REPORT OF INVESTIGATIONS NO. 90

PROCEEDINGS
Gulf Coast Lignite Conference: Geology, Utilization, and Environmental Aspects

W.R. KAISER, EDITOR

Sponsored by
BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

NATIONAL SCIENCE FOUNDATION
RESEARCH APPLIED TO NATIONAL NEEDS (RANN)

JUNE 2, 3, and 4, 1976, AUSTIN, TEXAS

Bureau of Economic Geology
The University of Texas at Austin
W.L. Fisher, Director

1978

Funding supplied in part by the U.S. Energy Research and Development Administration, University Programs, Fossil Energy Research, Washington, D.C., under ERDA Purchase Order 76-15.

EDITOR'S NOTE

Papers in this volume were presented at the Gulf Coast Lignite Conference held in Austin, Texas, June 1976. Papers were edited, in some cases extensively, and subjectively grouped by discipline paralleling that of their presentation at the Conference.

Kudos to Cecille Haynie and Susann Doenges, Bureau of Economic Geology, for their unflagging editorial help with this volume. Charles G. Groat, now State Geologist, Louisiana Geological Survey, Baton Rouge, Louisiana, acted as general chairman, and W. R. Kaiser, Bureau of Economic Geology, was program chairman for the Conference. The freely given cooperation of the Aluminum Company of America, Elgin-Butler Brick Company, and Texas Utilities Company made the field trips possible. The Conference was held in cooperation with The Center for Energy Studies, The University of Texas at Austin.

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THE IMPORTANCE OF COAL AND LIGNITE IN THE NATIONAL ENERGY OUTLOOK

W. L. Fisher[1]

I appreciate the opportunity you have given me to start the ball rolling at this important Gulf Coast Lignite Conference.

Coal is the major ingredient in the American energy resource base, accounting for 90 percent of that base. United States coal is three times the energy base of Middle Eastern oil, but in the past 75 years, we have gone from coal supplying 90 percent of our energy consumption to a current 18 percent. Now we use oil and gas for 75 percent of our consumption, and import nearly half the oil. In 1975 our per capita expenditure for imported oil was $125, 8.5 times what it was in 1970. That situation will worsen if we do not take steps to prevent it. We can prevent it. Our total domestic energy supply can increase by 40 percent by 1985.

> Coal production can go to 1.0 billion tons per year.
> Oil can increase to 13.9 million barrels per day if the outer Continental Shelf is aggressively leased and is productive.
> Natural gas can go to 22.3 trillion ft^3 per year with appropriate price incentives.
> Nuclear capacity could go from 8.6 percent to 26 percent of our electrical generation.
> We can conserve and keep energy growth at around 2.2 percent rather than the historical rate of 3.6 percent.
> Synthetics can play an important part in our post-1985 supply.

To accomplish these goals, we face a difficult but possible job. For example, to arrest decline in existing oil fields, we will have to bring on a productive capacity equal to a Prudhoe Bay field every 3 years.

It can be done and will be done if the Nation as a whole can take a page from the Texas experience, particularly regarding coal. In 1970 Texas produced less than 0.4 percent of United States coal. Now it produces 2 percent and by 1985 will probably account for nearly 10 percent of the projected total coal production in the United States. These are excellent strides for a State that is also the main oil and gas producer of the Nation.

Texas has tremendous lignite coal reserves, with near-surface resources of ten billion tons, enough to fuel 50 steam plants, each generating 1,000 megawatts, for 35 years. This bountiful blessing of coal resources applies to the United States as a whole, also, with large deposits of coal found on public lands in Wyoming, Montana, Colorado, Utah, New Mexico, and North Dakota.

Both Texas, as a single State, and the Nation, as a group of 50 states, face the same general problem. The indicated solution is to switch the electric generation from oil and gas to coal and to solve another part of the problem by spurring exploration and development of new sources of oil and gas.

The Federal Government is involved in the pricing of gas which moves in interstate commerce. Most gas men would call that the understatement of the year. The Federal Government has mighty little to do with the pricing of gas which moves only in intrastate commerce.

Let's compare a few bits of recent history—what has happened in Texas, and what has happened in the United States as a whole.

In Texas, the price of intrastate gas rose as a result of an unregulated market-pricing system.

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[1] Director, Bureau of Economic Geology, The University of Texas at Austin 78712. On leave as Assistant Secretary for Energy and Minerals, U.S. Department of the Interior in 1976.

This was the simple, almost classical, working of the laws of supply and demand. The supply was down, so the price went up to the $2.00 figure while the federally regulated price of gas moving in interstate commerce stayed down at the artificially low, regulated price of about $0.54. Texas produces about 40 percent of all the natural gas produced in America, and Texas consumes about 55 percent of what it produces.

Because natural gas is a versatile fuel, preferred for many purposes, manufacturers sought it and were willing to pay for it in Texas (and in Louisiana) in accordance with prices set by the laws of economics. Naturally, this unregulated price of an item in short supply went up.

There were two fundamental results of this higher price. First and foremost, it spurred exploration and production of natural gas in Texas —priced in Texas, sold in Texas, and used in Texas—without being affected by the artificially regulated price of natural gas in interstate commerce. The second result was a prompt switch to coal, a plentiful fuel, to replace natural gas, which is not plentiful, to fuel steam plants. Texas lignite production has risen from 4.5 million tons in 1972 to 7.6 million tons in 1974, and preliminary Bureau of Mines figures show almost 11.5 million tons in 1975. The increase of the past 4 years is certain to continue, simply because new plants are now being built and new mines are being opened. It is not a possibility that Texas will use more coal —it is a certainty, and the 1980 production of lignite will be double that of 1976, estimated at 25 million tons.

Continue the solid projection curve, based on fact, not oratory, and we predict that the 1985 annual production of lignite in Texas will exceed 50 million tons.

It is predicted that Texas Utilities Generating Company's Martin Lake plant at full capacity will mine approximately 15 to 17 million tons per year.

Texas has a long history of lignite mining. The Darco mine has been producing 250,000 tons per year for some time now. It began operations in 1931 and is the oldest continuously operated coal mine in Texas. But the past history in lignite coal production in Texas was merely a prologue to what is now underway. Let me remind you of some of the new projects which are building toward the impressive totals I have forecast.

The San Miguel project in Atascosa and McMullen Counties will generate 800 megawatts at full development. The Twin Oak project in Robertson County will generate 1,500 megawatts for the Texas Power and Light and ALCOA companies. The Bryan Project in Brazos County will add 800 megawatts for the Texas Municipal Power pool, using Grimes County Manning lignite. Texas Utilities Generating Company will be generating in Rusk County at its Martin Lake plant of 3,000 megawatts. And 750 megawatts will be added to its Monticello plant in Titus County. Shell plans to mine in Milam County around 1980 or 1981. Other plants and mines are contemplated.

