular nature of FGD gypsum could also be a detriment to its use by some cement plants equipped and accustomed to handling crushed gypsum rock. This could be avoided by briquetting the gypsum marketed to cement plants. To evaluate the effects of briquetting, the costs of briquetting were obtained from industry sources and included in the FGD costs along with drying, which is necessary for briquetting. For briquetting, the gypsum must be dried to 1% water. The briquetting machine consists of two driven, counter-rotating rolls with matching cavities. The dried gypsum is fed from above into the confluence of the rolls, where it fills the cavities and is compacted into briquettes at the point of contact of the rolls. The compression raises the temperature of the gypsum about 100°F, producing a briquette that is almost moisture free and impervious to water. The briquettes fall from the bottom of the rolls where they are screened to remove undersized material and conveyed to a stockpile. Fines are collected in cyclones and bag filters and returned with the undersized material to the briquetting machine.

RESULTS

The following sections present (1) the results of an evaluation of power plant characteristics that affect their potential to market FGD gypsum economically; (2) the characteristics of the 14 power plants used in the marketing study, along with their individual relationships to the cement and wallboard plant gypsum market; and (3) the results of evaluations of marketing potential under various conditions for the 14-power-plant marketing model. The 14-power-plant model constitutes the main body of the study. In it, the 14 power plants produced and marketed FGD gypsum under essentially competitive conditions. The procedures used and the development of costs are discussed in detail in the methodology section. Briefly, only sales to the 114 cement plants and 52 wallboard plants in the 37-state study area were considered. Sales were based on the ability of the power plant to supply FGD gypsum at a "savings," a lower delivered cost than an "allowable cost" based on the cost of natural gypsum determined for each cement and wallboard plant. The savings is essentially a sales revenue. In this study, it was used only as an indication of the competitiveness of the FGD gypsum. If two or more power plants could supply the same cement or wallboard plant, the power plant producing the largest savings was selected as being the most competitive. In most of the evaluations, the delivered cost of the FGD gypsum was the freight cost offset by the incremental cost of the power plant. The incremental cost is the difference, in $/ton, between the cost of the gypsum-producing and the waste-producing FGD processes. It was negative for all of the power plants used in the study (the gypsum-producing process was less expensive) and thus the incremental cost served to offset freight costs.

The 14-power-plant model was used to evaluate the FGD gypsum marketing potential under the following marketing conditions:

- Sale of granular as-produced gypsum containing 10% water with freight costs offset by the incremental cost and an allowable cost equal to 90% of the cost of the natural gypsum supply of each cement and wallboard plant. Three cases were evaluated:

  - Sales only to cement plants

  - Sales only to wallboard plants

  - Sales to a combined market of cement and wallboard plants

- Sale of granular as-produced gypsum containing 10% water with a zero incremental cost (a delivered cost equal to freight costs) and an allowable cost equal to 90% of the cost of the natural gypsum supply of each cement and wallboard plant. Three cases were evaluated:

- Sales only to cement plants

- Sales only to wallboard plants

- Sales to a combined market of cement and wallboard plants

- Sale of granular gypsum dried to a 2.5% water content with an allowable cost equal to the cost of the natural gypsum supply of each cement and wallboard plant. Sales to a combined market of cement and wallboard plants were determined.

- Sale of granular gypsum dried to a 2.5% water content to wallboard plants and the same gypsum briquetted to cement plants with an allowable cost equal to the cost of the natural gypsum supply of each cement and wallboard plant. Sales to a combined market of cement and wallboard plants were determined.

- Production of wallboard in hypothetical wallboard plants located at the power plants, with shipment of the wallboard to hypothetical regional distribution centers. Freight costs were compared with wallboard freight costs from existing wallboard plants to the same distribution centers.

POWER PLANT CHARACTERISTICS

One hundred and four power plants were evaluated, using the scrubbing cost generator described previously, to compare the costs of the fixation and landfill process and the gypsum process. From these, the 14 power plants used in this study were selected. The cost differences are expressed in dollars per ton of gypsum produced, determined by subtracting the annual revenue requirements of the fixation and landfill process from those of the gypsum process and dividing by the tons of gypsum produced annually by the gypsum process. This incremental cost provides a direct means of determining the delivered cost of the gypsum. A negative incremental cost results when the gypsum process is less expensive than the fixation and landfill process.

A comparison of the average power plant characteristics for cases in which the incremental cost was negative and positive, and the average power plant conditions for the 14 power plants used in the study, is shown in Table 9. Fifty-two of the one hundred and four power plants had negative incremental costs, which ranged from near zero to -26 $/ton. The gypsum process was economically favored by large gypsum production rates in relation to boiler size. The power plants with negative incremental costs produced an average of 310,000 ton/yr of gypsum (a total of 16.1 million ton/yr), while the power plants with positive incremental costs produced an average of only 48,000 ton/yr (a total of 2.5 million ton/yr). This is reflected in the coal sulfur content, which averaged 3.3% for the power plants with negative incremental costs and 1.4% for the power plants with positive incremental costs. The total boiler size (MW scrubbed) was also higher for the power plants with negative incremental costs, but size alone did not favor the gypsum process unless combined with high gypsum production rates. The ratio of gypsum produced to MW scrubbed was 0.32 kton/MW for the power plants with negative incremental costs and 0.07 kton/MW for power plants with positive incremental costs, although the average MW scrubbed for those with negative incremental costs was only 40% higher. In general, the gypsum process was economically favored by high coal sulfur contents combined with low emission limits, resulting in a high gypsum production rate in relation to the MW scrubbed.

TABLE 9. CHARACTERISTICS OF ALL POWER PLANTS SCREENED

Lowest cost process	MW scrubbed	Coal, %S	Gypsum, kton/yr
Gypsum			
Average	960	3.3	310
High	3,248	5.5	1,599
Low	150	1.3	39
No. of plants	52	52	52
Fixation-landfill			
Average	709	1.4	48
High	2,533	3.2	163
Low	115	0.4	<1
No. of plants	52	52	52
Power plants selected			
Average	1,077	3.6	336
High	3,248	5.5	700
Low	425	1.7	160
No. of plants	14	14	14

These relationships are further illustrated by the average characteristics of the 14 power plants selected from those with negative incremental costs for evaluation in this study. The average gypsum production rate was 336,000 ton/yr, the average coal sulfur content was 3.6%, and the average MW scrubbed was 1,077. The ratio of gypsum produced to MW scrubbed, however, was 0.31 kton/MW, essentially equivalent to the average of all power plants with negative incremental costs.

The locations of the 14 power plants used in the study are shown in Figure 19. Features of the power plants are shown in Table 10. The incremental costs were the most favorable of those among the power plants screened, ranging from -13 to -26 $/ton of gypsum produced. The plant

Figure 19. Locations of power plants.

TABLE 10. CHARACTERISTICS OF POWER PLANTS USED IN THE STUDY

Power plant, County, State	MW scrubbed	Boilers	Initial operation	Coal		SO_2 Removal, %	Gypsum production[a]		
				Btu/lb	%S		kton/yr	kton/MW/yr	Incremental cost, $/ton
Pleasants, W. Va.	1,252	2	1979-1980	12,000	3.5	78	307	0.25	-19
Coshocton, Ohio	750	2	1976-1978	10,300	4.4	85	483	0.64	-20
Monroe, Mich.	3,248	4	1971-1974	12,400	3.0	73	700	0.22	-18
Boone, Ky.	600	1	1981	11,000	4.2	83	197	0.33	-13
Trimble, Ky.	495	1	1985	10,400	4.2	90	166	0.34	-23
Jefferson, Ky.	1,582	4	1972-1982	10,900	3.8	90	577	0.36	-24
Muhlenberg, Ky.	1,408	2	1963	10,300	4.2	84	544	0.39	-18
Pike, Ind.	1,030	2	1977-1983	11,000	3.2	78	254	0.25	-20
Sullivan, Ind.	980	2	1981-1982	10,700	3.7	81	282	0.29	-20
Randolph, Mo.	670	1	1981	9,500	5.5	89	363	0.54	-16
Atascosa, Tex.	800	2	1980-1984	5,000	1.7	81	222	0.28	-22
Hillsborogh, Fla.	425	1	1985	11,600	3.2	88	160	0.38	-20
Putnam, Fla.	1,240	2	1983-1985	11,500	3.0	88	271	0.22	-26
Duval, Fla.	600	1	1985	10,500	3.2	89	182	0.30	-22
Total	15,080	27					4,708		
Average	1,077		1978	10,500	3.6	84	336	0.34	-20

a. Dry weight, 100% gypsum

locations range from West Virginia to Texas and Michigan to Florida, with a concentration in the Ohio River valley. The plants are characterized by high-sulfur coal and stringent emission limitations (4 of the 14 plants are scheduled for startup in 1985, and for this study were assumed to be subject to the 1979 NSPS). Twelve of the plants are using or are committed to limestone or lime FGD and two have not announced definite emission control plans.

The individual boilers range from 326 to 826 MW in size, with an average size of 559 MW, and are relatively new. The startup dates range from 1963 to 1985, but only two boilers were started up before 1971, and the average startup date is 1978. Seven boilers are scheduled for startup in 1983 through 1985. As a result, the boilers are subject to stringent emission limitations. The SO_2 reduction requirements range from 73% to 90% and average 84%. All of the boilers burn bituminous coal except the two boilers at one power plant, which burn lignite. The lignite is unusual, however; it has an unusually low heating value and a very high-sulfur content compared with most lignites (66). This was the only lignite-fired power plant among several evaluated that had a negative incremental cost.

MARKET CHARACTERISTICS AND POTENTIAL

As an initial step in evaluating the market for FGD gypsum, the delivered cost (freight offset by incremental cost) of the gypsum produced by each of the 14 power plants was determined for every cement plant within 500 miles and every wallboard plant within 250 miles of the power plant. The number of these plants within these ranges--which represent the approximate marketing limitations imposed by freight costs--is an indication of the structure of the market within reach of the power plant. The number of these consumers to which FGD gypsum can be delivered at a cost competitive with the cost of natural gypsum is a measure of the potential market for the power plant.

The geographic relationships of the power plants to cement plants are shown in Figure 20 and comparative data are shown in Table 11. Only 2 of the 114 cement plants in the study area do not lie within 500 miles of at least 1 of the power plants. The smallest number of cement plants within 500 miles of a power plant is 19 for the Hillsborough plant. The location of this power plant, on the coast of the Florida peninsula, limits the number of cement plants available, as it does for some of the other power plants on the periphery of the study area. The power plants in the eastern interior of the study area are within 500 miles of 50 or more cement plants.

The percentage of cement plants within 500 miles to which gypsum could be supplied at a savings (a delivered cost less than 90% of the natural gypsum supply) from each power plant ranged from 64% to 94%. On the average, the power plants were able to supply gypsum at a savings to 82% of the cement plants within 500 miles of them. Overall, 108 of the 114 cement plants in the study area could be supplied at a savings by at least 1 of the power plants. The delivered cost (freight costs offset by the incremental cost) of gypsum

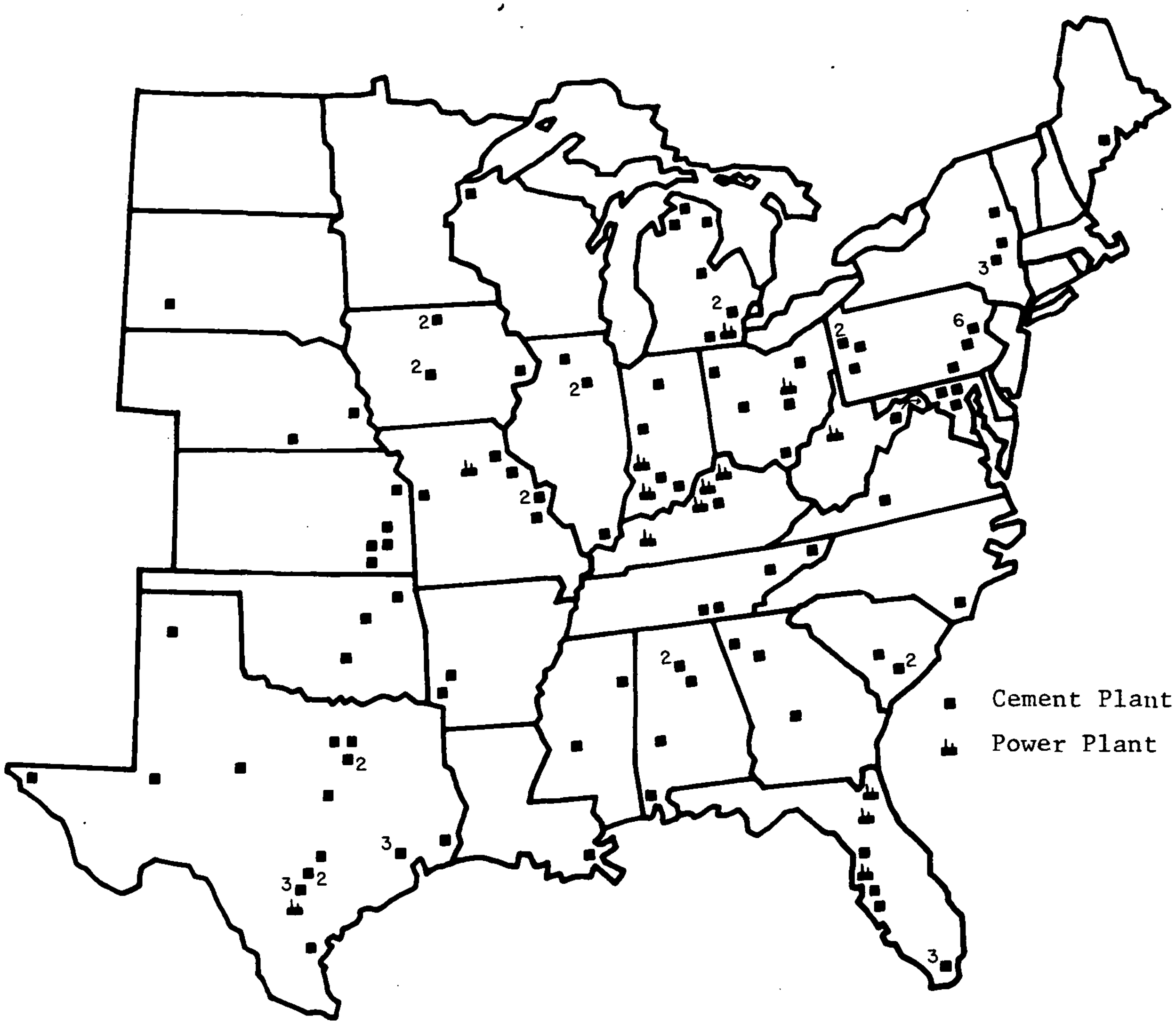

Figure 20. Geographic relationship of study power plants to cement plants.

TABLE 11. RELATIONSHIP OF POWER PLANTS TO CEMENT PLANTS

County, State	Power plant: Incremental cost, $/ton	Power plant: Production, kton/yr	Cement plants within 500 miles: Number	Distance, miles	Requirement, kton/yr	Freight, $/ton	Delivered cost, $/ton
Pleasants, W. Va.	-19	307	53	60 - 485	11 - 108	9 - 49	-10 - 30
Coshocton, Ohio	-20	483	57	20 - 500	11 - 108	3 - 50	-17 - 30
Monroe, Mich.	-18	700	48	10 - 500	12 - 108	1 - 50	-17 - 32
Boone, Ky.	-13	197	50	60 - 490	11 - 108	9 - 49	-4 - 36
Trimble, Ky.	-23	166	55	20 - 500	11 - 108	3 - 50	-20 - 27
Jefferson, Ky.	-24	577	52	10 - 500	11 - 108	1 - 50	-23 - 26
Muhlenberg, Ky.	-18	544	58	80 - 500	10 - 58	12 - 50	-6 - 32
Pike, Ind.	-20	254	55	50 - 500	10 - 64	7 - 50	-13 - 30
Sullivan, Ind.	-21	282	54	55 - 495	11 - 108	8 - 50	-13 - 29
Randolph, Mo.	-16	363	37	55 - 500	9 - 58	8 - 50	-8 - 34
Atascosa, Tex.	-22	222	23	35 - 500	10 - 62	5 - 50	-17 - 28
Hillsborough, Fla.	-20	160	19	10 - 500	11 - 54	1 - 50	-19 - 30
Putnam, Fla.	-26	271	22	90 - 500	11 - 53	13 - 50	-13 - 24
Duval, Fla.	-22	182	25	130 - 500	11 - 54	19 - 50	-3 - 28

County, State	Cement plants with gypsum sales at savings: Number	Percent of total	Distance, miles	Total requirement, kton/yr	Freight, $/ton	Delivered cost, $/ton
Pleasants, W. Va.	44	83	60 - 485	1,345	8 - 49	-10 - 30
Coshocton, Ohio	52	91	20 - 500	1,668	3 - 50	-17 - 30
Monroe, Mich.	31	65	10 - 500	948	1 - 50	-17 - 32
Boone, Ky.	32	64	60 - 465	966	9 - 47	-4 - 37
Trimble, Ky.	46	84	20 - 500	1,367	3 - 50	-20 - 27
Jefferson, Ky.	46	88	10 - 480	1,358	1 - 48	-23 - 24
Muhlenberg, Ky.	43	74	80 - 480	1,203	12 - 48	-6 - 30
Pike, Ind.	46	84	50 - 490	1,325	7 - 49	-13 - 29
Sullivan, Ind.	51	94	55 - 485	1,479	8 - 49	-13 - 28
Randolph, Mo.	28	76	55 - 500	788	8 - 50	-8 - 34
Atascosa, Tex.	20	87	35 - 500	545	5 - 50	-17 - 28
Hillsborough, Fla.	17	89	10 - 490	532	1 - 49	-19 - 29
Putnam, Fla.	20	91	90 - 490	554	13 - 49	-13 - 23
Duval, Fla.	21	84	130 - 470	612	19 - 47	-3 - 25

ranged from -23 to -3 $/ton for the nearest cement plant to each power plant and reached into the 30 $/ton range for the more distant cement plants. Considered on an individual basis (with no competition from other power plants), all of the power plants were able to market all of their gypsum production to cement plants at a savings.

The gypsum requirements of cement plants are much smaller than the production rates of the power plants, however. With few exceptions, the projected 1985 gypsum requirements of the 114 cement plants in the study area lie in the 10,000- to 60,000-ton/yr range and the average for all of the plants is 30,000 ton/yr. The total requirement is 3.42 million ton/yr. The power plant production rates, on the other hand, range from 160,000 to 700,000 ton/yr, with an average of 336,000 ton/yr and a total production of 4.71 million ton/yr. An effective marketing structure requires an average of 12 cement plants for each power plant. Ten power plants with an average gypsum production of 336,000 ton/yr could fill all of the gypsum requirements of cement plants in the study area.

Cement plants offer a theoretical market for the gypsum production of most individual power plants, but they have a very limited capacity to sustain widespread production of FGD gypsum. The cement plant market is also diffuse. There is no large localized concentration of cement plants, so the marketing structure for most power plants would require a large number of cement plants scattered over a wide geographic area.

A similar evaluation for wallboard plants is shown in Figure 21 and Table 12, using a 250-mile distance because of the lower price attainable for wallboard gypsum. Reflecting the shorter distance and the smaller number of wallboard plants (52 in the study area), there are fewer potential wallboard plant customers for each power plant. For favorably situated power plants, there are up to eight wallboard plants within 250 miles; unfavorably situated plants have access to only one. On the average, there are five wallboard plants within 250 miles of the power plants used in this study. The delivered cost of gypsum ranged from -19 to 22 $/ton. There were potential sales with savings for every power plant to at least one wallboard plant and at up to eight wallboard plants for some. Three power plants, however, did not have markets for all of their production.

The wallboard plant market structure differs appreciably from the cement plant market structure. Although smaller in number, the wallboard plants have much larger gypsum requirements, both individually and in total. The 52 wallboard plants in the study area have a total gypsum requirement, projected to 1985, of 10.78 million ton/yr. The average plant requirement is 194,000 ton/yr and the range of individual plant requirements is 34,000 to 383,000 ton/yr. Thirty-two power plants with the same average production as the fourteen power plants used would be necessary to meet the projected 1985 wallboard gypsum demand in the study area. Wallboard gypsum thus has the potential to support a much wider use of gypsum-producing processes than cement plants do. In addition, the larger gypsum requirements of the wallboard plants result in a concentrated market. One or more power plants could

Figure 21. Geographic relationship of study power plants to wallboard plants.

TABLE 12. RELATIONSHIP OF POWER PLANTS TO WALLBOARD PLANTS

	Power Plant		Wallboard plants within 250 miles				
County, State	Incremental cost, $/ton	Production, kton/yr	Number	Distance, miles	Requirement, kton/yr	Freight, $/ton	Delivered cost, $/ton
Pleasants, W. Va.	-19	307	7	150 - 245	111 - 272	22 - 35	3 - 16
Coshocton, Ohio	-20	483	6	80 - 250	94 - 255	12 - 36	-8 - 16
Monroe, Mich.	-18	700	8	30 - 210	68 - 213	4 - 30	-14 - 12
Boone, Ky.	-13	197	8	110 - 245	85 - 358	16 - 35	3 - 22
Trimble, Ky.	-23	166	5	75 - 235	85 - 358	11 - 34	-12 - 11
Jefferson, Ky.	-24	577	4	75 - 250	85 - 358	11 - 36	-13 - 12
Muhlenberg, Ky.	-18	544	3	110 - 230	170 - 341	16 - 33	-2 - 15
Pike, Ind.	-20	254	3	40 - 210	85 - 358	6 - 30	-14 - 10
Sullivan, Ind.	-21	282	5	45 - 240	85 - 358	7 - 35	-15 - 14
Randolph, Mo.	-16	363	6	125 - 230	149 - 281	18 - 33	2 - 17
Atascosa, Tex.	-22	222	1	205	<222	30	8
Hillsborough, Fla.	-20	160	4	10 - 250	170 - 315	1 - 36	-19 - 16
Putnam, Fla.	-26	271	6	50 - 175	170 - 315	7 - 25	-19 - 1
Duval, Fla.	-22	182	6	10 - 180	170 - 315	1 - 26	-21 - 4

	Wallboard plants with gypsum sales at savings					
County, State	Number	Percent of total	Distance, miles	Total requirement, kton/yr	Freight, $/ton	Delivered cost, $/ton
Pleasants, W. Va.	1	14	150	<307	22	3
Coshocton, Ohio	4	67	80 - 160	580	12 - 23	-8 - 3
Monroe, Mich.	8	100	30 - 210	945	4 - 30	-14 - 12
Boone, Ky.	3	38	110 - 220	440	16 - 32	3 - 19
Trimble, Ky.	3	60	75 - 230	784	11 - 33	-12 - 10
Jefferson, Ky.	3	75	75 - 250	784	11 - 36	-13 - 12
Muhlenberg, Ky.	3	100	110 - 230	869	16 - 33	-2 - 15
Pike, Ind.	3	100	40 - 210	784	6 - 30	-14 - 10
Sullivan, Ind.	4	80	45 - 235	912	7 - 34	-15 - 13
Randolph, Mo.	1	17	125	<363	18	2
Atascosa, Tex.	1	100	205	<222	30	8
Hillsborough, Fla.	4	100	10 - 250	961	1 - 36	-19 - 16
Putnam, Fla.	6	100	50 - 175	1,403	7 - 25	-19 - 1
Duval, Fla.	6	100	10 - 180	1,403	1 - 26	-21 - 4

supply one wallboard plant in some cases and the production of a single power plant would seldom exceed the requirements of more than a very few wallboard plants. However, the lack of a wallboard plant market for all of the production of 3 of the 14 power plants shows that the geographic relationships of the power plants and the wallboard plants are more important in the wallboard plant market than they are in the cement plant market.

SALES TO CEMENT PLANTS

The FGD gypsum marketing potential of the 14 power plants considered collectively, with sales only to cement plants, is shown in Table 13. Only sales that produced a savings (freight costs offset by the incremental cost and a delivered cost less than the allowable cost of 90% of the natural gypsum supply) were included. If more than one power plant could supply a cement plant--which was usually the case--the supply producing the largest savings was used.

Previously it was shown that all of the power plants, considered individually, could market all of their gypsum to cement plants at a savings. When considered collectively, with competition among power plants, some power plant sales were replaced by other power plants. Overall, 60%, 2.84 million ton/yr, of the power plant production was marketed. It supplied, wholly or in part, the requirements of 95 of the 108 cement plants which were potential markets and met 82% of the gypsum consumption of the 114 cement plants in the study area. Sales of individual power plants ranged from 100% of their production for four plants to none for two plants.

The power plant locations determined the sales pattern. Usually there was a high degree of competition between power plants for the available market. Only 25 cement plants could be supplied by only 1 power plant and 20 of these were Texas plants that were within 500 miles of only the Atascosa plant. In the model used, the Atascosa plant was unique in being a sole FGD gypsum supplier for a 545,000-ton/yr cement plant gypsum market, which was over twice its production and thus assured 100% sales independent of competition from other power plants in the model. Only two other power plants were sole suppliers. The Randolph plant was a sole supplier for four cement plants, two of which accounted for 4% of its sales, and the Putnam plant was a sole supplier for one plant, which accounted for 18% of its sales. With these exceptions, the power plants competed with at least 1 and, in several cases, 8 to 10 other power plants for each cement plant market. On the average, each cement plant could be supplied at a savings by any of seven power plants. A comparison of this competition with sales and power plant characteristics is shown in Table 14. This high level of competition was the result of the diffuse and relatively uniform geographic distribution of cement plants, the relatively nonuniform distribution of the power plants used in the model, and the large range over which FGD gypsum could be economically supplied to cement plants, particularly using incremental costs to offset freight costs. The degree of competition is illustrative of the cement plant market for FGD gypsum but it was reflected only imperfectly in sales because it does not

TABLE 13. SALE TO CEMENT PLANTS

Power plant County, State	Incremental cost, $/ton	Cement plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$/yr
Pleasants, W. Va.	-19	Greene, N.Y.	440	30	26	25	130
(307 kton/yr)		Frederick, Md.	210	23	19	11	228
		Carroll, Md.	230	21	42	14	294
		Roanoke, Va.	165	28	53	5	1,219
		Lawrence, Ohio	95	30	14	-5	490
		Greene, N.Y.	440	29	31	25	124
		Washington, Md.	190	24	27	8	432
		Berkeley, W. Va.	170	25	41	6	779
		Berks, Pa.	295	24	39	17	273
					292		3,969
Coshocton, Ohio	-20	Albany, N.Y.	450	32	68	25	476
(483 kton/yr)		Muskingum, Ohio	20	29	35	-17	1,610
		Northhampton, Pa.	350	23	44	19	176
		Northhampton, Pa.	350	24	33	19	165
		Northhampton, Pa.	350	24	28	19	140
		Greene, N.Y.	450	31	20	25	120
		Northhampton, Pa.	350	23	29	19	116
		Lawrence, Pa.	100	32	40	-6	1,520
		Greene, N.Y.	450	29	6	25	24
		Allegheny, Pa.	100	35	28	-6	1,148
		Northhampton, Pa.	350	23	18	19	72
		Lawrence, Pa.	100	32	31	-6	1,178
		York, Pa.	290	23	20	15	160
		Butler, Pa.	120	35	15	-3	570
		Stark, Ohio	50	27	13	-13	520
		Northhampton, Pa.	350	24	35	19	175
		Warren, N.Y.	490	36	20	29	140
					483		8,310

(Continued)

TABLE 13. (Continued)

Power plant County, State	Incremental cost, $/ton	Cement plant County, State	Distance, miles	Allowable cost, $/ton	Sales, kton/yr	Delivered cost, $/ton	Savings, k$/yr
Monroe, Mich.	-18	Bay, Mich.	125	20	22	0	440
(700 kton/yr)		Monroe, Mich.	10	20	44	-17	1,628
		Paulding, Ohio	80	23	24	-6	696
		Wayne, Mich.	30	20	48	-14	1,632
		Charlevoix, Mich.	250	26	64	18	512
		Alpena, Mich.	220	20	108	14	648
		Emmet, Mich.	260	25	29	17	232
		Wayne, Mich.	30	19	18	-14	594
					357		6,382
Boone, Ky.	-13	None					
(197 kton/yr)							
Trimble, Ky.	-23	Cass, Ind.	165	32	21	1	651
(166 kton/yr)		Greene, Ohio	115	29	32	-6	1,120
					53		1,771
Jefferson, Ky.	-24	Hamilton, Tenn.	220	40	21	8	672
(577 kton/yr)		Knox, Tenn.	190	29	24	3	624
		Lawrence, Tenn.	70	16	32	-14	960
		Clark, Ind.	25	21	51	-20	2,091
		Polk, Ga.	300	45	11	13	352
		Sullivan, Tenn.	220	16	15	8	120
		Lowndes, Miss.	370	43	23	15	644
		Jefferson, Ky.	10	23	29	-23	1,334
					206		6,797
Muhlenberg, Ky.	-18	Jefferson, Ala.	260	53	20	17	720
(544 kton/yr)		Rankin, Miss.	390	33	10	21	120
		Shelby, Ala.	285	50	30	17	990
		Massac, Ill.	80	32	58	-6	2,204
		Jefferson, Ala.	260	53	35	17	1,260
		Marion, Tenn.	175	43	12	7	432
					165		5,726

(Continued)

TABLE 13. (Continued)

Power plant County, State	Incremental cost, $/ton	Cement plant County, State	Distance, miles	Allowable cost, $/ton	Sales, kton/yr	Delivered cost, $/ton	Savings, k$/yr
Pike, Ind. (254 kton/yr)	-20	None					
Sullivan, Ind. (282 kton/yr)	-21	St. Louis City, Mo.	165	34	14	3	434
		La Salle, Ill.	180	27	18	5	396
		Cerro Gordo, Iowa	420	22	33	21	33
		Putnam, Ind.	55	22	33	-13	1,155
		Lee, Ind.	210	26	25	9	425
		La Salle, Ill	180	28	28	5	644
		St. Louis City, Mo.	165	34	33	3	1,023
		Cerro Gordo, Iowa	420	22	51	21	51
					235		4,161
Randolph, Mo. (363 kton/yr)	-16	Neosho, Kan.	205	32	23	14	414
		Cass, Neb.	230	25	4	17	32
		Pike, Mo.	75	27	55	-5	1,760
		Wilson, Kan.	225	32	18	17	270
		Marion, Mo.	55	25	26	-8	858
		Montgomery, Kan.	245	34	17	19	255
		Mayes, Okla.	275	34	32	18	512
		Scott, Iowa	190	20	23	11	207
		Jackson, Mo.	110	28	25	0	700
		Allen, Kan.	195	32	26	12	520
		Polk, Iowa	170	19	13	9	130
		Douglas, Wis.	500	48	9	34	126
		Polk, Iowa	170	19	21	9	210
		Jefferson, Mo.	135	37	51	4	1,683
		Wyandotte, Kan.	130	27	20	3	480
					363		8,157

(Continued)

TABLE 13. (Continued)

Power plant County, State	Incremental cost, $/ton	Cement plant County, State	Distance, miles	Allowable cost, $/ton	Sales, kton/yr	Delivered cost, $/ton	Savings, k$/yr
Atascosa, Tex.	-22	Bexar, Tex.	35	22	30	-17	1,170
(222 kton/yr)		Bexar, Tex.	35	22	16	-17	624
		Nueces, Tex.	100	36	14	-8	616
		Hayes, Tex.	90	23	28	-9	896
		Comal, Tex.	65	21	41	-13	1,394
		Ellis, Tex.	265	36	20	13	460
		Bexar, Tex.	35	22	22	-17	858
		McLennan, Tex.	200	30	14	7	322
		Comal, Tex.	65	21	37	-13	1,258
					222		7,598
Hillsborough, Fla.	-20	Hillsborough, Fla.	10	20	48	-19	1,872
(160 kton/yr)		Dade, Fla.	200	20	32	9	352
		Manatee, Fla.	40	22	15	-14	540
		Dade, Fla.	200	20	11	9	121
		Dade, Fla.	200	20	28	9	308
		Hernando, Fla.	40	25	26	-14	1,014
					160		4,207
Putnam, Fla.	-26	Marengo, Ala.	410	41	33	15	858
(271 kton/yr)		Dorchester, S.C.	275	26	38	8	684
		New Hanover, N.C.	405	18	26	15	78
		Mobile, Ala.	405	32	21	15	357
		Dade, Fla.	295	20	42	3	714
		Fulton, Ga.	330	43	28	12	868
		Orangeburg, S.C.	290	24	54	9	810
					242		4,369
Duval, Fla.	-22	Dorchester, S.C.	210	26	25	8	450
(182 kton/yr)		Houston, Ga.	200	37	35	7	1,050
					60		1,500
(4,708 kton/yr)					2,838		62,947

TABLE 14. CEMENT PLANT SALES VERSUS COMPETITION AND POTENTIAL SALES

	Incremental cost, $/ton	Production, kton/yr	Sales		Average competing power plants[a]	Potential sales, kton/yr[b]	Potential customers[b]
			kton/yr	No. plants			
Pleasants, W. Va.	-19	307	292	9	5.3	1,345	44
Coshocton, Ohio	-20	483	483	17	5.3	1,668	52
Monroe, Mich.	-18	700	357	8	6.6	948	31
Boone, Ky.	-13	197	0	0	7.8	966	32
Trimble, Ky.	-23	166	53	2	7.0	1,367	46
Jefferson, Ky.	-24	577	206	8	7.0	1,358	46
Muhlenberg, Ky.	-18	544	165	6	6.9	1,203	43
Pike, Ind.	-20	254	0	0	6.9	1,325	46
Sullivan, Ind.	-21	282	235	8	6.3	1,479	51
Randolph, Mo.	-16	363	363	15	4.3	788	28
Atascosa, Tex.	-22	222	222	9	none	545	20
Hillsborough, Fla.	-20	160	160	6	4.8	532	17
Putnam, Fla.	-26	271	242	7	4.5	554	20
Duval, Fla.	-22	182	60	2	5.7	612	21

Note: All gypsum quantities are dry weight, 100% gypsum.
Freight costs are offset by the incremental cost.
Allowable cost is 90% of the cost of the native gypsum supply.

a. Average number of other power plants that can sell with a saving to each cement plant that can be supplied at a saving by the listed power plant.

b. All cement plants that can be supplied at a savings by the listed power plant.

indicate the effectiveness of the competition. A power plant may have a high degree of competition but be so situated that some of the competition is ineffective. For example, the Muhlenberg plant, with access to the South and West, had sales of 165,000 ton/yr, while the Pike plant, more nearly surrounded by effective competition, had no sales.