Basing predictions on solid projections, we can say that the 8-year period between 1974 and 1982 will see lignite coal increase its share of the electric generating load in Texas from 7 to 13 percent, and that is what can normally be expected to happen in a state where the normal operations of the laws of supply and demand are allowed to proceed without undue governmental regulation and without undue restrictions upon the use of coal.

Contrast what the United States has not been able to do in increasing total coal consumption with what Texas has done, and you'll have to agree with the little girl who said, "Wouldn't it be wonderful if the whole world could be like Texas?" United States total consumption of coal has moved up very slightly in the past 50 years. Because oil and natural gas both are priced by the Federal Government through its powers to regulate fuels moving in interstate commerce, these fuels are such bargains that there is no incentive for any energy consumer to move away from them toward coal.

Because petroleum fossil fuels are so cheap in interstate commerce, our efforts to reduce our dependency upon imports have been seriously hampered. Because oil and gas prices are regulated, proved reserves have declined. We once were a nation of oil and gas exporters. We have imported 35 percent of our oil needs in 1975 and import 42 percent of our oil needs right now with a probability that we will import more than 50 percent after another 12 months have passed.

Because there was no price-differential incentive to spur the conversion from natural gas to coal, and because environmental restrictions make it difficult to burn the coal we do produce, we have succeeded in increasing the Nation's coal production including exports by only 37 million tons per year—12 million tons of that 37 million ton increase is burned in Texas. The picture of failure on the national scene is even more apparent.

We might as well face facts. The production of coal in the United States is demand constrained. We could double our national production if we could sell that doubled production. We could sell that doubled production if the utilities were allowed to burn it and if it were economically cheaper to burn it. But we can't sell coal if there is no price incentive urging the utilities to switch from gas and oil to coal. We can't sell coal if Clean Air Act requirements, which are arbitrary and which are not based on fact or on need, remain on the books.

The President of the United States [Ford] has repeatedly asked the Congress for amendments to the Clean Air Act, amendments which will not cause any significant deterioration of human health standards. We have not had any progress to date on those important changes. Until we do have progress on that front, it is doubtful that we can materially increase the natural production to the point where it will eliminate the need for foreign oil—even if that foreign oil price is set low by the Organization of Petroleum Exporting Countries (OPEC).

The President proposed a determined effort to develop synthetic fuels and to develop other technologies for sending the energy contained in coal into the market place. We have very little results to display after several years of prodding the Congress. Gasification proposals for the public and Indian lands of the west are bogged down in a welter of environmental-impact studies, law suits, Indian claims, and other delaying mechanisms.

In the magnificent empire of Texas, Texas Utilities hopes to have a pilot underground gasifier operating this year. Central Power and Light will repower a 20 megawatt unit at San Benito with low-Btu gas using a fluidized bed process developed by Esso. Other Texas groups are investigating other gasifiers, such as the Koppers-Totzek process. Is it only pride in my home state which tempts me to say that Texas has made more progress here than the other 49 put together? I'll leave that verdict to you, but I will say again, "Yes, it would be nice if all the world could be like Texas."

Plans for using lignite are so far advanced in Texas and progress so real that we confidently expect that the State will import a lot of low-sulfur coal from other western states by 1985. At present, local coal, with sulfur dioxide removal, has a two-to-one advantage in price over the low-sulfur coal which will be brought in. But demand may well dictate the importation of more than 25 million tons per year by 1985 from other western states.

At the present time, Texas stands alone among the Gulf coastal states in mining lignite coal, but there are signs that the example is spreading and that the success of Texas lignite operations may well become contagious. We hear that Consol (Consolidation Coal Company) is going to mine lignite in Alabama by 1980, and we hear that Phillips Petroleum controls 2 billion tons of lignite reserves in the Gulf Coast area. We do not think that they hold these vast reserves for the pleasure of thinking about them. They will be used.

The basic truth is that coal is our most plentiful and our surest source of energy for the next century. Texas is leading the way in showing how lignite can be used to best advantage. The honest, free market of Texas is showing how it works—to force conversion to coal, to spur petroleum exploration, to increase dependence upon coal.

The Nation can and must do the same. The Nation can do the same if it has the will to do what must be done. As I see it, those changes which must be made include:

1. Changes in the Clean Air Act requirements which will allow more use of coal in firing utility generators without significant deterioration in human health standards.
2. A return to the free market principles which made this country and a move away from the over-regulated, government-dictated economy.

A few months ago, we would have had to list other objectives, such as the formulation of realistic rules under which coal can be leased and mined on the public lands of the west. But that has been done, and the regulations which the Department of the Interior published in the Federal Register last month do a good job of prescribing mining and reclamation plans which will get the coal out and protect the environment. The sufficiency of the environmental safeguards was demonstrated when both the Environmental Protection Agency and the Council on Environmental Quality joined the U. S. Department of Interior in sponsoring the regulations. We are requesting more than $22 million and more than 400 permanent positions to supervise the operations by which public coal is mined on the public lands and by which those lands are reclaimed after the extraction process. This expenditure is large, even by Texas standards, but it is amply justified by the royalties which will accrue to the American taxpayer as a result of the coal production.

We in the Department of the Interior have done a lot against formidable obstacles to make coal take its rightful place as this Nation's most used energy fuel. Now it is time for the Nation to follow the example of Texas and move into the greatly expanded use of lignite coal. I think we can do it. I think we have to do it. But I have to admit, it would be much easier if the whole world were like Texas.

ENVIRONMENTS OF PEAT ACCUMULATION — COASTAL LOUISIANA

D. E. Frazier[1], A. Osanik[2], and W. C. Elsik[3]

ABSTRACT

The principal peat-forming environments in coastal Louisiana are the inland fresh-water cypress-gum swampland and the peripheral coastal marshland where the marsh flora is zoned coastward from fresh-water to brackish to saline-tolerant grasses and sedges. The broad floodbasins in the centralized alluvial valley diminish in size and increase in number downstream caused by the Mississippi River trunk stream bifurcating into major distributary-channel networks which enclose smaller interdistributary basins.

The inner swampland terminates basinward within a short distance along the flanks of the distributary levee systems, and the coastward widening interdistributary areas transform into the slowly subsiding peripheral coastal marshlands. Additional peat-forming environments exist in western coastal Louisiana on the contiguous marshes of the chenier plain between relict beaches and in eastern Louisiana in small saline mangrove swamps on the washover (landward) side of the Chandeleur Islands.

Thicknesses and radiocarbon dates of peats from more than a thousand shallow borings verify that peats have been forming in these environments for the past several thousand years. The thickest peats encountered are in the inland swamps and are attributed to environmental stability. Subsiding marshes, genetically related to thin, overlapped delta lobes, form repetitive layers of peat in the peripheral areas. Each thick inland swamp peat, therefore, may be time correlative with several coastal marsh peats. These thick swamp peats make the inland swampland the most prospective ancient coal-forming environment.