Power plant location, combined with the small gypsum requirements of cement plants, was the determining factor in the sales pattern. The cluster of power plants in the lower Ohio River valley saturated the nearby market with only a portion of their production and was unable to compete for most more distant markets because of other more favorably situated power plants. The Trimble and Jefferson plants, both with a cement plant nearby and large incremental costs, were the most successful, able to capture the nearby market, and compete successfully for some more distant markets, but two of the plants in this area could market none of their production.

Power plants on the periphery of the marketing area were more successful because their locations usually allowed them to dominate a portion of the marketing area. The Coshocton and Pleasants plants had favorable access to a large eastern market, the Monroe plant to a large Michigan market, and the Randolph plant to almost all of the large market west of the Mississippi River. In the South, the Hillsborough plant had a very favorable access to the central and south Florida market and the two other Florida plants, although competing with each other, were able to compete effectively in the Southeast. The Sullivan plant had favorable access toward the Northwest and the Muhlenberg plant toward the South and West. All of these plants, in addition to the Atascosa plant with no competition, had substantial sales and four were able to market all of their production.

Sales patterns were also influenced by the allowable cost, based on the cost of natural gypsum at each cement plant. The high allowable cost of cement plants in the Southeast, permitting transportation of FGD gypsum over longer distances, accounted for most of the Muhlenberg plant sales and appreciable sales by three other power plants.

Transportation distances ranged upward to 500 miles and averaged 208 miles for the 97 cement plant sales. Transportation distances had little relationship to the percentage of gypsum production marketed. Shorter average transportation distances resulted from a favorable location, illustrated by the Atascosa plant (99-mile average), or competition that precluded distant markets, illustrated by the Trimble plant (140-mile average). Longer transportation distances were primarily the result of locations that allowed competitive access to distant markets, such as the Coshocton plant (278-mile average) and the Putnam plant (344-mile average), and of economic factors such as the allowable cost, as previously discussed.

The total savings was 62.95 million \$/yr, 22 \$/ton based on the gypsum marketed and 13 \$/ton based on the gypsum produced. The savings ranged from 14 to 35 \$/ton of gypsum marketed for the individual power plants and 8 to 34 \$/ton of gypsum produced. Short transportation distances and high allowable costs, of course, produced higher savings. In terms of $/ton of the gypsum sold, the effect of high allowable costs was substantial. The Atascosa plant, in an area of low-cost gypsum, sold all of its production at a savings of 34 $/ton and had an average transportation distance of 99 miles. The Muhlenberg plant, with most of its sales in the Southeast, had an average transportation distance of 242 miles and an average savings of 35 $/ton of gypsum marketed because of an average 44 $/ton allowable cost.

The effect of the incremental cost on the marketing pattern was also substantial. The primary effect was on sales volume (which it increased by offsetting freight costs and allowing sales over longer distances, as is discussed in a following evaluation) but it also affected the distribution of some sales among power plants. The large incremental costs of the Trimble and Jefferson plants were responsible for five out of their nine sales, at the expense of the Boone, Sullivan, Muhlenberg (two), and Duval plants. The Putnam plant captured four of its five sales from the Duval plant because of its larger incremental cost. Otherwise, only scattered sales were captured by one power plant from another because of incremental cost differences.

Overall, the FGD gypsum was highly successful in capturing the cement plant gypsum market. The production of the 14 plants exceeded the requirements of the 114 cement plants in the study area by 36% and was limited to supplying 77% of these requirements only by the locations of the power plants. On the basis of individual power plants, however, the results reveal a highly interactive relationship in which the ability of a power plant to market FGD gypsum depended on competition from other power plants both nearby and distant.

SALES TO WALLBOARD PLANTS

The FGD gypsum marketing potential of the 14 power plants considered collectively, with sales only to wallboard plants, is shown in Table 15. Again, only sales that produced a savings (freight costs offset by the incremental cost and a delivered cost less than 90% of the cost of the natural gypsum supply) were included. In cases in which more than one power plant could supply the same wallboard plant, the supply producing the largest savings was used.

Previously it was shown that all of the power plants could market gypsum to wallboard plants when treated individually, although, unlike the cement plant market, only 11 of the power plants could market all of their production. Considered collectively, competition eliminated or reduced sales to wallboard plants as it did for sales to cement plants. Overall, 58%, 2.72 million ton/yr, of the power plant production was marketed by 12 power plants. It supplied, wholly or in part, the requirements of 17 of the 20 wallboard plants to which sales could be made at a savings. The sales represented 27% of the 10.78 million ton/yr gypsum requirements of the 52 wallboard plants in the study area and 74% of the requirements of the 20 wallboard plants to which sales could be made at a savings. Sales ranged from 100% of their production for six power plants to none for two power plants.

TABLE 15. SALE TO WALLBOARD PLANTS

Power plant County, State	Incremental cost, $/ton	Wallboard plant, County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Pleasants, W. Va. (307 kton/yr)	-19	None					
Coshocton, Ohio (483 kton/yr)	-20	Lorain, Ohio	80	14	128	-8	2,816
					128		2,816
Monroe, Mich. (700 kton/yr)	-18	Kent, Mich.	120	9	102	-1	1,020
		Kent, Mich.	120	9	68	-1	680
		Iosco, Mich.	170	9	78	7	1,248
		Wayne, Mich.	30	13	213	-14	5,751
		Ottawa, Ohio	35	9	128	-13	2,816
		Ottawa, Ohio	35	9	111	-13	2,442
					700		13,957
Boone, Ky. (197 kton/yr)	-13	None					
Trimble, Ky. (166 kton/yr)	-23	Lake, Ind.	165	24	85	1	1,955
					85		1,955
Jefferson, Ky. (577 kton/yr)	-24	Martin, Ind.	75	9	59	-13	1,298
		Martin, Ind.	75	9	104	-13	2,288
					163		3,586
Muhlenberg, Ky. (544 kton/yr)	-18	Crittenden, Ark.	230	33	170	15	3,060
					170		3,060
Pike, Ind. (254 kton/yr)	-20	Martin, Ark.	40	9	254	-14	5,842
					254		5,842
Sullivan, Ind. (282 kton/yr)	-21	Martin, Ark.	45	9	282	-14	6,486
					282		6,486

(Continued)

TABLE 15. (Continued)

Power plant County, State	Incremental cost, $/ton	Wallboard plant, County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Randolph, Ind.	-16	Des Moines, Iowa	125	12	170	2	1,700
(363 kton/yr)					170		1,700
Atascosa, Tex.	-22	Harris, Tex.	205	17	153	8	1,377
(222 kton/yr)					153		1,377
Hillsborough, Fla.	-20	Hillsborough, Fla.	10	14	160	-19	5,280
(160 kton/yr)					160		5,280
Putnam, Fla.	-26	Duval, Fla.	50	14	170	-19	5,610
(271 kton/yr)		Duval, Fla.	50	14	101	-19	3,333
					271		8,943
Duval, Fla.	-22	Glynn, Ga.	60	23	182	-17	7,280
(182 kton/yr)					182		7,280
(4,708 kton/yr)					2,718		62,282

Note: All gypsum quantities are dry weight, 100% gypsum.
Freight costs are offset by the incremental cost.
Allowable cost is 90% of the cost of the natural gypsum supply.

Because of the shorter economical transportation distances (a maximum of 250 miles, as compared with 500 miles for sales to cement plants) and the uneven geographic distribution and fewer number of wallboard plants, sole suppliers were more numerous among power plants in the wallboard plant market. Five power plants were sole suppliers for seven wallboard plants, all of which had a smaller gypsum requirement than the power plant production. These markets accounted for 40% of the sales for the Monroe plant (three wallboard plants) and all of the sales for the Sullivan, Muhlenberg, Randolph, and Atascosa plants. For the remaining wallboard plants, there were two to six potential power plant suppliers. A comparison of the competition for each power plant is shown in Table 16. As with the cement plants, the degree of competition was only poorly reflected in sales success. Location was even more important in marketing to wallboard plants than for cement plants because the lower allowable costs made freight costs a more important factor. Even with incremental costs offsetting freight costs, sales with savings could not be made to wallboard plants at gypsum mines or at import points with unusually low gypsum costs unless the power plant was very near the wallboard plant.

The total savings was 62.28 million $/yr, 23 $/ton based on the gypsum marketed and 13 $/ton based on the gypsum produced. The savings on the gypsum marketed ranged from 9 to 40 $/ton for the individual power plants and had no relationship to their success in marketing a large portion of their production. Essentially fortuitous geographic relationships of power plants and wallboard plants and the allowable costs determined the savings. Allowable costs ranged from 33 to 9 $/ton and averaged 14 $/ton. In the results, high allowable costs were more often associated with longer transportation distances than with high savings.

In contrast to the high degree of interaction among power plants in the cement plant market, in which distant power plants influenced the sales potential of other power plants, interactions were only effective over much shorter distances in the wallboard plant market. The average transportation distance was 93 miles, the maximum was 230 miles, and only 7 of the 19 sales involved transportation distances over 100 miles. There was competition among the cluster of power plants in the lower Ohio River valley, among the three Florida power plants, and to a lesser degree among the Michigan, Ohio, and West Virginia plants, but there was no interaction among these groups. Transportation distance eliminated all of the large Eastern Seaboard market north of Georgia where use of FGD gypsum can be regarded as particularly attractive because of the higher cost of imported gypsum, and all of the potential market extending from western Texas into Iowa.

In general, the wallboard plant market structure was more compact and rigid than the cement plant market structure. The shorter distances over which gypsum could be economically marketed to wallboard plants, the lesser number and uneven geographic distribution of wallboard plants, and the fewer number of wallboard plants needed to market the production of a power plant resulted in a simpler, and usually more localized, market structure. Power plant location was more critical but the market of favorably situated power plants was less susceptible to influences of other power plants.

TABLE 16. WALLBOARD PLANT SALES VERSUS COMPETITION AND POTENTIAL SALES

	Incremental cost, $/ton	Production, kton/yr	Sales kton/yr	Average competing power plants[a]	Potential sales, kton/yr	Potential customers	Sales, %
Pleasants, W. Va.	-19	307	None	2	<307	1	0
Coshocton, Ohio	-20	483	128	1.3	580	4	27
Monroe, Mich.	-18	700	700	1.3	945	8	100
Boone, Ky.	-13	197	None	5.0	440	3	0
Trimble, Ky.	-23	166	85	5.0	784	3	51
Jefferson, Ky.	-24	577	163	5.0	784	3	28
Muhlenberg, Ky.	-18	544	170	3.8	869	3	31
Pike, Ind.	-20	254	254	5.0	784	3	100
Sullivan, Ind.	-21	282	282	3.8	912	4	100
Randolph, Mo.	-16	363	<363	None	<363	1	47
Atascosa, Tex.	-22	222	<222	None	<222	1	69
Hillsborough, Fla.	-20	160	160	2.0	961	4	100
Putnam, Fla.	-26	271	271	1.8	1,403	6	100
Duval, Fla.	-22	182	182	1.8	1,403	6	100
		4,708	2,718				

Note: All gypsum quantities are dry weight, 100% gypsum.
Freight costs are offset by the incremental cost.
Allowable cost is 90% of the cost of the native gypsum supply.

a. Average number of other power plants that can sell with a saving to each wallboard plant that can be supplied at a saving by the listed power plant.
b. All wallboard plants that can be supplied at a savings by the listed power plant.

SALES TO THE COMBINED CEMENT AND WALLBOARD PLANT MARKET

The market potential for FGD gypsum in the combined cement plant and wallboard plant market is shown in Table 17. As in the previous evaluations, the power plant supply producing the highest savings was selected for each consumer, the allowable cost was 90% of the cost of the natural gypsum supply, and the freight costs were offset by the incremental costs. The sales to the combined market were appreciably higher than those to each of the individual markets. A total of 4.35 million ton/yr of gypsum was marketed to 79 cement plants and 14 wallboard plants, as compared with 2.84 million ton/yr to 95 cement plants and 2.72 million ton/yr to 17 wallboard plants when the markets were considered separately. All of the production of 12 of the power plants was marketed and a portion of the production of the other 2 was marketed. Overall, 92% of the power plant production was marketed, filling 63% of the cement plant requirements and 20% of the wallboard plant requirements in the study area (31% of the total gypsum requirements in the study area).

Six of the eight power plants with sales in both markets that could market all of their production in one market had increased savings by marketing in both markets. The other two had higher savings when marketing in only one market. The markets abandoned by these power plants provided increased sales for five power plants. The larger market did not, however, reduce competition to the extent that all of the power plant production could be marketed.

The total savings was 109.57 million \$/yr, 25 \$/ton of gypsum marketed and 23 \$/ton of gypsum produced, and was divided almost equally between the cement plant and wallboard plant markets. The higher savings, 25 \$/ton as compared with 22 \$/ton for the cement plant market alone, and 23 \$/ton for the wallboard market alone, was a result of the abandonment of more distant markets for less distant markets with higher savings. The average transportation distance in the combined market was 200 miles for cement plants and 77 miles for wallboard plants, as compared with 208 miles and 91 miles in the individual markets.

SALES TO CEMENT PLANTS WITH INCREMENTAL COST EXCLUDED

Sales to cement plants without adjustment of the delivered cost by incremental cost are shown in Table 18. This marketing model is the same as that shown in Table 13 except that freight costs are not offset by the incremental cost. In addition to increasing the delivered cost by 13 to 26 \$/ton, this reduced competition among power plants to a matter of distance alone; power plants with operating conditions economically favorable for gypsum production had no marketing advantage because freight costs alone determined the delivered cost.

Overall, 1.58 million ton/yr of gypsum was marketed to 55 cement plants, a reduction of 44% in the quantity of gypsum marketed, as compared with the sales with incremental cost offsetting freight costs. Only one plant, the

TABLE 17. SALE TO CEMENT AND WALLBOARD PLANTS

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$/yr
Pleasants, W. Va.	-19	C-Greene, N.Y.	440	30	26	25	130
(307 kton/yr)		C-Frederick, Md.	210	23	19	11	228
		C-Carroll, Md.	230	21	42	14	294
		C-Roanoke, Va.	165	28	53	5	1,219
		C-Lawrence, Ohio	95	30	14	-5	490
		C-Greene, N.Y.	450	29	37	25	148
		C-Washington, Md.	190	24	27	8	432
		C-Berkeley, W. Va.	170	25	41	6	779
		C-Berks, Pa.	295	24	39	17	273
		C-Northhampton, Pa.	325	24	9	20	36
					307		4,029
Coshocton, Ohio	-20	C-Albany, N.Y.	450	32	68	25	476
(483 kton/yr)		C-Muskingum, Ohio	20	29	35	-17	1,610
		C-Northhampton, Pa.	350	24	33	19	165
		C-Northhampton, Pa.	350	24	28	19	140
		C-Greene, N.Y.	450	31	20	25	120
		C-Lawrence, Pa.	100	32	40	-6	1,520
		C-Allegheny, Pa.	100	35	28	-6	1,147
		C-Lawrence, Pa.	100	32	31	-6	1,178
		C-York, Pa.	290	23	20	15	160
		C-Butler, Pa.	120	35	15	-3	570
		C-Stark, Ohio	50	27	13	-13	520
		C-Northhampton, Pa.	350	24	4	19	20
		C-Warren, N.Y.	490	36	20	29	140
		WB-Lorain, Ohio	80	14	128	-8	2,816
					483		10,583

(Continued)

TABLE 17. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$/yr
Monroe, Mich.	-24	C-Bay, Mich.	125	20	22	0	440
(700 kton/yr)		C-Monroe, Mich.	10	20	44	-17	1,628
		C-Paulding, Ohio	80	23	24	-6	696
		C-Wayne, Mich.	30	20	48	-14	1,632
		C-Wayne, Mich.	30	19	18	-14	594
		WB-Kent, Mich.	120	9	92	-1	920
		WB-Wayne, Mich.	30	13	213	-14	5,751
		WB-Ottawa, Ohio	35	9	128	-13	2,816
		WB-Ottawa, Ohio	35	9	111	-13	2,442
					700		16,919
Boone, Ky.	-13	C-Emmet, Mich.	465	37	29	34	87
(197 kton/yr)					29		87
Trimble, Ky.	-23	C-Cass, Ind.	165	32	21	1	651
(166 kton/yr)		C-La Salle, Ill.	275	28	28	10	504
		C-Greene, Ohio	115	29	32	-6	1,120
		WB-Lake, Ind.	165	24	85	1	1,955
					166		4,230
Jefferson, Ky.	-24	C-La Salle, Ill.	290	27	18	11	288
(577 kton/yr)		C-Marengo, Ala.	440	41	33	20	693
		C-Hamilton, Tenn.	220	40	21	8	672
		C-Knox, Tenn.	190	29	24	3	624
		C-Lawrence, Ind.	70	16	32	-14	960
		C-Lee, Ill.	320	26	25	15	275
		C-Clark, Ind.	25	21	51	-20	2,091
		C-Polk, Ga.	300	45	11	13	352

(Continued)

TABLE 17. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$/yr
Jefferson, Ky.		C-Houston, Ga.	420	37	35	18	665
(Continued)		C-Sullivan, Tenn.	220	16	15	8	120
		C-Lowndes, Miss.	370	43	23	15	644
		C-Orangeburg, S.C.	445	23	17	21	34
		C-Jefferson, Ky.	10	23	29	-23	1,334
		WB-Martin, Ind.	75	9	139	-13	3,058
		WB-Martin, Ind.	75	9	104	-13	2,288
					577		14,098
Muhlenberg, Ky.	-18	C-Mobile, Ala.	450	32	21	27	105
(544 kton/yr)		C-Jefferson, Ala.	260	53	20	17	720
		C-Rankin, Miss.	390	33	10	21	120
		C-Shelby, Ala.	285	50	30	17	990
		C-Massac, Ill.	80	32	58	-6	2,204
		C-Jefferson, Ala.	260	53	35	17	1,260
		C-Marion, Tenn.	175	43	12	7	432
		WB-Crittenden, Ark.	230	33	170	15	3,060
					356		8,891
Pike, Ind.	-20	WB-Martin, Ind.	40	9	254	-14	5,842
(254 kton/yr)					254		5,842
Sullivan, Ind.	-21	C-St. Louis City, Mo.	165	34	14	3	434
(282 kton/yr)		C-Putnam, Ind.	55	22	33	-13	1,155
		C-St. Louis City, Mo.	165	34	33	3	1,023
		WB-Martin, Ind.	45	9	202	-14	4,646
					282		7,258

(Continued)

TABLE 17. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$/yr
Randolph, Mo.	-16	C-Neosho, Kan.	205	32	23	14	414
(363 kton/yr)		C-Pike, Mo.	75	27	55	-5	1,760
		C-Wilson, Kan.	225	32	18	17	270
		C-Marion, Mo.	55	25	26	-8	858
		C-Montgomery, Kan.	245	34	17	19	255
		C-Mayes, Okla.	275	34	32	18	512
		C-Jackson, Mo.	110	28	25	0	700
		C-Allen, Kan.	195	32	26	12	520
		C-Douglas, Wis.	500	48	9	34	126
		C-Jefferson, Mo.	135	37	51	4	1,683
		C-Wyandotte, Kan.	130	27	20	3	480
		WB-Des Moines, Iowa	125	12	61	2	610
					363		8,188
Atascosa, Tex.	-22	C-Bexar, Tex.	35	22	30	-17	1,170
(222 kton/yr)		C-Bexar, Tex.	35	22	16	-17	624
		C-Nueces, Tex.	100	36	14	-8	616
		C-Hayes, Tex.	90	23	28	-9	896
		C-Comal, Tex.	65	21	41	-13	1,394
		C-Ellis, Tex.	265	36	20	13	460
		C-Bexar, Tex.	35	22	22	-17	858
		C-McLennan, Tex.	200	30	14	7	322
		C-Comal, Tex.	65	21	37	-13	1,258
					222		7,598

(Continued)

TABLE 17. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$/yr
Hillsborough, Fla.	-20	C-Hillsborough, Fla.	10	20	48	-19	1,872
(160 kton/yr)		C-Manatee, Fla.	40	22	15	-14	540
		C-Hernando, Fla.	40	25	26	-14	1,014
		WB-Hillsborough, Fla.	10	14	71	-19	2,343
					160		5,769
Putnam, Fla.	-26	C-Fulton, Ga.	330	43	28	12	868
(271 kton/yr)							
		WB-Duval, Fla.	50	14	170	-19	5,610
		WB-Duval, Fla.	50	14	73	-19	2,409
					271		9,002
Duval, Fla.	-22	WB-Glynn, Ga.	60	23	182	-17	7,280
(182 kton/yr)					182		7,280
(4,708 kton/yr)					4,352		109,559

Note: All gypsum quantities are dry weight, 100% gypsum.
Freight costs are offset by the incremental cost.
Allowable cost is 90% of the cost of the natural gypsum supply.

TABLE 18. SALES TO CEMENT PLANTS WITH INCREMENTAL COST EXCLUDED

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Pleasants, W. Va.	335	Roanoke, Va.	165	28	53	24	212
(307 kton/yr)		Lawrence, Ohio	95	30	14	14	224
		Berkeley, W. Va.	170	25	41	25	0
					108		436
Coshocton, Ohio	244	Muskingum, Ohio	20	29	35	3	910
(483 kton/yr)		Lawrence, Pa.	100	32	40	14	720
		Allegheny, Pa.	100	35	28	14	588
		Lawrence, Pa.	100	32	31	14	558
		Butler, Pa.	120	35	15	17	270
		Stark, Ohio	50	27	13	7	260
					162		3,306
Monroe, Mich.	371	Bay, Mich.	125	20	22	18	44
(700 kton/yr)		Monroe, Mich.	10	20	44	1	836
		Paulding, Ohio	80	23	24	12	264
		Wayne, Mich.	30	20	48	4	768
		Wayne, Mich.	30	19	18	4	270
					156		2,182
Boone, Ky.	506	Greene, Ohio	70	29	32	10	608
(197 kton/yr)					32		608
Trimble, Ky.	501	Clark, Ind.	20	21	51	3	918
(166 kton/yr)					51		918
Jefferson, Ky.	525	Knox, Tenn.	190	29	24	27	48
(577 kton/yr)		Jefferson, Ky.	10	23	29	1	638
					53		686

(Continued)

TABLE 18. (Continued)

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Muhlenberg, Ky.	473	Maringo, Ala.	345	41	33	39	66
(544 kton/yr)		Hamilton, Tenn.	190	40	21	27	273
		Jefferson, Ala.	260	53	20	35	360
		Polk, Ga.	250	45	11	36	99
		Shelby, Ala.	285	50	30	35	450
		Massac, Ind.	80	32	58	12	1,160
		Jefferson, Ala.	260	53	35	35	630
		Marion, Tenn.	175	43	12	25	216
		Lowndes, Miss.	280	43	23	34	207
					243		3,461
Pike, Ind.	502	Lawrence, Ind.	50	16	32	7	288
(254 kton/yr)					32		288
Sullivan, Ind.	529	Putnam, Ind.	55	22	33	8	462
(282 kton/yr)		Cass, Ind.	135	32	21	20	252
		La Salle, Ill.	180	27	18	26	18
		La Salle, Ill.	180	28	28	26	56
					100		788
Randolph, Mo.	273	St. Louis City, Mo.	135	34	14	20	196
(363 kton/yr)		Neosho, Kan.	205	32	23	30	46
		Pike, Mo.	75	27	55	11	880
		Marion, Mo.	55	25	26	8	442
		Wyandotte, Kan.	130	27	20	19	160
		St. Louis City, Mo.	135	34	33	20	462
		Jackson, Mo.	110	28	25	16	300
		Allen, Kan.	195	32	26	28	104
		Jefferson, Mo.	135	37	51	20	867
					273		3,457

(Continued)

TABLE 18. (Continued)

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Atascosa, Tex.	301	Bexar, Tex.	35	22	30	5	510
(222 kton/yr)		Bexar, Tex.	35	22	16	5	272
		Nueces, Tex.	100	36	14	14	308
		Hayes, Tex.	90	23	28	13	280
		Comal, Tex.	65	21	41	9	492
		Ellis, Tex.	265	36	38	35	37
		Bexar, Tex.	35	22	22	5	374
		McLennan, Tex.	200	30	14	29	14
		Comal, Tex.	65	21	20	9	240
					222		2,527
Hillsborough, Fla.	213	Hillsborough, Fla.	10	20	48	1	912
(160 kton/yr)		Manatee, Fla.	40	22	15	6	240
		Hernando, Fla.	40	25	26	6	494
					89		1,646
Putnam, Fla.	251	None					
(271 kton/yr)							
Duval, Fla.	230	Fulton, Ga.	290	43	28	35	224
(182 kton/yr)		Houston, Ga.	200	37	35	29	280
					63		504
(4,708 kton/yr)					1,584		20,807

Note: All gypsum quantities are dry weight, 100% gypsum.
Allowable cost is 90% of the cost of the natural gypsum supply.

Atascosa plant with no competition, marketed all of its production, but all the plants had at least one sale. Again, competition was a controlling factor in the distribution of sales for most plants, but it was not the only limit to marketing of all of the power plant production, as it was in the model using incremental cost. Only eight power plants could market all of their production without competition. The average cement plant requirements within range of a power plant were 375,000 ton/yr and ranged from 213,000 to 529,000 ton/yr. This is reflected in the lower average marketing range of 125 miles, as compared with 208 miles in the model using incremental cost.

The sales of individual power plants were affected by different factors to different extents by the exclusion of incremental costs. Power plants competing equally were usually able to market gypsum to a few nearby plants but the quantity was often small and usually only a small fraction of the production of the plants with larger production rates. Most plants, except those on the periphery of the marketing area, were also excluded from more distant available markets by competition of other power plants. The power plants in the lower Ohio River valley, highly competitive and dependent on advantages of incremental cost to capture local markets and to reach and compete for distant markets, suffered sharply reduced sales. The cost of the existing natural gypsum supply also influenced sales. Power plants dependent on the incremental cost to offset freight costs to areas with low natural gypsum costs (the Randolph plant, for example) had reduced sales. In the case of the Muhlenberg plant, however, with a favorable location closest to an area of high natural gypsum cost in the Southeast, elimination of the incremental cost increased sales to cement plants. In general, the exclusion of the incremental cost from the determination of delivered costs reduced (to varying extents, depending on the cost of natural gypsum in the sales area) the potential marketing range. Without incremental cost, sales could be made to between 8 and 18 cement plants by each power plant, with an average of 13, as compared with 17 to 52 and an average of 36 with incremental cost. The lower number of cement plants that could serve as potential markets precluded the marketing solely to cement plants of all the production of some power plants, regardless of the competition.

SALES TO WALLBOARD PLANTS WITH INCREMENTAL COST EXCLUDED

Sales to wallboard plants without adjustment of the delivered cost by incremental cost are shown in Table 19. The marketing model is the same as that used to develop the results in Table 15, except that the freight costs are not offset by the incremental cost, thus increasing the delivered cost by 13 to 26 $/ton, as compared with those in Table 15, and reducing competition to a matter of shipping distance.

Sales were 1.90 million ton/yr to 10 wallboard plants, a reduction of 30% in the quantity of gypsum marketed with incremental costs offsetting freight costs. There were both a decrease in the potential marketing range and a reduction in the importance of competition. Only 8 power plants had potential sales to 12 wallboard plants at a savings (in two cases, with freight equal to

TABLE 19. SALES TO WALLBOARD PLANTS WITH INCREMENTAL COST EXCLUDED

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Pleasants, W. Va. (307 kton/yr)	None	None					
Coshocton, Ohio (483 kton/yr)	128	Lorain, Ohio	80	14	128	12	256
					128		256
Monroe, Mich. (700 kton/yr)	580	Wayne, Ohio	30	13	213	4	1,917
		Ottawa, Ohio	35	9	128	5	512
		Ottawa, Ohio	35	9	111	5	444
					452		2,873
Boone, Ky. (197 kton/yr)	None	None					
Trimble, Ky. (166 kton/yr)	None	None					
Jefferson, Ky. (577 kton/yr)	None	None					
Muhlenberg, Ky. (544 kton/yr)	170	Crittenden, Ark.	230	33	170	33	0
					170		0
Pike, Ind. (254 kton/yr)	699	Martin, Ind.	40	9	254	7	508
					254		508
Sullivan, Ind. (282 kton/yr)	827	Martin, Ind.	45	9	282	7	564
					282		564

(Continued)

TABLE 19. (Continued)

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Randolph, Mo.	None	None					
(363 kton/yr)							
Atascosa, Tex.	None	None					
(222 kton/yr)							
Hillsborough, Fla.	221	Hillsborough, Fla.	10	14	160	1	2,080
(160 kton/yr)					160		2,080
Putnam, Fla.	740	Duval, Fla.	50	14	271	7	1,897
(271 kton/yr)					271		1,897
Duval, Fla.	740	Duval, Fla.	10	14	170	1	2,210
(182 kton/yr)		Duval, Fla.	10	14	12	1	156
					182		2,366
(4,708 kton/yr)					1,899		10,544

Note: All gypsum quantities are dry weight, 100% gypsum.
Allowable cost is 90% of the cost of the natural gypsum supply.

the allowable cost) as compared with all 14 when incremental cost was included. Of the eight, only five had a potential market that exceeded their production and, in these cases, the market was so large that competition did not limit sales by the power plants. The average distance over which gypsum could be delivered to a wallboard plant at a cost less than or equal to the allowable cost was 77 miles, as compared with 91 miles when incremental cost was included. This average includes an anomalous situation in which gypsum could be delivered to a wallboard plant 230 miles away because the location of the wallboard plant gave it an unusually high allowable cost. Excluding this case, the average distance over which gypsum was delivered was 35 miles, with a range of 10 to 80 miles.

The relatively short distances over which gypsum could be marketed to wallboard plants at a savings without incremental cost to offset freight costs essentially reduced the marketing potential to a chance relationship of power plant and wallboard plant location. Power plants in wallboard manufacturing areas could, however, compete successfully with both domestic gypsum from nearby mines and imported gypsum if they were very close to the wallboard plant.

SALES TO CEMENT AND WALLBOARD PLANTS WITH INCREMENTAL COSTS EXCLUDED

Sales to the combined market without adjustment of the delivered cost by incremental cost are shown in Table 20. With the exception that freight costs are not offset by incremental costs, the marketing model is the same as that shown in Table 17.

A total of 3.23 million ton/yr of gypsum was marketed to 52 cement plants and 10 wallboard plants, a reduction of 25% as compared with the sales with incremental cost offsetting freight costs. All of the power plants had sales and six marketed all of their production. Three power plants did not have a sufficient potential market to market all of their production even without competition. Competition in the cement plant and (in the case of one plant) wallboard plant markets reduced the sales of seven of the eight plants that did not market all of their production.

The results in the combined market were an almost completely additive total of the separate cement plant and wallboard plant results. Two power plants each abandoned two cement plant markets (one of which was acquired by another power plant) to increase more profitable wallboard plant sales. All of the other power plant sales were the sum of their sales when the cement plant and wallboard plant markets were treated separately. This contrasts with the results using the incremental cost in which a larger potential market and a higher degree of competition resulted in greater differences between the power plant market distribution in the separate and combined markets.