INTRODUCTION

Accumulations of peat which formed in ancient swamps and marshes have long been recognized as precursors of lignites and coals. More sophisticated studies on coals (Wanless and others, 1969) have shown that the ancient peats formed in a variety of environmental settings. Earlier, Fisk (1960) suggested that some coals originated as delta-plain peats and referred to examples in the Carboniferous Yoredale series (Moore, 1958) and in the Netherlands coal measures (Thiadens and Haites, 1944). His study of the development of an interdistributary peat in a local area near New Orleans led to comparisons between these deposits and ancient coals. The "splits" in coals were related to wedges of levee deposits, the local destruction of coals was related to erosion by tidal channels to create "washouts," and local absences—"wants"—were related to contemporaneous development of distributary channels and their associated levees.

Byrne and others (1959) described the marsh peats in the central area of the chenier plain; Gould and Morgan (1962) described marsh peats at several localities across the deltaic and chenier plains; and Coleman and Smith (1964) described two types of peat in the southwest area of the deltaic plain: one being interdistributary peats that accumulated in restricted basins between active distributaries, and the other being blanket peats that developed on the coastal deltaic marshes, keeping pace with submergence during the following abandonment of the distributary network.

Since recognizing peat-forming environments is important in determining where ancient coals and lignites were likely to be formed, this paper is concerned with the stratigraphic framework of the near-surface coastal facies sequences.

Figure 1 shows the relationship of the study area, coastal Louisiana, to the northwest Gulf of Mexico. Offshore are the relict Holocene sands deposited during postglacial sea-level rise. Also rep-

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[1] Deceased.

[2] Exxon Production Research Company; Houston, Texas 77001.

[3] Exxon Company, U.S.A.; Houston, Texas 77001.

resented are the post Holocene (or Recent) progradational sediments, Pleistocene, and Tertiary deposits. Note the greater width of coastal deposits in the deltaic area (around New Orleans) and narrower belt in the interdeltaic area (west of Atchafalaya Bay).

The composite physiographic province of coastal Louisiana, consisting of fluvial, deltaic, and interdeltaic environments favorable for peat formation, is shown in figure 2. Broad floodbasins exist between ancient and modern Mississippi River courses and between these courses and the Pleistocene margins of the alluvial valley. These major courses bifurcate downstream and form distributary networks which first enclose smaller floodbasins by coalescing and then allow the interdistributary basins to widen coastward as the distributaries spread apart. Two additional environments for peat accumulation in coastal Louisiana include the contiguous chenier plain to the west, which consists of a flat coastal plain interspersed with relict paralic beach ridges, and the small basins on the washover side of the Chandeleur Islands in the east.

The floral zonation of coastal Louisiana (fig. 3) shows a centralized inland fresh-water cypress-gum swampland and a peripheral marshland. The flora of the marshland, based on the work of O'Neil (1949), is zoned coastward from fresh water to brackish to saline-tolerant grasses and sedges. The exception to the rule is the fresh-water marsh floral zonation of the modern delta where the volume of river water is sufficient to flush the marshland due to the lack of levees. A typical marsh and a swamp are illustrated by Frazier and Osanik (1969).

The stable inland swampland terminates coastward along the levee flanks a short distance beyond where the coalescing distributaries spread apart. As the more stable distributaries spread, the interdistributary basins widen and transform into slowly subsiding peripheral coastal marshlands. Peats may develop in both swamp and marsh complexes.

The following discussion includes conclusions from Frazier (1967, 1969, 1974) and Frazier and Osanik (1969) and is an attempt to relate peats to the many environments in which they formed and are forming during development of the Louisiana coastal plain and to show their relationships to the underlying stratigraphic facies framework utilizing data obtained from more than a thousand cored borings which are deeper and more extensive than those of previous studies. Although the coastal plain is relatively simple in appearance, the mass of underlying sediments is very complex.

This study is limited to the last 10,000 years and related water depths shown in the upper right-hand corner of the sea-level curve shown in figure 4. The curve was constructed using radiocarbon dates determined on faunal and floral specimens from their present subsea depth used in conjunction with their depth range at the time they were living. Figure 5 is a chronology of the delta lobes based on the ages of the delta-plain peats, illustrating their complexity.

DELTA COMPLEXES

Since the delta complex is the most dominant and influences the stratigraphic framework of the narrower contiguous interdeltaic area to the west, its development will be considered first. The deltaic mass is the composite result of the many progradations of the Mississippi River. As previously mentioned, the plain is transected by numerous natural levees flanking major stream courses and their distributary networks. The pattern of the natural levees reveals that four delta complexes (fig. 6) make up the modern deltaic plain—the Teche, St. Bernard, Lafourche, and Plaquemines-Modern. Each delta complex consists of several progradations or lobes (fig. 6) of the ancient Mississippi river.

DEVELOPMENT OF A TYPICAL DELTA COMPLEX

The four successive diagrams of figure 7 illustrate the development of the repetitive deltaic facies sequences in the unstable coastal portion of a typical delta complex.

Initial Progradation (Block A)

Delta formation begins as a stream debouches its sediment load into a standing body of water. In the stream-mouth environment, the sediment load is naturally sorted. The finer grained sediments are carried farther into the basin (but only to a certain limit) where they settle out of suspension.

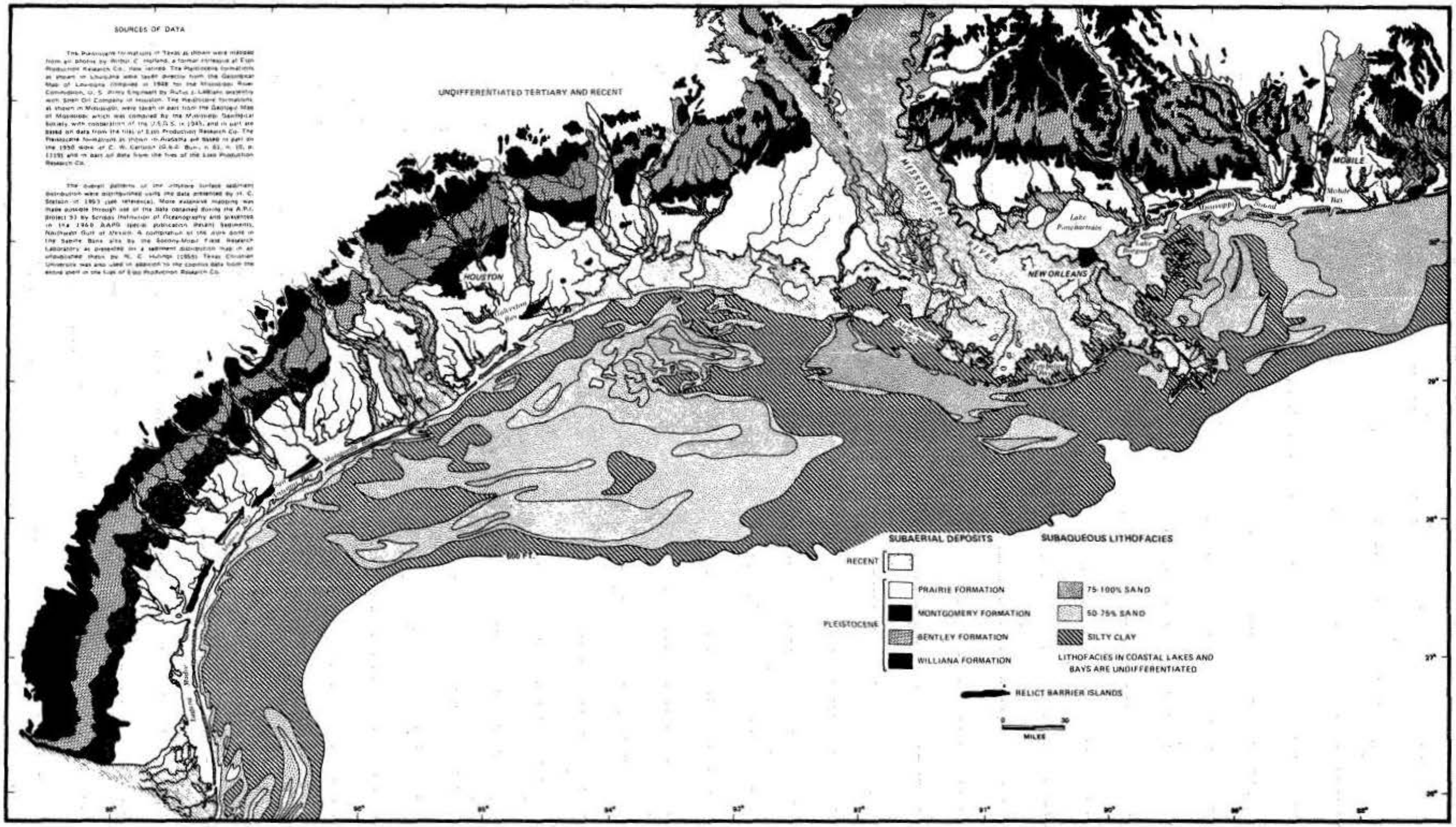


Figure 1. Area of Mississippi River Delta and relict Holocene sands (from Frazier, 1974).

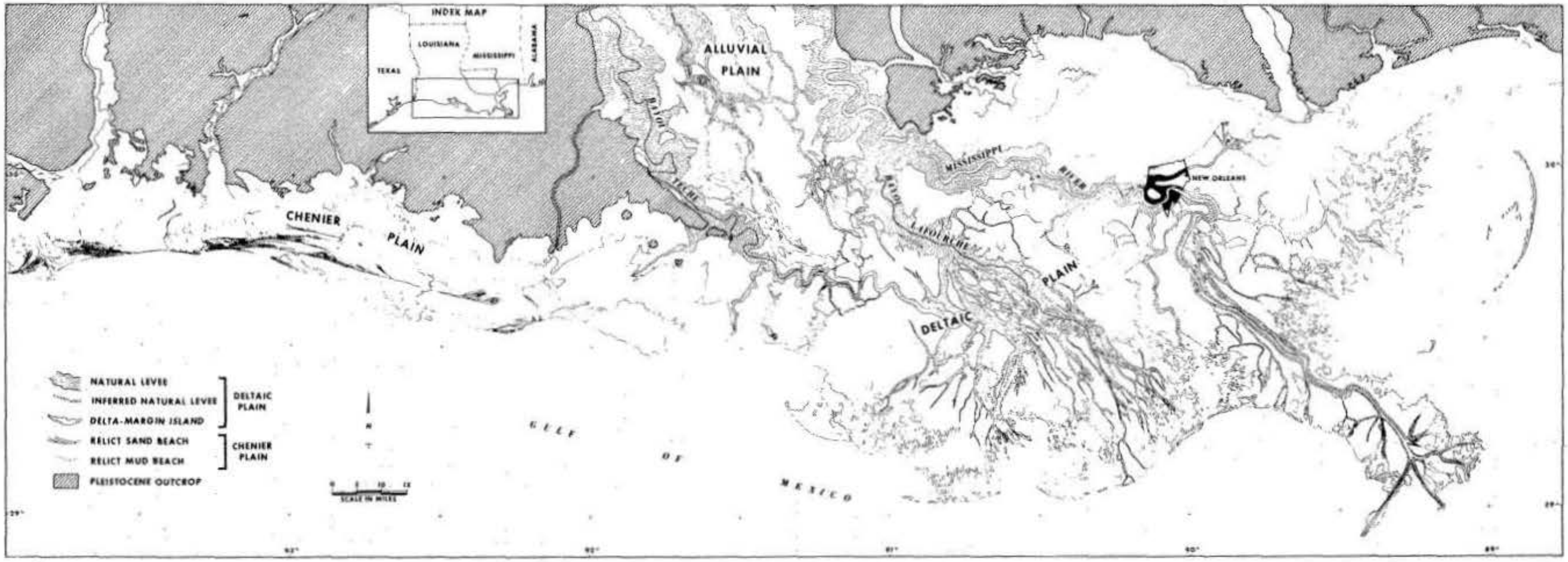


Figure 2. Physiographic features of coastal Louisiana (Frazier and Osanik, 1969).