TABLE 20. SALES TO CEMENT AND WALLBOARD PLANTS WITH INCREMENTAL COST EXCLUDED

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Pleasants, W. Va.	335	C-Roanoke, Va.	165	28	53	24	212
(307 kton/yr)		C-Lawrence, Ohio	95	30	14	14	224
		C-Berkeley, W. Va.	170	25	41	25	0
					108		436
Coshocton, Ohio	372	C-Muskingum, Ohio	20	29	35	3	910
(483 kton/yr)		C-Lawrence, Pa.	100	32	40	14	720
		C-Allegheny, Pa.	100	35	28	14	588
		C-Lawrence, Pa.	100	32	31	14	558
		C-Butler, Pa.	120	35	15	17	270
		C-Stark, Ohio	50	27	13	7	260
		WB-Lorain, Ohio	80	14	128	12	256
					290		3,562
Monroe, Mich.	951	C-Bay, Mich.	125	20	22	18	44
(700 kton/yr)		C-Monroe, Mich.	10	20	44	1	836
		C-Paulding, Ohio	80	23	24	12	264
		C-Wayne, Mich.	30	20	48	4	768
		C-Wayne, Mich.	30	19	18	4	270
		WB-Wayne, Mich.	30	13	213	4	1,917
		WB-Ottawa, Ohio	35	9	128	5	512
		WB-Ottawa, Ohio	35	9	111	5	444
					608		5,055
Boone, Ky.	506	C-Greene, Ohio	70	29	32	10	608
(197 kton/yr)					32		608

(Continued)

TABLE 20. (Continued)

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Trimble, Ky.	501	C-Clark, Ind.	20	21	51	3	918
(166 kton/yr)					51		918
Jefferson, Ky.	525	C-Knox, Tenn.	190	29	24	27	48
(577 kton/yr)		C-Jefferson, Ky.	10	23	29	1	638
					53		686
Muhlenberg, Ky.	643	C-Maringo, Ala.	345	41	33	39	66
(544 kton/yr)		C-Hamilton, Tenn.	190	40	21	27	273
		C-Jefferson, Ala.	260	53	20	35	360
		C-Polk, Ga.	250	45	11	36	99
		C-Fulton, Ga.	295	43	28	36	196
		C-Shelby, Ala.	285	50	30	35	450
		C-Massac, Ill.	80	32	58	12	1,160
		C-Jefferson, Ala.	260	53	35	35	630
		C-Marion, Tenn.	175	43	12	25	216
		C-Lowndes, Miss.	280	43	23	34	207
		WB-Crittenden, Ark.	230	33	170	33	0
					441		3,657
Pike, Ind.	1,201	C-Lawrence, Ind.	50	16	32	7	288
(254 kton/yr)		WB-Martin, Ind.	40	9	222	7	444
					254		732
Sullivan, Ind.	1,356	C-Putnam, Ind.	55	22	33	8	462
(282 kton/yr)		C-Cass, Ind.	135	32	21	20	252
		WB-Martin, Ind.	45	9	228	7	456
					282		1,170

(Continued)

TABLE 20. (Continued)

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Randolph, Mo.	273	C-St. Louis City, Mo.	135	34	14	20	196
(363 kton/yr)		C-Neosho, Kan.	205	32	23	30	46
		C-Pike, Mo.	75	27	55	11	880
		C-Marion, Mo.	55	25	26	8	442
		C-Wyandotte, Kan.	130	27	20	19	160
		C-St. Louis City, Mo.	135	34	33	20	462
		C-Jackson, Mo.	110	28	25	16	300
		C-Allen, Kan.	195	32	26	28	104
		C-Jefferson, Mo.	135	37	51	20	867
					273		3,457
Atascosa, Tex.	301	C-Bexar, Tex.	35	22	30	5	510
(222 kton/yr)		C-Bexar, Tex.	35	22	16	5	272
		C-Nueces, Tex.	100	36	14	14	308
		C-Hayes, Tex.	90	23	28	13	280
		C-Comal, Tex.	65	21	41	9	492
		C-Ellis, Tex.	265	36	20	35	20
		C-Bexar, Tex.	35	22	22	5	374
		C-McLennan, Tex.	200	30	14	29	14
		C-Comal, Tex.	65	21	37	9	444
					222		2,714
Hillsborough, Fla.	434	C-Hillsborough, Fla.	10	20	48	1	912
(160 kton/yr)		C-Manatee, Fla.	40	22	15	6	240
		C-Hernando, Fla.	40	25	26	6	494
		WB-Hillsborough, Fla.	10	14	71	1	923
					160		2,569

(Continued)

TABLE 20. (Continued)

Power plant County, State	Available market, kton/yr	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Putnam, Fla.	991	WB-Duval, Fla.	50	14	271	7	1,897
(271 kton/yr)					271		1,897
Duval, Fla.	970	WB-Duval, Fla.	10	14	170	1	2,210
(182 kton/yr)		WB-Duval, Fla.	10	14	12	1	256
					182		2,366
(4,708 kton/yr)					3,227		29,827

Note: All gyspum quantities are dry weight, 100% gypsum.
Allowable cost is 90% of the cost of the natural gypsum supply.

SALE OF DRIED GYPSUM TO CEMENT AND WALLBOARD PLANTS

The sale of gypsum dried at the power plant, instead of the as-produced gypsum containing residual water, could be a desirable or necessary marketing approach. The economic practicality of this was evaluated by adding the cost of drying the gypsum from 10% to 2.5% water to the FGD costs, as described in the methodology section.

The marketing potential of the dried gypsum to the combined cement and wallboard market was evaluated using the same techniques used in the same evaluation for undried gypsum shown previously in Table 17. For the dried gypsum, however, an allowable cost equal to the cost of the natural gypsum supply was used rather than the 90% value used for the as-produced gypsum. The freight costs for the dried gypsum were also about 0.01 $/ton-mile lower because of the lower water content. The costs of drying were 4 to 6 $/ton, depending on the quantity produced. The overall effect of these factors--lower freight costs, higher allowable cost, and higher production costs as compared with as-produced gypsum--can either reduce or enhance the market potential for dried gypsum, as compared with as-produced gypsum. Longer transportation distances can recover all or most of the drying costs, as can the higher allowable cost for consumers with high natural gypsum costs. Drying thus reduces the marketing potential for nearby consumers with low-to-moderate natural gypsum costs, and enhances it for distant consumers with high natural gypsum costs. These effects are illustrated by the results of marketing evaluation shown in Table 21, which may be compared with Table 17, showing the same marketing evaluation for as-produced gypsum.

The two results are very similar. The distribution of sales is the same except for three additional sales of dried gypsum to cement plants by the Muhlenberg plant, made possible by the lower freight costs and the relatively high natural gypsum costs of these cement plants and the loss of the Boone plant sale. All of the other power plants also had increases in the number of cement plants to which sales could be made at a savings, but were able to sell all of their production at higher savings elsewhere. The Boone plant had no sales of dried gypsum because it had no sales other than the single cement plant that it had in the as-produced gypsum marketing model, making the cost of drying prohibitive.

Overall, 4.41 million ton/yr of dried gypsum was marketed to 81 cement plants and 14 wallboard plants, a difference of only 61,000 ton/yr from the as-produced gypsum marketing results. The sales represented 94% of the power plant production and constituted 66% of the cement plant requirements and 22% of the wallboard plant requirements in the study area.

The total savings was 107.89 million $/yr, about 2% less than the savings for as-produced gypsum sales. Unlike the savings from as-produced gypsum sales, which were almost equally divided between sales to cement plants and wallboard plants, 54% of the savings from dried gypsum sales was derived from sales to cement plants. This reflects the freight-cost advantage of dried gypsum, which increases with distance. As compared with as-produced gypsum,

TABLE 21. SALE OF DRIED GYPSUM TO CEMENT AND WALLBOARD PLANTS

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Pleasants, W. Va.	-15	C-Greene, N.Y.	440	33	26	25	208
(307 kton/yr)		C-Frederick, Md.	210	26	19	12	266
		C-Carroll, Md.	230	23	42	15	336
		C-Roanoke, Va.	165	31	53	7	1,272
		C-Lawrence, Ohio	95	33	14	-2	490
		C-Greene, N.Y.	450	32	37	25	259
		C-Washington, Md.	190	27	27	9	486
		C-Berkeley, W. Va.	170	28	41	8	820
		C-Berks, Pa.	295	27	39	17	780
		C-Northhampton, Pa.	325	27	9	20	63
					307		4,980
Coshocton, Ohio	-16	C-Albany, N.Y.	450	36	68	25	748
(483 kton/yr)		C-Muskingum, Ohio	20	32	35	-13	1,575
		C-Northhampton, Pa.	350	27	33	19	264
		C-Northhampton, Pa.	350	27	28	19	224
		C-Greene, N.Y.	450	34	20	25	180
		C-Lawrence, Pa.	100	36	40	-3	1,560
		C-Allegheny, Pa.	100	39	28	-3	1,176
		C-Lawrence, Pa.	100	36	31	-3	1,209
		C-York, Pa.	290	26	20	16	200
		C-Butler, Pa.	120	39	15	-1	600
		C-Stark, Ohio	50	30	13	-10	520
		C-Northhampton, Pa.	350	27	4	19	32
		C-Warren, N.Y.	490	40	20	28	240
		WB-Lorain, Ohio	80	16	128	-5	2,688
					483		11,216

(Continued)

TABLE 21. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Monroe, Mich. (700 kton/yr)	-14	C-Bay, Mich.	125	22	22	2	440
		C-Monroe, Mich.	10	22	44	-13	1,540
		C-Paulding, Ohio	80	26	24	-3	696
		C-Wayne, Mich.	30	22	48	-10	1,536
		C-Wayne, Mich.	30	21	18	-10	558
		WB-Kent, Mich.	120	10	92	1	828
		WB-Wayne, Mich.	30	14	213	-10	5,112
		WB-Ottawa, Mich.	35	10	128	-10	2,560
		WB-Ottawa, Mich.	35	10	111	-10	2,220
					700		15,490
Boone, Ky. (197 kton/yr)	-7	None					
Trimble, Ky. (166 kton/yr)	-17	C-Cass, Ind.	165	36	21	5	651
		C-La Salle, Ill.	275	31	28	13	504
		C-Greene, Ohio	115	32	32	-2	1,088
		WB-Lake, Ind.	165	27	85	5	1,870
					166		4,113
Jefferson, Ky. (577 kton/yr)	-20	C-La Salle, Ill.	290	30	18	12	324
		C-Marengo, Ala.	440	46	33	20	858
		C-Hamilton, Tenn.	220	44	21	9	735
		C-Knox, Tenn.	190	32	24	4	672
		C-Lawrence, Ind.	70	18	32	-11	928
		C-Lee, Ill.	320	29	25	15	350
		C-Clark, Ind.	25	23	51	-16	1,989
		C-Polk, Ga.	300	50	11	13	407
		C-Houston, Ga.	420	41	35	18	805

(Continued)

TABLE 21. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Jefferson, Ky. (Continued)		C-Sullivan, Tenn.	220	18	15	9	135
		C-Lowndes, Miss.	370	48	23	15	759
		C-Orangeburg, S.C.	445	26	17	21	85
		C-Jefferson, Ky.	10	26	29	-19	1,305
		WB-Martin, Ind.	75	10	139	-10	2,780
		WB-Martin, Ind.	75	10	104	-10	2,080
					577		14,212
Muhlenberg, Ky. (544 kton/yr)	-14	C-Dorchester, S.C.	450	29	38	27	76
		C-Mobile, Ala.	450	36	21	27	189
		C-Jefferson, Ala.	260	59	20	18	1,062
		C-Rankin, Miss.	390	37	10	21	160
		C-Shelby, Ala.	285	56	30	18	1,140
		C-Scott, Iowa	375	23	22	21	44
		C-Tulsa, Okla.	500	33	28	31	56
		C-Massac, Ill.	80	36	58	-3	2,262
		C-Jefferson, Ala.	260	59	35	18	1,435
		C-Marion, Tenn.	175	48	12	9	468
		WB-Crittenden, Ark.	230	37	170	16	3,570
					444		10,462
Pike, Ind. (254 kton/yr)	-16	WB-Martin, Ind.	40	10	254	-11	5,334
					254		5,334
Sullivan, Ind. (282 kton/yr)	-16	C-St. Louis City, Mo.	65	38	14	6	448
		C-Putnam, Ind.	55	24	33	-9	1,089
		C-St. Louis City, Mo.	65	38	33	6	1,056
		WB-Martin, Ind.	45	10	202	-10	4,040
					282		6,633

(Continued)

TABLE 21. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Randolph, Mo.	-12	C-Neosho, Kan.	205	36	23	14	506
(363 kton/yr)		C-Pike, Mo.	75	30	55	0	1,650
		C-Wilson, Kan.	225	36	18	18	324
		C-Marion, Mo.	55	28	26	-5	858
		C-Montgomery, Kan.	245	38	17	20	306
		C-Mayes, Okla.	275	38	32	19	608
		C-Jackson, Mo.	110	31	25	2	725
		C-Allen, Kan.	195	36	26	13	598
		C-Douglas, Wis.	500	53	9	33	180
		C-Jefferson, Mo.	135	41	51	6	1,785
		C-Wyandotte, Kan.	130	30	20	5	500
		WB-Des Moines, Iowa	125	13	61	4	549
					363		8,589
Atascosa, Tex.	-17	C-Bexar, Tex.	35	24	30	-13	1,110
(222 kton/yr)		C-Bexar, Tex.	35	24	16	-13	592
		C-Nueces, Tex.	100	40	14	-4	616
		C-Hayes, Tex.	90	26	28	-5	868
		C-Comal, Tex.	65	23	41	-9	1,312
		C-Ellis, Tex.	265	40	20	15	500
		C-Bexar, Tex.	35	24	22	-13	242
		C-McLennan, Tex.	200	33	14	9	336
		C-Comal, Tex.	65	23	37	-9	1,184
					222		6,760

(Continued)

TABLE 21. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Hillsborough, Fla. (160 kton/yr)	-14	C-Hillsborough, Fla.	10	22	48	-13	1,680
		C-Manatee, Fla.	40	24	15	-9	495
		C-Hernando, Fla.	40	28	26	-9	962
		WB-Hillsborough, Fla.	10	16	71	-13	2,059
					160		5,196
Putnam, Fla. (271 kton/yr)	-20	C-Fulton, Ga.	330	48	28	14	952
		WB-Duval, Fla.	50	16	170	-14	5,100
		WB-Duval, Fla.	50	16	73	-14	2,190
					271		8,242
Duval, Fla. (182 kton/yr)	-16	WB-Glynn, Ga.	60	26	182	-12	6,916
					182		6,916
(4,708 kton/yr)					4,411		108,143

savings derived from dried gypsum sales to cement plants, with an average shipping distance of 200 miles, increased 3% while the savings derived from dried gypsum sales to wallboard plants, with an average shipping distance of 77 miles, decreased 8%. Only the Muhlenberg plant, which shipped 230 miles to a wallboard plant, had increased savings from dried gypsum sales to a wallboard plant.

SALE OF BRIQUETTED GYPSUM TO CEMENT PLANTS AND DRIED GYPSUM TO WALLBOARD PLANTS

A further possible marketing innovation is the production of gypsum briquettes for sales to cement plant consumers that prefer or demand gypsum in a form that resembles their natural gypsum supply. The economic effects of briquetting the portion of the gypsum sold to cement plants were evaluated using the same model used for the evaluation of dried gypsum sales to cement and wallboard plants. (The gypsum must be dried for briquetting, so dried gypsum was used for all sales.) The briquetting process is described in the methodology section. The briquetting costs were added to the FGD costs. They ranged from 2 to 11 $/ton, depending on the quantity sold.

The results of this evaluation can be compared with both the evaluation of as-produced gypsum sales shown in Table 17, and the evaluation of dried gypsum sales shown in Table 21. In comparison with as-produced gypsum sales, all of the sales have an advantage of lower freight costs and a higher allowable cost that serve to offset some or all of the drying and briquetting costs. In comparison with dried gypsum sales, briquetting is simply an economic penalty on sales to cement plants.

The results of the evaluation are shown in Table 22. The marketing pattern was the same as the pattern for as-produced gypsum sales, except that the sale of the Boone plant was excluded because of the prohibitive costs for drying and briquetting of the small quantity marketed. In comparison to the dried gypsum marketing pattern, sales by the Muhlenberg plant to the three cement plants obtained by drying the gypsum were lost because of the added briquetting costs. Briquetting thus did not materially affect the marketing pattern. A total of 4.32 million ton/yr of gypsum, 92% of the production, was marketed to 78 cement plants and 14 wallboard plants.

Savings were not drastically affected by inclusion of briquetting for cement plant sales. The total savings was reduced to 101 million $/yr, 8% less than the savings for sales of as-produced gypsum and 6% less than the savings for sale of dried gypsum. The reduction was, of course, almost all in cement plant sales. (The Muhlenberg plant had a slight reduction in wallboard plant savings because the loss of sales to the three cement plants increased drying costs.)

TABLE 22. SALE OF BRIQUETTED GYPSUM TO CEMENT PLANTS AND DRIED GYPSUM TO WALLBOARD PLANTS

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Pleasants, W. Va.	-12	C-Greene, N.Y.	440	33	26	28	130
(307 kton/yr)		C-Frederick, Md.	210	26	19	15	209
		C-Carroll, Md.	230	23	42	18	210
		C-Roanoke, Va.	165	31	53	10	1,113
		C-Lawrence, Ohio	95	33	14	1	448
		C-Greene, N.Y.	450	32	37	28	148
		C-Washington, Md.	190	27	27	12	405
		C-Berkeley, W. Va.	170	28	41	11	697
		C-Berks, Pa.	295	27	39	20	273
		C-Northhampton, Pa.	325	27	9	23	36
					307		3,669
Coshocton, Ohio	-14	C-Albany, N.Y.	450	36	68	27	612
(483 kton/yr)		C-Muskingum, Ohio	20	32	35	-11	1,505
		C-Northhampton, Pa.	350	27	33	21	198
		C-Northhampton, Pa.	350	27	28	21	168
		C-Greene, N.Y.	450	34	20	27	140
		C-Lawrence, Pa.	100	36	40	-1	1,480
		C-Allegheny, Pa.	100	39	28	-1	1,128
		C-Lawrence, Pa.	100	36	31	-1	1,147
		C-York, Pa.	290	26	20	18	160
		C-Butler, Pa.	120	39	15	1	570
		C-Stark, Ohio	50	30	13	-8	494
		C-Northhampton, Pa.	350	27	4	21	24
		C-Warren, N.Y.	490	40	20	30	200
	-16	WB-Lorain, Ohio	80	16	128	-5	2,688
					483		10,514

(Continued)

TABLE 22. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Monroe, Mich.	-10	C-Bay, Mich.	125	22	22	6	352
(700 kton/yr)		C-Monroe, Mich.	10	22	44	-9	1,364
		C-Paulding, Ohio	80	26	24	1	600
		C-Wayne, Mich.	30	22	48	-6	1,344
		C-Wayne, Mich.	30	21	18	-6	486
	-14	WB-Kent, Mich.	120	10	92	1	828
		WB-Wayne, Mich.	30	14	213	-10	5,112
		WB-Ottawa, Ohio	35	10	128	-10	2,560
		WB-Ottawa, Ohio	35	10	111	-10	2,220
					700		14,866
Boone, Ky.	-13	None					
(197 kton/yr)							
Trimble, Ky.	-11	C-Cass, Ind.	165	36	21	11	525
(166 kton/yr)		C-La Salle, Ill.	275	31	28	19	336
		C-Greene, Ohio	115	32	32	4	896
	-17	WB-Lake, Ind.	165	27	85	5	1,757
					166		3,627
Jefferson, Ky.	-18	C-La Salle, Ill.	290	30	18	14	288
(577 kton/yr)		C-Marengo, Ala.	440	46	33	22	792
		C-Hamilton, Tenn.	220	44	21	11	693
		C-Knox, Tenn.	190	32	24	6	624
		C-Lawrence, Ind.	70	18	32	-9	864
		C-Lee, Ill.	320	29	25	17	300
		C-Clark, Ind.	25	23	51	-14	1,887
		C-Polk, Ga.	300	50	11	15	385

(Continued)

TABLE 22. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Jefferson, Ky. (Continued)		C-Houston, Ga.	420	41	35	20	735
		C-Sullivan, Tenn.	220	18	15	11	105
		C-Lowndes, Miss.	370	48	23	17	713
		C-Orangeburg, S.C.	445	26	17	23	51
		C-Jefferson, Ky.	10	26	29	-17	1,247
	-20	WB-Martin, Ind.	75	10	139	-10	2,780
		WB-Martin, Ind.	75	10	104	-10	2,080
					577		13,544
Muhlenberg, Ky. (544 kton/yr)	-10	C-Mobile, Ala.	450	36	21	31	105
		C-Jefferson, Ala.	260	59	20	22	740
		C-Rankin, Miss.	390	37	10	25	120
		C-Shelby, Ala.	285	56	30	22	1,320
		C-Massac, Ill.	80	36	58	1	2,030
		C-Jefferson, Ala.	260	59	35	22	1,295
		C-Marion, Tenn.	175	48	12	13	420
	-13	WB-Crittenden, Ark.	230	37	170	17	3,400
					356		9,430
Pike, Ind. (254 kton/yr)	-16	WB-Martin, Ind.	40	10	254	-11	5,334
					254		5,334
Sullivan, Ind. (282 kton/yr)	-10	C-St. Louis City, Mo.	165	38	14	12	364
		C-Putnam, Ind.	55	24	33	-3	891
		C-St. Louis City, Mo.	165	38	33	12	858
	-16	WB-Martin, Ind.	45	10	202	-10	4,040
					282		6,153

(Continued)

TABLE 22. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Randolph, Mo.	-9	C-Neosho, Kan.	205	36	23	18	414
(363 kton/yr)		C-Pike, Mo.	75	30	55	1	1,595
		C-Wilson, Kan.	225	36	18	21	252
		C-Marion, Mo.	55	28	26	-2	780
		C-Montgomery, Kan.	245	38	17	23	255
		C-Mayes, Okla.	275	38	32	22	512
		C-Jackson, Mo.	110	31	25	5	650
		C-Allen, Kan.	195	36	26	16	520
		C-Douglas, Wis.	500	53	9	27	234
		C-Jefferson, Mo.	135	41	51	9	1,632
		C-Wyandotte, Kan.	130	30	20	8	440
	-12	WB-Des Moines, Iowa	125	13	61	4	549
					363		7,833
Atascosa, Tex.	-14	C-Bexar, Tex.	35	24	30	-10	1,020
(222 kton/yr)		C-Bexar, Tex.	35	24	16	-10	544
		C-Nueces, Tex.	100	40	14	-1	546
		C-Hayes, Tex.	90	26	28	-2	784
		C-Comal, Tex.	65	23	41	-6	1,189
		C-Ellis, Tex.	265	40	20	18	440
		C-Bexar, Tex.	35	24	22	-10	748
		C-McLennan, Tex.	200	33	14	12	294
		C-Comal, Tex.	65	23	37	-6	1,073
					222		6,638
Hillsborough, Fla.	-9	C-Hillsborough, Fla.	10	22	48	-8	1,440
(160 kton/yr)		C-Manatee, Fla.	40	24	15	-4	420
		C-Hernando, Fla.	40	28	26	-4	832
	-14	WB-Hillsborough, Fla.	10	16	71	-13	2,059
					160		4,751

(Continued)

TABLE 22. (Continued)

Power plant County, State	Incremental cost, $/ton	Plant County, State	Distance, miles	Allowable cost, $/ton	Sales kton/yr	Delivered cost, $/ton	Savings, k$
Putnam, Fla. (271 kton/yr)	-9	C-Fulton, Ga.	330	48	28	25	644
	-20	WB-Duval, Fla.	50	16	170	-14	5,100
		WB-Duval, Fla.	50	16	73	-14	2,190
					271		7,934
Duval, Fla. (182 kton/yr)	-16	WB-Glynn, Ga.	60	26	182	-12	6,916
					182		6,916
(4,708 kton/yr)					4,323		110,092

PRODUCTION OF WALLBOARD AT POWER PLANT LOCATIONS

The increasing importance of transportation in wallboard cost raises the possibility of wallboard manufacture at sources of FGD gypsum, which may be closer to wallboard marketing areas than existing wallboard plants. Aspects of these costs, and the traditional location of wallboard plants at sources of gypsum to minimize transportation costs, have been discussed in the background and methodology sections. These sources, at inland mines and coastal import points, do not always coincide with major marketing areas. Power plants producing gypsum can be regarded as a source of gypsum in the same sense as mines and ports. In addition, the production rate of FGD gypsum by power plants is frequently in the same range as the requirements of wallboard plants. Power plants are much more geographically dispersed than sources of natural gypsum and might, in some cases, serve as a gypsum source from which wallboard could be more economically shipped to marketing areas than from existing wallboard plant locations.

To evaluate the economic potential of manufacturing wallboard at power plant locations, a model using the 14 power plants used in the previous evaluations was developed in which a system of hypothetical regional wallboard distribution centers was used to determine and compare wallboard freight costs. The regional distribution centers were situated in 43 population centers in the 37-state study area. Their locations and those of the power plants and existing wallboard plants are shown in Figure 22. Each was assigned a wallboard demand projected to 1985 and based on census data and projected construction activity, as described in the methodology section (see Figure 18 and Table 8). For purposes of this study, all wallboard shipments were assumed to pass through these distribution centers as a means of comparing wallboard freight costs. Rail and truck freight costs were used, as described in the methodology section. The evaluation compared freight costs for wallboard from the power plants and from the existing wallboard manufacturing locations nearest the regional distribution center.

The projected 1985 wallboard requirements for the study area represent a gypsum requirement of 10.78 million tons. The projected existing wallboard manufacturing capacity in the study area will be able to meet the 1985 wallboard requirements, but there will be local and regional over- and undercapacities that will result in relatively long distance wallboard shipments. The production capacity of 14 power plants in the model is 4.71 million ton/yr, so at the most, the power plants could supply only 44% of the 1985 gypsum requirements for wallboard manufacture.

The results of evaluation are shown in Table 23. The requirements of each regional distribution center are listed, along with the allocated supply from existing wallboard plant sources and the weighted freight costs (an average freight cost based on the distance and the tons shipped from each wallboard plant). In cases in which all or some of the wallboard could be delivered at a lower cost by a wallboard plant at a power plant, the quantity, freight cost, and savings are listed.

Figure 22. Geographic relationship of existing wallboard and power plants to regional distribution centers.

TABLE 23. SALE OF WALLBOARD FROM POWER PLANT MANUFACTURING SITES THROUGH REGIONAL DISTRIBUTION CENTERS

Distribution center		Existing wallboard plant allocated supply				Power plant wallboard plant supply					
Location	Demand, ktons[a]	Source, State	Weighted distance, miles	Weighted freight rate, $/ton	Total freight costs, k$/yr	Power plant, source	Quantity, ktons	Freight distance, miles	Total freight rate, $/ton	Total freight costs, k$	Total freight savings, k$
Boston, Maine	460	Maine	48	6.25	2,873						
		N.H.									
		N.Y.									
New York, N.Y.	560	N.Y.	30	3.90	2,184						
		N.Y.									
Philadelphia, Pa.	367	Pa.	11	1.43	525						
		N.J.									
		N.J.									
Pittsburgh, Pa.	321	Md.	213	27.72	8,897	Coshocton, Ohio	243	100	13.00	3,159	3,576
		Md.				Pleasants, W. Va.	78	100	13.00	1,014	1,148
		Ohio									
		Ohio									
		Del.									
Buffalo, N.Y.	267	N.Y.	28	3.83	1,022						
		N.Y.									
		N.Y.									
Washington, D.C.	508	Md.	40	5.20	2,642						
		Md.									
Norfolk, Va.	236	Va.	14	1.86	439						
		Md.									
		Md.									
Roanoke, Va.	100	Va.	120	15.60	1,170						
		N.C.	240	31.20	780	Pleasants, W. Va.	25	170	22.10	553	227

(Continued)

TABLE 23. (Continued)

Distribution center: Location	Distribution center: Demand, ktons[a]	Existing wallboard plant allocated supply: Source, State	Weighted distance, miles	Weighted freight rate, $/ton	Total freight costs, k$/yr	Power plant wallboard plant supply: Power plant, source	Quantity, ktons	Freight distance, miles	Total freight rate, $/ton	Total freight costs, k$	Total freight savings, k$
Raleigh, N.C.	147	N.C.	110	14.30	2,120						
Charlotte, N.C.	180	Va. N.C. Ga. Ga.	169	22.03	3,965						
Charleston, W. Va.	100	Va. Ohio	150	19.50	1,950	Pleasants, W. Va.	100	70	9.10	910	1,040
Charleston, S.C.	118	Ga. Ga.	90	11.70	1,381						
Atlanta, Ga.	592	Ga. Ga. Ga.	234	18.72	11,082						
Jacksonville, Fla.	220	Fla. Fla.	10	1.30	286						
Tampa, Fla.	500	Fla.	10	1.30	338						
		Fla.	180	23.40	5,616	Hillsborough, Fla.	160	10	1.30	208	3,536
						Putnam, Fla.	80	140	18.20	1,456	416
Miami, Fla.	500	Fla. Ga. Del.		24.45	12,225	Putnam, Fla.	191	300	22.14	4,229	468
Columbus, Ohio	240	Ohio Ohio Ohio	104	13.49	3,237	Coshocton, Ohio	240	70	9.10	2,184	1,053

(Continued)

TABLE 23. (Continued)

Distribution center: Location	Demand, ktons[a]	Existing wallboard plant allocated supply: Source, State	Weighted distance, miles	Weighted freight rate, $/ton	Total freight costs, k$/yr	Power plant wallboard plant supply: Power plant, source	Quantity, ktons	Freight Distance, miles	Total freight rate, $/ton	Total freight costs, k$	Total freight savings, k$
Detroit, Mich.	344	Mich.	10	1.30	325						
		Ohio	60	7.80	733	Monroe, Mich.	94	20	2.60	244	489
Chicago, Ill.	548	Ind.	40	5.20	520						
		Mich.	150	19.50	2,340						
		Mich.	150	19.50	1,560						
		Iowa	190	24.70	2,470						
		Iowa	220	28.60	4,233	Sullivan, Ind.	148	200	26.00	3,848	385
Indianapolis, Ind.	240	Ind.	80	10.40	2,496						
		Ind.									
Milwaukee, Wis.	306	Ill.	188	21.17	6,479						
		Iowa									
		Iowa									
		Iowa									
		Iowa									
Louisville, Ky.	110	Ind.	70	9.10	1,001	Jefferson, Ky.	110	10	1.30	143	858
		Ind.									
Memphis, Tenn.	110	Ark.	20	2.60	286						
Nashville, Tenn.	102	Ind.	180	23.40	2,387	Muhlenberg, Ky.	102	80	10.40	1,061	1,326
		Ind.									
Knoxville, Tenn.	100	Va.	120	15.60	1,170						
		Ind.	240	31.20	780	Jefferson, Ky.	25	190	24.70	618	162
Birmingham, Ala.	105	Ind.	487	42.67	4,480	Muhlenberg, Ky.	105	260	19.60	2,058	2,422
		Iowa									

(Continued)

TABLE 23. (Continued)

Distribution center		Existing wallboard plant allocated supply				Power plant wallboard plant supply					
Location	Demand, ktons[a]	Source, State	Weighted distance, miles	Weighted freight rate, $/ton	Total freight costs, k$/yr	Power plant, source	Quantity, ktons	Freight Distance, miles	Total freight rate, $/ton	Total freight costs, k$	Total freight savings, k$
Mobile, Ala.	100	La. Ga.	244	21.67	2,167						
Jackson, Miss.	100	Ark. Ar.	205	26.65	2,665						
St. Paul, Minn.	175	Iowa Iowa Iowa Iowa	190	24.70	4,323						
Davenport, Iowa	100	Iowa	60	7.80	780						
Des Moines, Iowa	100	Iowa Iowa Iowa Iowa	60	7.80	780						
Omaha, Neb.	100	Iowa Iowa Iowa Iowa	130	16.90	1,690						
St. Louis, Mo.	175	Ind. Ind.	190	24.70	4,323	Randolph, Mo.	175	150	19.50	3,413	910
Kansas City, Kan.	139	Kan.	110	14.30	1,988						
Witchita, Kan.	100	Kan.	80	10.40	1,040						

(Continued)

TABLE 23. (Continued)

Distribution center: Location	Distribution center: Demand, ktons[a]	Existing wallboard plant allocated supply: Source, State	Existing wallboard plant allocated supply: Weighted distance, miles	Existing wallboard plant allocated supply: Weighted freight rate, $/ton	Existing wallboard plant allocated supply: Total freight costs, k$/yr	Power plant wallboard plant supply: Power plant, source	Power plant wallboard plant supply: Quantity, ktons	Power plant wallboard plant supply: Freight Distance, miles	Power plant wallboard plant supply: Total freight rate, $/ton	Power plant wallboard plant supply: Total freight costs, k$	Power plant wallboard plant supply: Total freight savings, k$
Springfield, Mo.	100	Kan. Kan.	282	33.56	3,356	Randolph, Mo.	100	180	23.40	2,340	1,016
Oklahoma City, Okla.	170	Okla.	60	7.80	1,326						
Little Rock, Ark.	100	Ark.	110	14.30	1,430						
Dallas, Tex.	500	Ark. Okla.	195	25.38	12,688						
San Antonio, Tex.	386	Tex. Tex.	230 230	29.90 29.90	6,638 4,904	Atascosa, Tex.	222	40	5.20	1,154	5,484
Houston, Tex.	700	Tex. Tex. Tex. Tex. Tex.	271	27.27	19,090						
New Orleans, La.	250	La. La.	12	1.56	390						
Shreveport, La.	100	Ark.	110	14.30	1,430						
TOTAL	10,776						2,198				24,516

a. 1985 projection.

The power plant wallboard plants were able to supply some or all of the wallboard requirements at a savings to 15 of the 43 regional distribution centers. The power plant wallboard supplied 19% of the total wallboard requirements in the study area. All of the wallboard requirements for the Pittsburgh, Charleston, Columbus, Louisville, Nashville, Birmingham, St. Louis, and Springfield regional distribution centers were met by power plant wallboard. Portions ranging from 25% of the Roanoke and Knoxville requirements to 58% of the San Antonio requirements were supplied by power plant wallboard at these and the Tampa, Detroit, Chicago, and Miami regional distribution centers.

Some of the results require further explanation. The Duval plant, for example, is in the same county as the Jacksonville distribution center, but supplied no wallboard to it. Recent wallboard plant expansions in the Jacksonville area have created a surplus supply in the local market. Therefore the Duval plant had no freight advantage over the existing wallboard plants. The Tampa area, on the other hand, is not wholly supplied by local production, allowing wallboard shipments from the Hillsborough and Putnam plants to replace almost one-half of the conventional supply. The Miami area is remote from existing wallboard plants. The nearest wallboard plant is in the Tampa area, which is itself an area of short supply. Thus, the remaining production of the Putnam plant was able to replace 191,000 tons of wallboard shipments from the Jacksonville area.