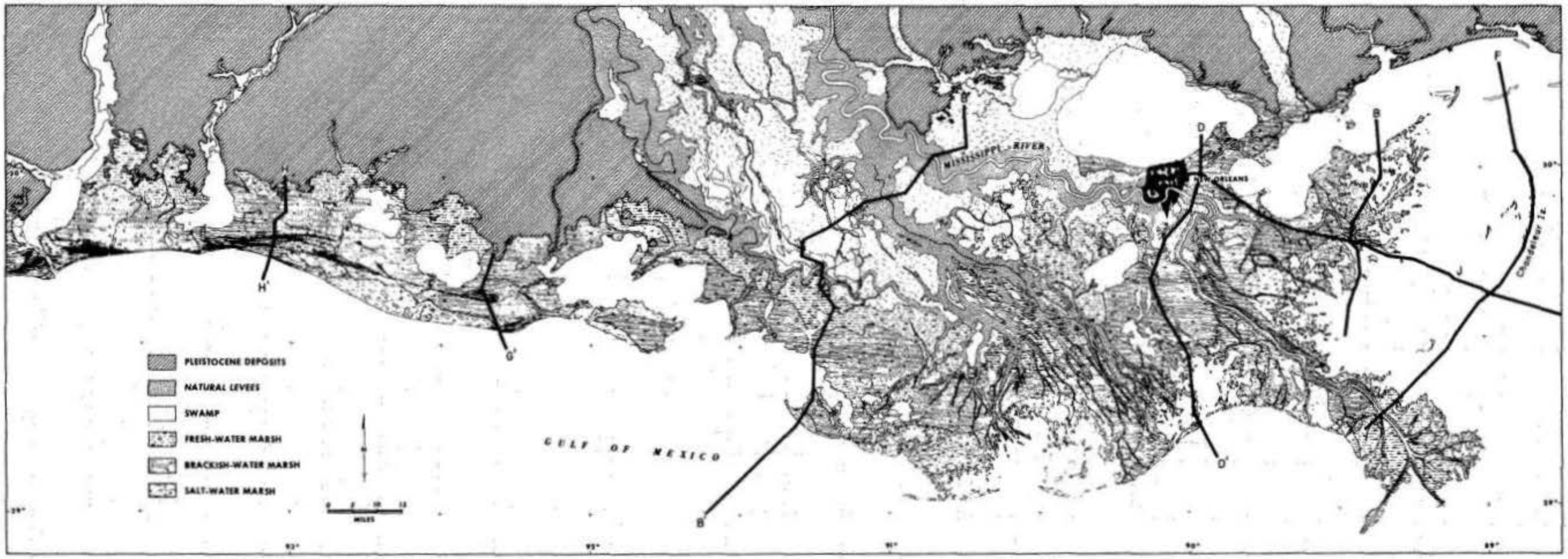
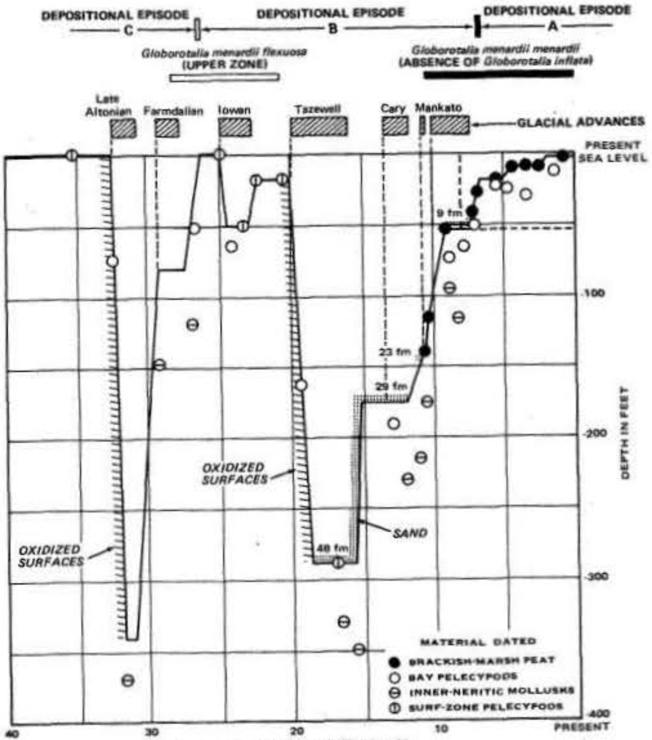


Figure 3. Swamp and marsh zonation of coastal Louisiana (Frazier and Osanik, 1969, in part modified from O'Neil, 1949) and lines of section in this paper.



This condition leads to the normal vertical sequence of progradational facies consisting of prodelta silty clays overlain by intercalated delta-front silty sands and clayey silts. The depth of water into which the stream is emptying controls the thickness and instability of the fine-grained prodelta facies.

During progradation the unconfined stream mouth bifurcates, and in this manner the distributary network is initiated as pointed out by Welder (1959). One course is favored over the other, and the distributary which receives the lesser flow is abandoned perhaps to become a prime avenue for later stream diversion because of a steeper gradient course, forming a new distributary network.

Enlargement by Further Progradation (Block B)

Once the progradational platform is deposited, the delta plain is aggraded by floodwater de-

Figure 4. Sea level during last 40,000 years for the Gulf of Mexico (from Frazier, 1974). Area within dashed line upper righthand corner discussed in this paper.

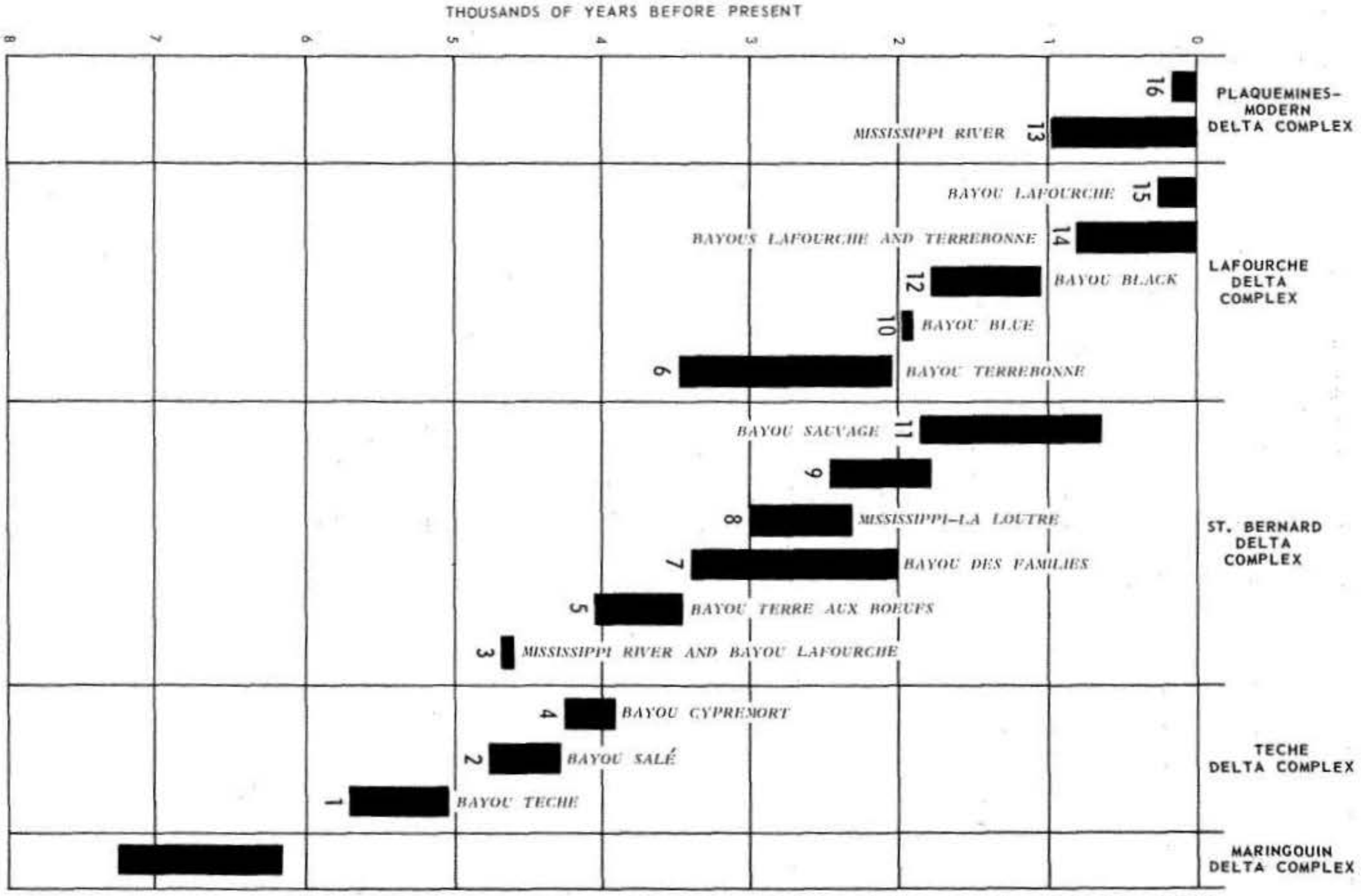


Figure 5. Chronology of delta lobes based on carbon-14 age of delta-plain peats (from Frazier, 1967).

position. Adjacent to the stream, natural levees are formed. As the levees are aggraded, they confine increasingly higher water stages until only the highest of seasonal floodwaters overflow the banks of the stream. Once stability of the delta plain is reached, vegetation flourishes, and carbonaceous deposits accumulate. Adjacent to the natural levees, however, the peats are often clayey and are commonly split by wedges of silty clay indicating a "choking out" of the vegetation.

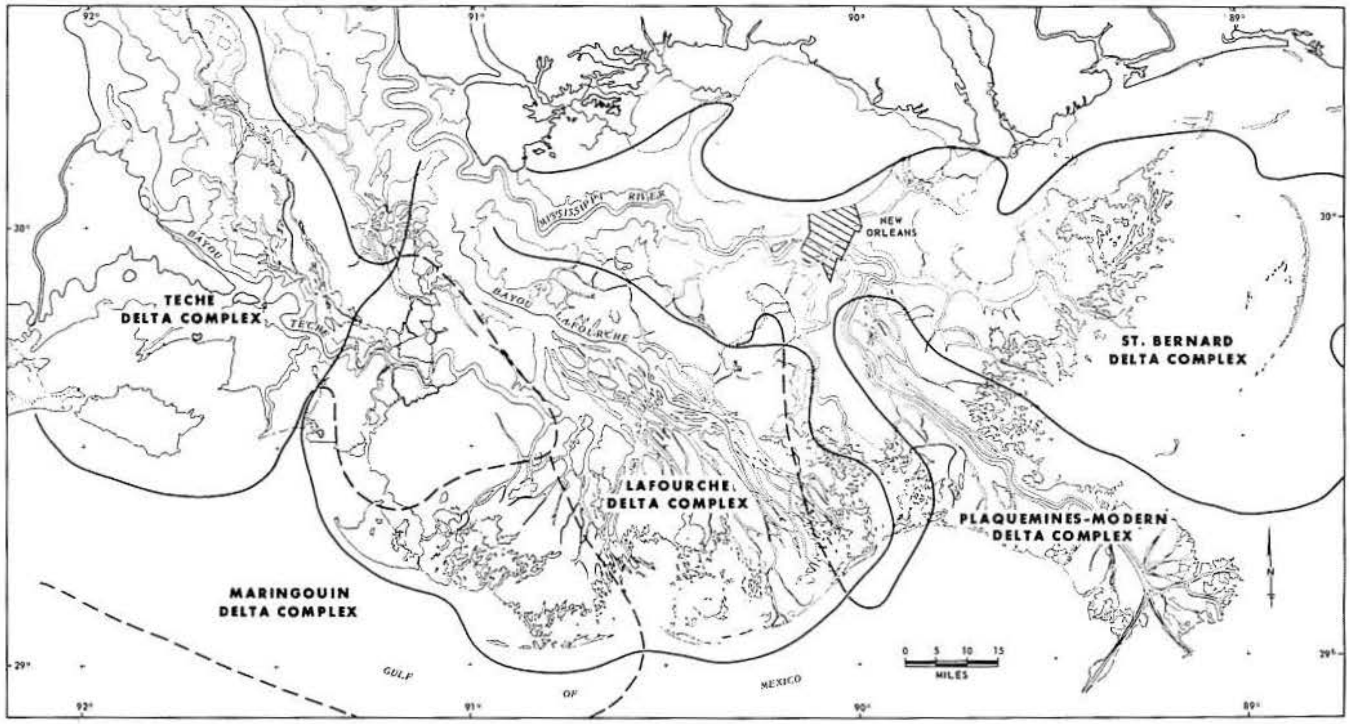
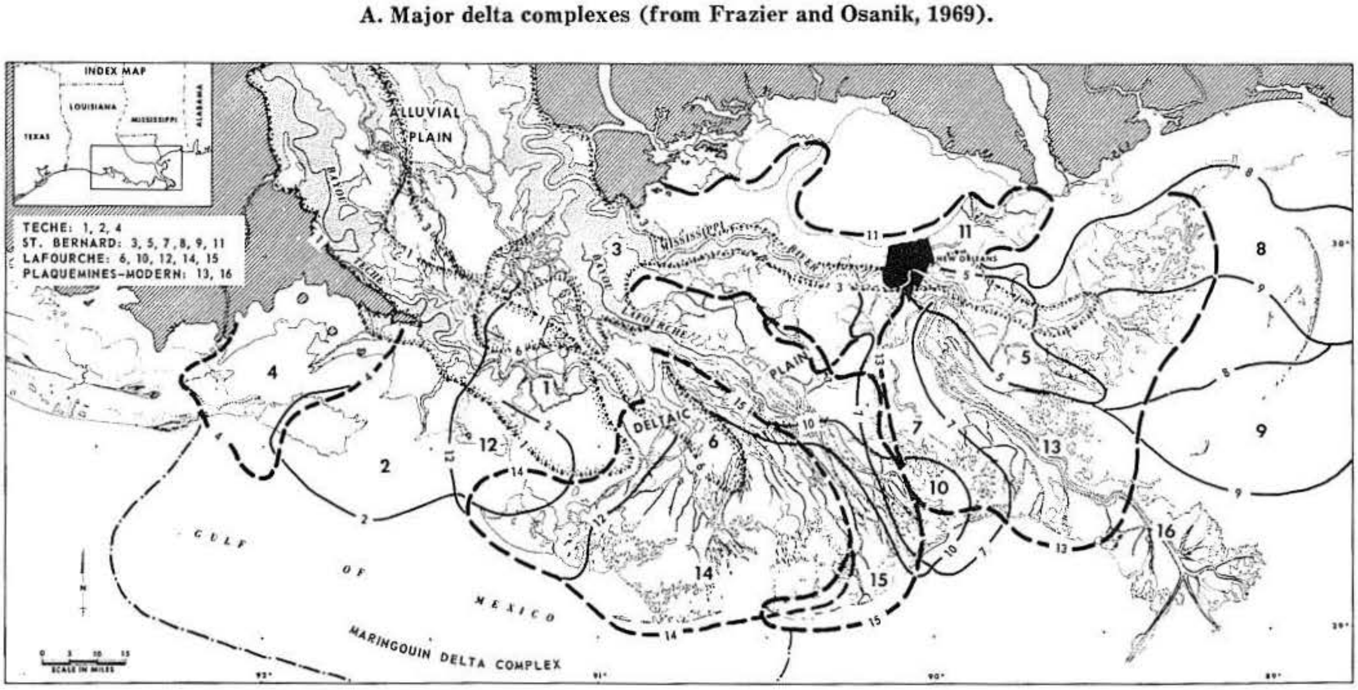


Figure 6. Delta complexes of the Mississippi River deltaic plain.