The results are summarized, by power plant, in Table 24. Wallboard equivalent to 2.20 million ton/yr of gypsum was shipped by 10 of the 14 power plants, which is 47% of the total production of the 14 power plants. Four of the power plants marketed all of their production. The total freight savings was 24.52 million $/yr, 11 $/ton of gypsum equivalent. Freight savings for the individual power plants ranged from 2 to 25 $/ton of gypsum equivalent. Freight savings can be regarded as a measure of the strength of the potential market. Power plants with high freight savings occupied a more competitive position, close to potential markets that were relatively remote from existing wallboard plants, for example, and would be less likely to be affected by changes in the wallboard manufacturing industry. The Atascosa plant, which marketed all of its production, had, for example, a freight savings of 25 $/ton of gypsum equivalent because of its proximity to the San Antonio market, which is remote from existing wallboard plants. The Putnam plant, which also marketed all of its production, had savings of only 3 $/ton of gypsum equivalent because it depended on relatively distant areas for its market.

The marketability of the power plant wallboard, based as it was solely on lower freight costs, depended upon a more favorable geographic relationship to a distribution center for a power plant than for a wallboard plant. Usually this came about because of the uneven geographic distribution of wallboard plants. The power plant wallboard sales were usually to distribution centers distant from wallboard plants or which had an insufficient supply from local wallboard plants and required shipments from distant wallboard plants. This is evident from the weighted freight costs for wallboard from existing wallboard plants in Table 23. The average weighted freight costs for the wallboard replaced by power plant wallboard was 25 $/ton, as compared with an average freight cost of 16 $/ton for all wallboard plant shipments to the distribution centers. Only in two cases was wallboard from existing plants with weighted freight costs less than 16 $/ton replaced by power plant wallboard. In some cases the power plant was near the distribution center. In these cases (the Atascosa and Hillsborough plants, for example), the freight savings was correspondingly high. In others (the Putnam plant, for example), power plant wallboard was shipped to distant distribution centers and there was only a small freight savings.

TABLE 24. POWER PLANT WALLBOARD SUPPLY TO REGIONAL DISTRIBUTION CENTERS

Power plant County, State	Gypsum equivalent shipped kton/ry	Gypsum equivalent shipped % of production	Freight savings, k$/yr
Pleasants, W. Va. (307 kton/yr)	203	66	2,415
Coshocton, Ohio (483 kton/yr)	483	100	4,629
Monroe, Mich. (700 kton/yr)	94	13	489
Boone, Ky. (197 kton/yr)	None		
Trimble, Ky. (166 kton/yr)	None		
Jefferson, Ky. (577 kton/yr)	135	23	1,020
Muhlenberg, Ky. (544 kton/yr)	207	38	3,748
Pike, Ind. (254 kton/yr)	None		
Sullvian, Ind. (282 kton/yr)	148	52	385
Randolph, Mo. (363 kton/yr)	275	76	1,926
Atascosa, Tex. (222 kton/yr)	222	100	5,484
Hillsborough, Fla. (160 kton/yr)	160	100	3,536
Putnam, Fla. (271 kton/yr)	271	100	884
Duval, Fla. (182 kton/yr)	None		
(4,708 kton/yr)	2,198	47	24,516

The results indicate a moderate economic feasibility for the manufacture of wallboard at sites adjacent to gypsum-producing power plants as a means of reducing wallboard costs by reducing freight costs. It should be recognized that the results are based solely on freight costs for wallboard and do not include the effects of reduced gypsum costs, which was the basis of the preceding evaluations. The particular results are in part an artifact of the model used. Selection of different power plants would obviously have a large effect on the results of the evaluation. The 14 power plants used in the model were selected on the basis of FGD economics, without regard to the marketing aspects of the gypsum they produced. It is apparent from this evaluation, as it was from previous evaluations, that the geographical distribution of the power plants is less than ideal from a marketing standpoint. Particularly significant is the absence in the model of power plants in the inland Southeast, where there are no natural gypsum supplies and few wallboard plants.

SUMMATION AND DISCUSSION OF RESULTS

The basis of this study was a determination (projected to 1985 under various conditions) of the economic feasibility of substituting FGD gypsum produced at utility power plants for the natural gypsum used in the wallboard and portland cement manufacturing industries in the eastern 37 states. The FGD gypsum sources were 14 utility power plants, screened from all power plants in the study area, using a type of coal and having emission control limits that made gypsum marketing more economical than fixation and landfill disposal under suitable site-specific conditions. The results are summarized in Table 25.

In contrast to most byproduct-producing processes, the gypsum-producing process in this study was less expensive than the alternative limestone process with fixation and landfill for all of the power plants used in the study. This was due in large part to the use of a conceptual design incorporating recently demonstrated advances in in-loop forced oxidation, the use of additives in limestone FGD for the gypsum-producing process, and the use of fixation and landfill--the most widely used waste disposal method--for the alternative limestone FGD process instead of a less expensive untreated waste disposal method. The FGD cost relationships have important implications in the choice of FGD processes as well as important effects on the economics of gypsum sales when the cost difference between the processes--called the "incremental cost" in this study--is regarded as a savings that can be applied to the cost of marketing the gypsum.

Conditions that favored the gypsum-producing process were a high flue gas SO_2 concentration and high SO_2 removal rates--i.e., a large quantity of sulfur removed in comparison to the volume of flue gas scrubbed. As a result, the power plants at which a gypsum-producing FGD process was the most highly favored tended to have new boilers (with stringent emission limitations) and burn high-sulfur bituminous coal. The average age of the boilers of the 14 power plants used in the study was 7 years (a 1978 startup) and only 2 boilers were started up before 1970. The size of the FGD systems, in terms of MW scrubbed, ranged from 425 to 3,248 and the gypsum production rates ranged from 160,000 to 700,000 ton/yr.

GYPSUM PRICES

Gypsum is an abundant mineral with little intrinsic value whose cost is determined largely by mining and transportation costs. Wallboard manufacturers almost invariably produce their own gypsum and assign a low value to

TABLE 25. SUMMARY OF GYPSUM MARKETING RESULTS

Power plant	Incremental	Sales with incremental cost, kton/yr							Sales without incremental cost, kton/yr				
		Cement plants only	Wallboard plants only	Cement and wallboard plants					Cement plants only	Wallboard plants only	Cement and wallboard plants		
County, State	cost, $/ton			Cement	Wallboard	Total	Dried[a]	Dried and briquetted[b]			Cement	Wallboard	Total
Pleasants, W. Va. (307 kton/yr)	-19	292	None	307	None	307	307	307	108	None	108	None	108
Coshocton, Ohio (483 kton/yr)	-20	483	128	355	128	483	483	483	162	128	162	128	290
Monroe, Mich. (700 kton/yr)	-18	357	700	156	544	700	700	700	156	452	156	452	608
Boone, Ky. (197 kton/yr)	-13	None	None	29	None	29	None	None	32	None	32	None	32
Trimble, Ky. (166 kton/yr)	-23	53	85	81	85	166	166	166	51	None	51	None	51
Jefferson, Ky. (577 kton/yr)	-24	206	163	334	243	577	577	577	53	None	53	None	53
Muhlenberg, Ky. (544 kton/yr)	-18	165	170	186	170	356	444	356	243	170	271	170	441
Pike, Ind. (254 kton/yr)	-20	None	254	None	254	254	254	254	32	254	32	222	254
Sullivan, Ind. (282 kton/yr)	-21	235	282	80	202	282	282	282	100	282	54	228	282
Randolph, Mo. (363 kton/yr)	-16	363	170	302	61	363	363	363	273	None	273	None	273
Atascosa, Tex. (222 kton/yr)	-22	222	153	222	None	222	222	222	222	None	222	None	222
Hillsborough, Fla. (160 kton/yr)	-20	160	160	89	71	160	160	160	89	160	89	71	160
Putnam, Fla. (271 kton/yr)	-26	242	271	28	243	271	271	271	None	271	None	271	271
Duval, Fla. (182 kton/yr)	-22	60	182	None	182	182	182	182	63	182	None	182	182
(4,708 kton/yr)		2,838	2,718	2,169	2,183	4,352	4,411	4,323	1,584	1,899	1,503	1,724	3,227
% of total market		83	25	63	20	31	31	30	46	18	44	16	23

Note: All gypsum quantities are dry weight, 100% gypsum. Except as noted, all sales are as-produced gypsum containing 10% water and the allowable cost is 90% of the cost of the natural gypsum supply.

a. Sales of gypsum dried to 2.5% water to cement and wallboard plants with an allowable cost equal to the cost of the natural gypsum supply.
b. Sales of gypsum dried to 2.5% water to wallboard plants and dried and briquetted gypsum to cement plants with an allowable cost equal to the cost of the natural gypsum supply.

it, treating the cost of obtaining it as a manufacturing cost. Cement manufacturers usually purchase gypsum from suppliers and generally pay higher prices than those assigned to wallboard gypsum. In this study, a 1985 cost of 8.20 $/ton was used for domestic gypsum at the mine and a cost approximately double that, depending on the port, was used for gypsum imported by sea. The cost of gypsum assigned to wallboard plants (freight only) and to cement plants (freight plus profit) illustrates the importance of location and freight in gypsum costs. The cost of gypsum to wallboard plants ranged from 10 to 37 $/ton and averaged 15 $/ton, while the cost of gypsum to cement plants ranged from 17 to 52 $/ton and averaged 33 $/ton. In addition to the difference in the cost of gypsum to wallboard and cement plants, there were large geographical differences depending on the locations of the plants. Inland plants, roughly from Michigan to Texas, had generally low gypsum costs; those on the Eastern Seaboard and Gulf Coast had higher gypsum costs; and those between these areas--typically in the Appalachian region and the inland Southeast--had the highest. These differences had important effects on both the marketability and the market structure of FGD gypsum.

FREIGHT COSTS

The arbitrary distance limitations of 500 miles for shipments of gypsum to cement plants and 250 miles for shipments of gypsum to wallboard plants used in the marketing models proved to be representative of the distance limitations imposed by shipping costs. All 14 of the power plants were able to market gypsum at a savings, with incremental costs offsetting freight costs, to cement plants in the 400- to 500-mile range but only 5 were able to market at the full 500-mile range, and these at almost no savings. Nine of the power plants were able to market gypsum to wallboard plants in the 200- to 250-mile range but only two were able to market at the full 250-mile range, again at little savings.

CEMENT PLANT MARKET

There were projected to be 114 cement plants in the study area with a total gypsum requirement of 3.42 million ton/yr in 1985. The cement plants are geographically well dispersed and the individual plants have low gypsum requirements in comparison with the power plant production rates. Most cement plants require 10,000 to 60,000 ton/yr of gypsum and the average for all plants is 30,000 ton/yr. The 14 power plants used in the marketing models were within 500 miles of 19 to 58 cement plants, depending on their location. The average number of cement plants within 500 miles of the power plants was 43. Those not situated on the periphery of the study area were all within 500 miles of more than 50 cement plants. The power plants could market gypsum at a savings of 64% to 94% of the plants within 500 miles of them. Regarded individually, with no other FGD gypsum production, all of the power plants could market all of their production to cement plants. Usually, in fact, the cement plant market available to individual power plants far exceeded the individual power plant production. The 14 power plants could also reach almost the entire cement plant market; gypsum could be marketed at a savings to 108 of the cement plants by at least 1 power plant. Based on these results, it is apparent that most other power plants in the study area could, on an individual basis, market FGD gypsum to cement plants. The total cement plant market has a limited capacity to absorb FGD gypsum, however. Ten power plants with production rates similar to the power plants used in the model would supply the entire cement plant gypsum requirements in the study area.

WALLBOARD PLANT MARKET

There were projected to be 52 wallboard plants with a total gypsum requirement of 10.78 million ton/yr in the study area in 1985. The wallboard plants tend to be clustered in areas where gypsum is available, either far inland or on the seacoast. The average gypsum requirement of the wallboard plants in the study area is 194,000 ton/yr and the range is 34,000 to 383,000 ton/yr. Each of the 14 power plants is within 250 miles of at least 1 wallboard plant and 2 are within 250 miles of 8 wallboard plants (the average is about 5). Regarded individually, all of the power plants could market gypsum to wallboard plants, but only 11 could market all of their production in this manner. Usually, however, the available market comfortably exceeded the production of the individual power plants.

The 14 power plants could market gypsum at a savings to only a portion of the total wallboard plant market. Only 30 of the 52 wallboard plants in the study area were within 250 miles of 1 of the power plants and gypsum could be marketed at a profit to only 20 of these. The total gypsum requirements of these plants accessible to power plant sales were 3.67 million ton/yr. Thus, although the wallboard market is much larger than the cement plant market--able to absorb the production of 32 power plants with an average production of those used in this study--power plant location is an important factor in the ability to market to wallboard plants. Favorably situated power plants could, on an individual basis, market all of their gypsum production to one, or at the most, a few wallboard plants. Others, however, might find a market insufficient to consume their entire production, or no market at all.

MARKETING TO CEMENT PLANTS

When all 14 of the power plants are included in the cement plant marketing model, with sales assigned on the basis of the largest savings (i.e., the lowest delivered cost), the results were very good from the standpoint of market penetration. A total of 2.84 million ton/yr was marketed by 12 power plants at a savings of 62.95 million $/yr. The gypsum requirements of 95 of the 114 cement plants in the study area were met, wholly or in part, by FGD gypsum. The FGD gypsum sales represented 82% of the total cement plant gypsum requirements in the study area and 86% of the requirements of the 108 cement plants accessible to the power plant. From the standpoint of marketing the FGD gypsum, particularly for individual plants, however, the results were somewhat less favorable. Only 60% of the total gypsum was marketed and only four plants were able to market their entire production; two plants had no sales. These results were a consequence of the limited cement plant gypsum demand and competition among power plants.

The market structure was complex, with sales by individual plants to 2 to 17 cement plants at distances up to 500 miles. The plants that marketed over 90% of their production had sales to an average of 11 cement plants. The average distance for all sales was 208 miles.

Cement plants offer a FGD gypsum market readily available to most power plants in the study area. In order to market the quantities of gypsum produced by most power plants, however, a complex marketing structure covering a large area is required. This, and the limited capacity of the cement plant market to absorb FGD gypsum, would quickly introduce competition among power plants and possibly reduce sales in situations where more than a few widely spaced power plants were producing gypsum. There is a high degree of fluidity in the marketing structure; the entry of an additional power plant could drastically alter the marketing potential of other power plants.

MARKETING TO WALLBOARD PLANTS

When all 14 power plants were included in the wallboard plant marketing model, the quantity of gypsum marketed and total savings were very similar to the results for the cement plant marketing model; 2.72 million ton/yr was marketed by 12 power plants to 17 wallboard plants with a total savings of 62.28 million $/yr. The sales represented 74% of the total gypsum requirement of the 20 wallboard plants accessible to the power plants and 27% of the total wallboard plant gypsum requirement in the study area. Only six power plants were able to market all of their production, however. Competition among power plants was a factor in limiting sales, but power plant location was also an important factor. Proximity to a wallboard manufacturing area was important because of the shorter economical transportation distances. The marketing structure was simple in most cases. Only one power plant marketed to more than two wallboard plants and the average transportation distance was 90 miles. The marketing distance was over 200 miles in only two cases, both the result of anomalous high allowable costs.

Wallboard plants offer a FGD gypsum market of potential high volume and simple structure. One, or at the most a few, wallboard plants would absorb the production of most power plants, as compared with about 12 cement plants. Competition among power plants is also less important because of the shorter economical transportation distances and the high-volume gypsum requirements of wallboard plants. The wallboard market is less fluid because the shorter transportation distances limit power plant interactions; once established, a wallboard plant market would be less susceptible to the entry of other power plants. Power plant location is important to sales potential in the wallboard plant market, however. It is evident from the distribution of wallboard plants, and the low cost of natural gypsum at many plants, that an appreciable portion of power plants in the study area would be poor prospects for the production of FGD gypsum for sale to wallboard plants. This is particularly true of the inland Southeast where there are no wallboard plants. On the other hand, the geographic distribution of the power plants used in the marketing model was poorly suited for effective sales to wallboard plants. The locations precluded sales to large markets, particularly on the Eastern Seaboard. The results indicate, however, that an appreciable potential wallboard plant market exists for FGD gypsum for favorably located power plants, that FGD gypsum can be marketed to wallboard plants with high gypsum costs over considerable distances, and that FGD gypsum can compete with low cost natural gypsum if the power plant is near the wallboard plant.

MARKETING TO CEMENT AND WALLBOARD PLANTS

When all of the power plants were included in a combined model, with sales to both cement and wallboard plants, the results were largely additive as compared with the results of the individual markets. A total of 4.35 million ton/yr of gypsum was marketed to 79 cement plants and 14 wallboard plants at a savings of 109.66 million $/yr. This represented 92% of the power plant production, 63% of the cement plant requirements, 20% of the wallboard plant requirements, and 31% of the total gypsum requirements in the study area. Both the sales volume and savings were divided almost equally between cement plants and wallboard plants. Twelve of the plants marketed all of their production, one marketed a substantial portion, and one (which had no sales in either market when the sales were limited to a single market) acquired one cement plant sale.

The basic structure of the market did not change. The average delivery distance to cement plants was 203 miles and to wallboard plants 77 miles, only slightly less than those in the individual markets. For power plants with sales to cement plants, the maximum number of sales was 13 and the average was about 8, while the maximum number of wallboard plant sales by a power plant was 4 and the average was less than 2.

SALES WITHOUT INCREMENTAL COST

Without the incremental cost to offset freight costs, sales to more distant cement and wallboard plants were substantially reduced, with a corresponding decline in the marketability of the gypsum produced at some of the power plants used in the study. Without incremental cost, the individual power plants had sales with savings at 9 to 18 cement plants, with an average of 13 cement plants. The average cement plant market available (with sales at a savings) was 375,000 ton/yr and the total available market was 1.66 million ton/yr. Eight of the power plants were able, without competition from other power plants, to market their entire production to cement plants and all plants had sales. In the marketing model with the 14 power plants, almost the entire available cement plant market was filled. A total of 1.58 million ton/yr of gypsum was marketed to 55 cement plants by 13 of the 14 power plants at a savings of 20.81 million $/yr. Only one of the power plants marketed all of its production, however, and only two others marketed over 50% of their production. The average marketing range was 125 miles and few sales were made in the 400- to 500-mile range. The smaller economical marketing range reduced sales to distant cement plants that, with incremental cost, had served as an important portion of the cement plant market for most power plants. Location became more important because power plants adjacent to areas with high gypsum costs such as the Southeast could market over longer ranges. In general, a cement plant market remained generally available without incremental cost but in most cases it was incapable of absorbing the entire production of the power plants.

Without incremental cost, sales to wallboard plants were also reduced. Regarded individually, 8 of the 14 power plants could make sales with savings to 12 wallboard plants and 6 of these could market all of their production. In contrast to the readily available but low-volume cement plant market, wallboard plants were less likely to be available as a market but for those power plants with access to a wallboard plant market, the large volume more often absorbed all of the power plant production. This is also evident in the marketing model with all 14 power plants. The same 8 power plants marketed 1.90 million ton/yr to 11 wallboard plants at a savings of 10.5 million $/yr. Five of the power plants marketed all of their production. The average marketing range was 77 miles, including an anomalous distance of 230 miles to a wallboard plant with a very high natural gypsum cost.

In the combined model, marketing to both cement and wallboard plants, a total of 3.23 million ton/yr of gypsum was marketed to 52 cement plants and 10 wallboard plants at a total savings of 29.83 million $/yr. All 14 power plants had sales and 7 marketed all of their production. The average marketing distance was 123 miles to cement plants and 52 miles to wallboard plants. Access to a wallboard plant market was generally necessary for marketing a large volume of gypsum.

DRIED GYPSUM SALES

The inclusion of a drying process to dry the FGD gypsum to 2.5% water before shipment had little effect on the sales potential under the conditions assumed for the dried gypsum marketing model. The higher allowable cost and the reduction in freight costs due to the lesser quantity of water shipped were sufficient to offset the 4 to 6 $/ton cost of drying at longer shipping distances. In the combined cement and wallboard plant marketing model, with incremental costs offsetting freight costs, sales were made to the same plants to which sales of undried gypsum were made. In addition, sales were made to three additional cement plants because of the reduction in freight costs. Savings were reduced 2% as compared with the as-produced gypsum marketing model. Drying, if a desired or necessary marketing adjunct, has little overall effect on the marketability of FGD gypsum in marketing structures such as those used in this study. The added cost of drying does not materially affect the marketing range because of the offsetting reduction in freight costs.

Briquetting the gypsum sold to cement plants also had little effect on the marketing potential. As compared with sales of dried gypsum, three cement plant sales were lost and the total savings was reduced by 6%.

COMPARISON WITH PREVIOUS BYPRODUCT MARKETING STUDIES

In 1980, TVA published a FGD byproduct marketing study, also projected to 1985, for sulfur and sulfuric acid sales to sulfuric acid plants similar in structure and concept to this FGD gypsum study (1). The power plant data base consisted of 83 power plants selected as potential byproduct marketing candidates. Under the most favorable marketing model evaluated, sulfur production was an economical FGD option at 12 plants and sulfuric acid was an economical FGD option at 28 plants. Eleven of the sulfur-producing plants were able to market 165,000 ton/yr of sulfur (equivalent in sulfur to 887,000 ton/yr of gypsum). Eight of the acid-producing plants were able to market 868,000 ton/yr of acid (equivalent to 1,523,000 ton/yr of gypsum). In a combined sulfur and sulfuric acid marketing model, two of the acid-producing plants failed to find markets, leaving 11 sulfur-producing plants and 6 acid-producing plants that marketed the equivalent of 1,859,000 ton/yr of gypsum as sulfur and sulfuric acid with a total savings of 10 million $/yr. These sales were about 2% and 3% of the total sulfur and sulfuric acid requirements in the 37-state study area. In the closest equivalent FGD gypsum marketing model in this study, 52 of the 104 power plants in the marketing model could operate a gypsum-producing FGD process more economically than a fixation and landfill process. Of these, 14 selected power plants marketed 4,323,000 ton/yr of gypsum at a savings of 109 million $/yr, meeting 31% of the total gypsum demand in the study area.

In terms either of the quantity of byproduct marketed or the portion of market captured, the FGD gypsum was much more successful than either the FGD sulfur or the FGD acid, or the two combined. The results are in large proportion the result of the FGD costs associated with the three byproduct-producing processes. Both the sulfur- and acid-producing processes were substantially more expensive to operate than the limestone-scrubbing, fixation and landfill process used as the alternative FGD process, creating an additional cost that had to be offset by the sales revenue to make the byproduct-producing process economically competitive. The gypsum-producing process was less expensive than the alternative fixation and landfill process (assuming disposal of the gypsum) and the negative incremental cost was an additional revenue that could be used to ensure sale of the gypsum by offsetting freight costs. This occurred in spite of a considerable disadvantage for gypsum in price and freight costs. In the sulfur marketing model, a price of 80 $/ton was used and shipment of 1 ton of sulfur required shipment of 1 ton of product. In the acid marketing model, a price of 45 $/ton was used and shipment of 1 ton of sulfur required shipment of 3.1 tons of product. For the gypsum marketing model, the average price to cement plants was 33 $/ton, to wallboard plants it was 15 $/ton, and shipment of 1 ton of sulfur required shipment of 5.4 tons of product.

In terms of total potential market, however, FGD gypsum has less potential for disposal of large quantities of sulfur from FGD, which is the essential purpose of marketing FGD byproducts. The total cement and wallboard plant gypsum requirements in the study area were 14.20 million ton/yr, equivalent to the production of 42 power plants with an average production rate typical of the power plants used in the study. The total sulfur requirements of acid plants in the same area were 10 million ton/yr, equivalent to the sulfur production of 159 power plants with the same average production rate (63,000 ton/yr of sulfur, equivalent to 336,000 ton/yr of gypsum).

PRODUCTION OF WALLBOARD AT POWER PLANT LOCATIONS

Some aspects of the economics of manufacturing wallboard at power plants, as compared with manufacturing it at existing wallboard plant locations, were investigated by comparing wallboard freight costs from the 14 power plant locations to marketing areas with the freight costs from existing wallboard plants to the same marketing areas. To model the marketing areas, a stochastic array of 43 regional distribution centers based on population density and construction activity was used to calculate point-to-point freight costs. The premise upon which the study was based was that power plants could serve as sources of gypsum analogous to mines and ports, which now largely determine the location of wallboard plants, and that some power plants could be more favorably situated with respect to marketing areas than the mines and ports. The study only compared wallboard freight costs, exclusive of gypsum costs that determined the feasibility of gypsum sales in the previous evaluations.

Wallboard could be shipped at a freight savings from 10 of the 14 power plants to 15 of the 43 regional distribution centers. The total freight savings was 24.52 million $/yr, equivalent to 11 $/ton of gypsum. The wallboard represented 2.20 million ton/yr of gypsum, 47% of the total power plant production and 19% of the total wallboard sales in the study area. In all but 2 of the 17 individual cases in which shipments from power plants could be made at a savings, the power plant wallboard replaced wallboard shipped at relatively long distances to areas remote from wallboard plants or areas with an insufficient supply from nearby wallboard plants. Only in two cases did power plant wallboard replace wallboard from existing wallboard plants that was shipped less than 100 miles. In the other 15 cases, the power plant wallboard replaced wallboard from remote existing wallboard plants, either because there were no nearby existing wallboard plants or because the nearby existing wallboard plant could not satisfy all of the requirements of the distribution center. The power plants themselves were often quite far from the distribution center. The average shipping distance for the power plant wallboard was 123 miles and the maximum was 300 miles; in only five cases was the shipping distance less than 100 miles.

The results illustrate the unbalanced relationship of existing wallboard manufacturing facilities, rooted for the most part to sources of gypsum, and the marketing areas. In most cases, the 14 power plants used in the study were not particularly well situated to serve as gypsum sources. This is particularly well illustrated by the six distribution centers in the Southeast that were 120 to 300 miles from the nearest wallboard plant and, in the marketing model, imported wallboard from plants up to 575 miles away. The nearest power plant in the model was 190 miles away, however, and the average distance from these distribution centers to one of the power plants in the model was almost 300 miles.

CONCLUSIONS

Advances in limestone FGD technology have made gypsum-producing processes economically competitive with low-cost limestone processes that produce a waste requiring treatment before disposal. In some cases (typified by boilers with stringent emission limitations that burn a high-sulfur coal), gypsum production and marketing may be the lowest cost FGD option even without sales revenue to offset FGD costs. These developments have enhanced the prospects for marketing FGD gypsum since the byproduct gypsum process does not necessarily require sales revenue in all cases to make it economically competitive with other FGD processes in cases in which waste disposal is difficult or expensive. The sales revenue--and savings from the use of the gypsum process itself in some cases--can be an added economic inducement to gypsum marketing or used in part to offset marketing costs.

The only gypsum markets capable of supporting a general production of FGD gypsum are the portland cement and wallboard industries. The 114 cement plants east of the Rocky Mountains could consume the production of about 10 power plants and the 52 wallboard plants in the same area could consume the production of about 32 power plants typical of those used in this study. With the FGD cost savings offsetting freight costs, gypsum could be marketed to cement plants within a radius of about 500 miles and to wallboard plants within a radius of about 250 miles. At least several, and often more than a dozen, cement plants would be required for the production of each power plant whereas at the most a few wallboard plants could consume production of a power plant.

All of the marketing model evaluations in this study can be regarded as successful. Usually well over one-half of the 14 power plants in the marketing model could successfully market all of their production under the several model variations evaluated. Without competition, all of the power plants could market all of their production to cement plants and 11 of the power plants could market all of their production to wallboard plants. With all power plants marketing simultaneously (with the incremental cost offsetting freight costs and selling to both markets) all but two of the power plants were able to market all of their production in spite of extensive competition. Treatments such as drying and briquetting had little effect on the marketability of the gypsum. Elimination of the incremental cost reduced total sales by about one-fourth and savings by about three-fourths but seven power plants were able to market all of their production. Relocation of wallboard plants to sources of power plant gypsum would, in some cases, reduce costs of shipping wallboard to marketing areas.

The results show that, without competition from other power plants, most of the power plants in the study area for which a gypsum process is more economical than a waste-producing process could successfully market to cement plants, regardless of the power plant location, and that some could market successfully to wallboard plants, although power plant location would be a factor in marketing to wallboard plants.

In a competitive situation with several power plants marketing FGD gypsum, competition would limit sales in some cases. Competition for the cement plant market would be effective over long distances--between power plants separated by several hundred miles in some cases--and the cement plant marketing structure would be quite fluid, subject to activities of other, often distant, power plants. Competition in the wallboard plant market would be more localized and, in some cases, less severe because of the large gypsum requirements of wallboard plants and the tendency in some cases for wallboard plants to be clustered at sources of gypsum.

The power plants used in the marketing model were selected for fuel, boiler characteristics, and emission regulations favorable for gypsum production and for a theoretical capacity (possession of efficient fly ash control equipment, for example) to produce gypsum. The evaluation excluded site-specific situations that could have large effects on the comparative economics of gypsum marketing and waste disposal: lower land costs, more economical disposal practices, lower capacity factors and projected operating lives, and the necessity of upgrading other equipment. The results of the particular model used illustrate several important factors in the gypsum marketing strategy, particularly with respect to power plant location and competition among power plants, and they illustrate the generally favorable prospects for some FGD gypsum marketing, as well as the pitfalls of location and competition. It is evident, however, that the particular power plants used determined the specific results. Other equally suitable, or nearly so, power plants could have been selected using different procedures that would have produced different results. A model designed to maximize sales by selection of power plants near wallboard manufacturing areas, particularly on the Eastern Seaboard, would probably have resulted in much larger sales volumes, for example.

FGD gypsum marketing differs substantially, if not fundamentally, from the marketing of other FGD byproducts such as sulfur and sulfuric acid. Gypsum-producing FGD processes are economically competitive with alternative waste-producing processes and the sales revenue is not a critical factor in its economic justification. In many cases, simple removal of the gypsum at no cost is sufficient to justify adoption of the process and, in some cases, the savings in FGD costs by adopting a gypsum-producing process could be used to supplement freight costs, thus enhancing the marketability of the gypsum. On the other hand, byproduct processes usually involve higher costs to the point that sales revenue is an integral and important factor of their economics, making them more vulnerable to market conditions. However, even widespread adoption of byproduct processes that produce sulfur and sulfuric acid would supply only a small portion of the market requirements. This contrasts with the situation that would be created by a similar adoption of gypsum processes. The FGD gypsum supply would saturate the market (exceed the market requirements) and would result in intense competition.

RECOMMENDATIONS

The site-specific nature of power plant waste disposal economics has been widely and frequently commented upon; the situation is familiar to those who have evaluated these economics and has been well illustrated by the many studies that have been published. This general study--which excludes or uses representative averages for the many such site-specific situations that cannot be readily quantified or which would detract from a general overview--suggests that corresponding site-specific studies for specific situations should be performed for those faced with the necessity of disposing of FGD products.

Some of the specific conditions that should be included in such studies (which in this study have been assigned average values or which are assumed to be unnecessary in a general study) are: the actual production rates based on projected capacity factors and unit lives; land costs and availabilities; retrofit factors for existing units; actual allowable disposal practices, which differ among states; and other necessary costs, such as upgrading of existing equipment. All of these factors could have important effects on the costs of gypsum production and marketing versus production of a waste. In addition, this study has shown that both location and the potential of competition are important considerations. These factors too should be considerations in a site-specific study.

There is also a factor of industry acceptance that is difficult to quantify on economic or technical bases: the apparent reluctance--or inertia--of potential users to abandon traditional sources of raw materials without inducements other than a lower cost (which at best is all that FGD gypsum could offer either wallboard or cement plant operators). If this cannot be quantified, neither should it be ignored in any assessment of FGD gypsum marketing prospects.

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-84-019	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Marketing of Byproduct Gypsum from Flue Gas Desulfurization		5. REPORT DATE February 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) W.E.O'Brien, W.L.Anders, R.L.Dotson, and J.D.Veitch		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS TVA, Office of Power Division of Energy Demonstrations and Technology Muscle Shoals, Alabama 35660		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. EPA Interagency Agreement 79-D-X0511
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 1/81 - 4/83
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Julian W. Jones, Mail Drop 61, 919/ 541-2489.

16. ABSTRACT The report gives results of an evaluation of the 1985 marketing potential of byproduct gypsum from utility flue gas desulfurization (FGD), for the area east of the Rocky Mountains, using the calculated gypsum production rates of 14 selected power plants. The 114 cement plants and 52 wallboard plants in the area were assumed to be the potential market for FGD gypsum sales. Assuming use of an in-loop, forced-oxidation, limestone FGD process, results showed that producing marketable gypsum was less expensive than disposal by chemical fixation and landfill for many power plants in the area, including those used in the study. With this savings to offset freight costs, the power plants could market 4.35 million tons/year of gypsum (92% of their production), filling 63% of the cement plant requirements and 20% of the wallboard plant requirements. Cement plants are a geographically disperse market available to most power plants, but able to absorb the production of only a few power plants; wallboard plants are a larger market but, for them, power plant location is a more important marketing factor. Other variations of the marketing model indicated that: drying and briquetting had little effect on marketing potential; and sales were reduced 25% when the savings in the FGD cost were not used to offset freight costs.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Gypsum	Stationary Sources	08G
Marketing		05C
Flue Gases		21B
Desulfurization		07A, 07D
Byproducts		14G

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 170
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)