A. Major delta complexes (from Frazier and Osanik, 1969).



B. Delta lobes (from Frazier, 1967).

Distributary Abandonment and Transgression (Block C)

Overextension of the distributary network leads to diversion into a steeper gradient, underdeveloped, upstream distributary which has been reopened and developed as a favored course. The older, moribund distributary network, no longer capable of prograding or aggrading the delta plain in the unstable distal portion of the delta lobe, is transgressed. The sand is transported laterally and accumulates to form delta-margin islands. Carbonaceous deposits are eroded from the floodplain and distributed along the landward bar shore as finely comminuted organic debris.

Repetition of Cycle (Block D)

Commonly, the principal distributary of the abandoned network is reoccupied, and the vertical sequence of deltaic facies is repeated. Progradational facies in the distal portion of the newly forming delta lobe overlie transgressive bay deposits which have onlapped the older subsided delta plain. Inland, a younger aggradational peat-bearing sequence overlies the older peat deposits.

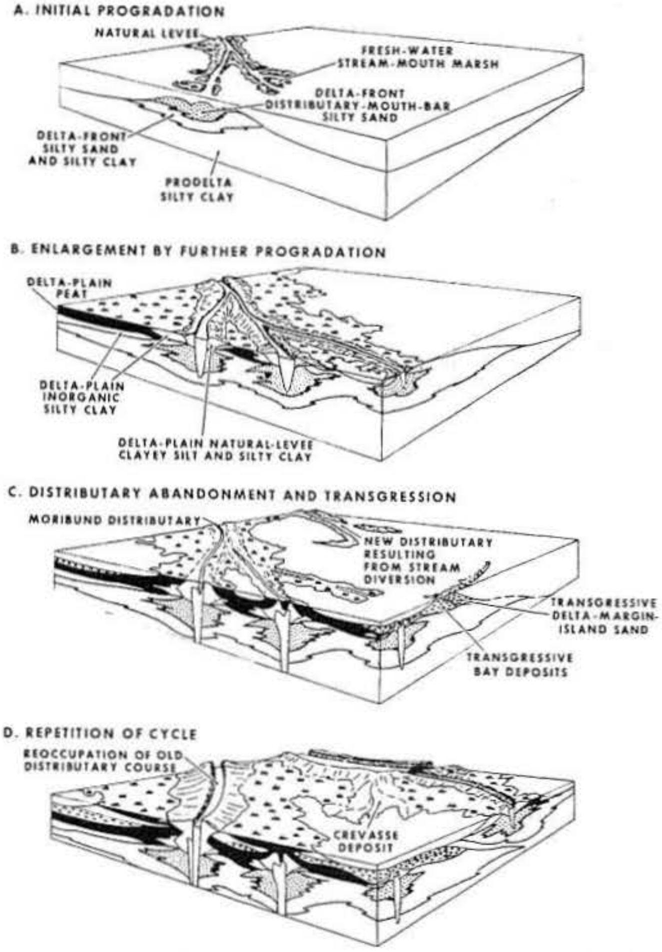


Figure 7. Development of delta sequences (from Frazier, 1967; Frazier and Osanik, 1969).

COASTAL INLAND FACIES SEQUENCES

The facies framework beneath a typical delta complex consists of repetitive coastal facies sequences (fig. 7, and fig. 8, block A) and the single sequence of the trunk stream in the stable inland area (fig. 8, block B). The prodelta and delta-front facies associated with the major stream course are the oldest deposits in the delta complex and represent progradation of the initial delta lobe from the major river course. The delta plain inorganic facies and overlying thick inland swamp peat accumulated while the many discrete delta lobes were prograded in the unstable coastal portion during development of the complex. The blocks may be compared to the depositional event (fig. 9) and depositional episode (fig. 10) which are time-distance diagrams. The depositional event represents a single delta sequence associated with coastal block A (fig. 8) and shows the progradational, aggradational, and transgressive phases and the hiatus and period of organic accumulation between the aggradational and transgressive phases. The depositional episode represents block B (fig. 8) which has a much longer hiatus inland for accumulation of organic material during development of the entire delta complex. Core photographs of progradational and aggradational facies encountered in a boring through sediments of a typical depositional event are illustrated by Frazier (1967, fig. 4). Fisk (1960) reports peats to 16 ft thick in the vicinity of New Orleans. The extent and facies relationships of these peats are shown in detail by Fisk and by Frazier (1967) and Frazier and Osanik (1969).

PEAT-BEARING FACIES SEQUENCES

Regional cross sections (fig. 3) are based on data from more than a thousand borings through the Mississippi River deposits and exhibit the subsurface coastal portions of the sediment mass.

DELTAIC INLAND AND COASTAL FACIES SEQUENCES

Demonstrated on the upper cross section B—B′ (fig. 11) are the differences between the inland facies sequences of the Teche, St. Bernard, and

Laforche delta complexes and the coastal facies sequences of the Teche and Lafourche delta lobes farther to the south. All the sequences are represented in this figure. The progradational, aggradational, and transgressive units are indicated as are the approximate limits of inland aggradational deposits which correlate with the discrete coastal delta lobes. The delta complexes are bounded by bolder lines. On the lower section, the facies relationships are shown.

The Holocene Maringouin delta complex is represented at the base of this section south of mile 66. A thin clayey peat (mile 69 to 79) is pre-

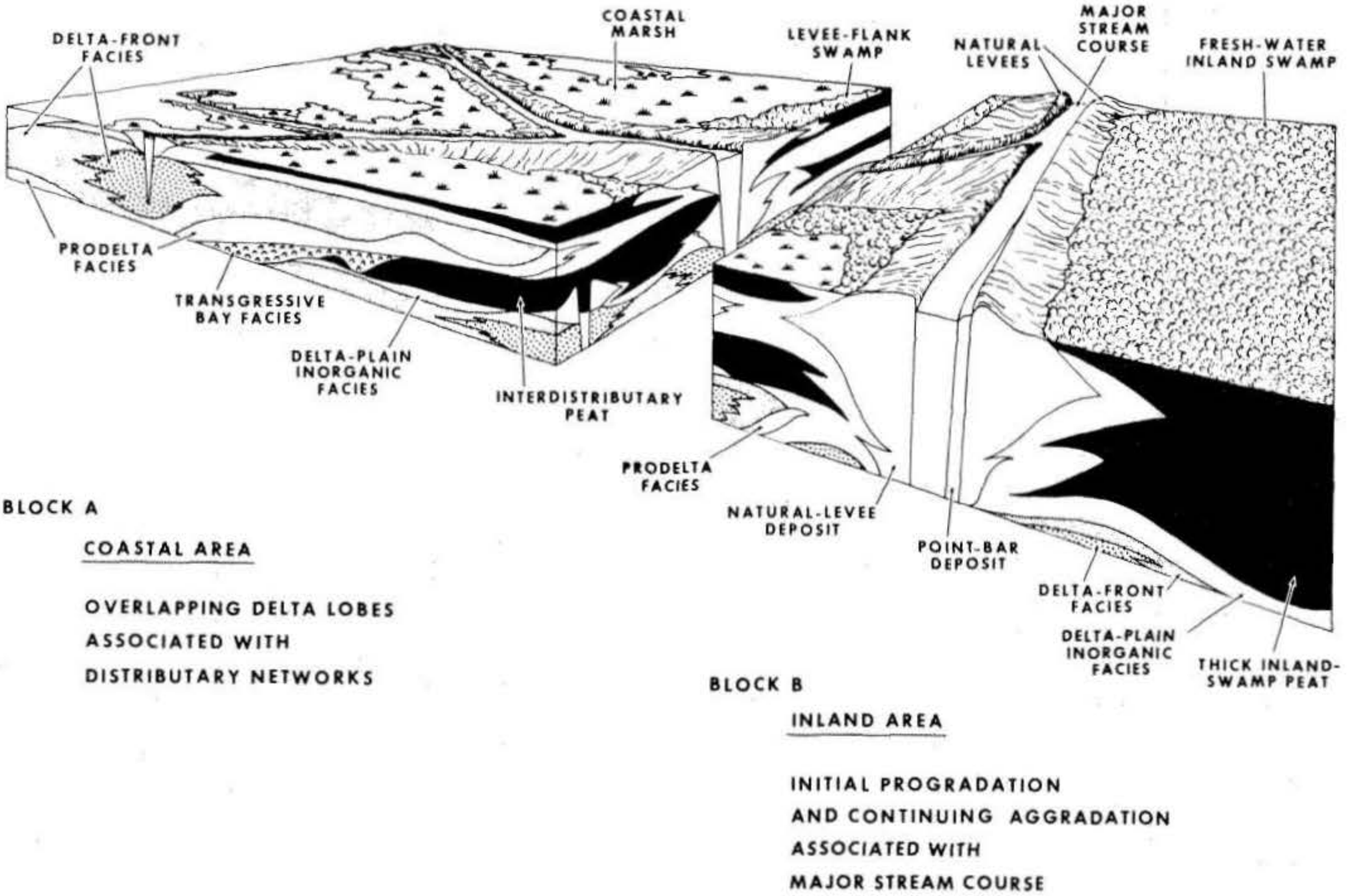
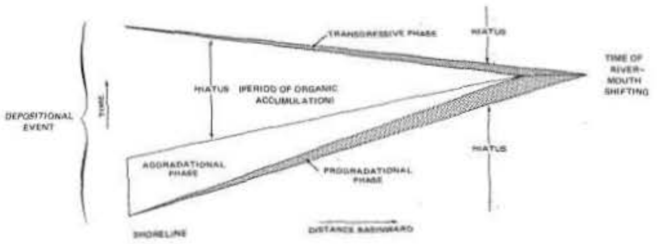


Figure 8. Facies relationships between coastal repetitive sequences (A) and the inland sequence of a typical delta complex (B) (from Frazier, 1967; Frazier and Osanik, 1969).



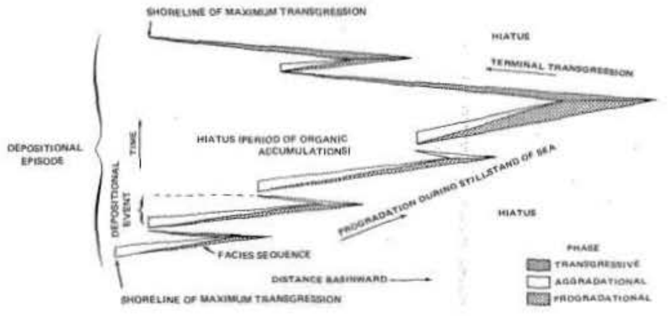


Figure 9. Depositional event; from Frazier, 1974.

Figure 10. Depositional episode; from Frazier, 1974.

sumed to be the younger Maringouin peat dated at 6,150 years before present at a location northwest of the section by Coleman and Smith (1964). In addition, radiocarbon assays by Stevens and others (1958) of total organic matter contained in an 8 ft length of Maringouin prodelta facies 8 miles gulfward from the southern end of this section yielded an average age of 7,880 years before present. These Maringouin deposits were apparently prograded during a Holocene stillstand. When sea level resumed its postglacial rise, the deposits were transgressed, and an estuary was formed.

On the initial progradation of the Teche delta complex (miles 40 to 60) an extensive swamp peat containing pollen of bald cypress (*Taxodium distichum*) accumulated and has been dated at 5,700 to 5,025 years before present. This peat was onlapped by brackish water bay deposits (containing shells of mature *Rangia cuneata*) as it subsided, while upstream diversions of Mississippi River flow from the Teche course into the eastern portion of the estuary occurred approximately 5,600 years before present. This was coincident with the accumulation of the first Teche peat 5,700 to 5,025 years before present. The Mississippi River and Bayou Laforche were responsible for the progradational sequence (mile 6 to 45). The aggradational deposits consist primarily of inorganic floodplain deposits and indicate a period of almost constant flooding. As a result, only patchy lenses of peat accumulated on the delta plain. Peats have been penetrated by borings to the east and west of the section and have been dated at 4,600 to 4,650 years before present at locations 4 and 7 miles to the northwest. A representation of these peat lenses is shown at mile 35. The main distributary of the second Teche delta (lobe 2) was Bayou Salé, 20 miles west of this section. The progradational deposits (miles 62 to 78) are near the eastern margin of the delta lobe. Aggradational facies, however, were penetrated as far south as mile 89. During the interval of peat accumulation (4,750 to 4,275 years before present), Bayou Laforche was almost entirely abandoned in favor of the Mississippi River course which continued progradation of the third delta lobe. The second Teche peats which accumulated in an inland cypress-gum swamp (miles 47 to 50) and in a brackish-water marsh on the peripheral portion of the delta lobe (miles 62 to 85), have been dated at 4,750 to 4,275 years before present. The coincidence in time of peat formation on the second Teche lobe

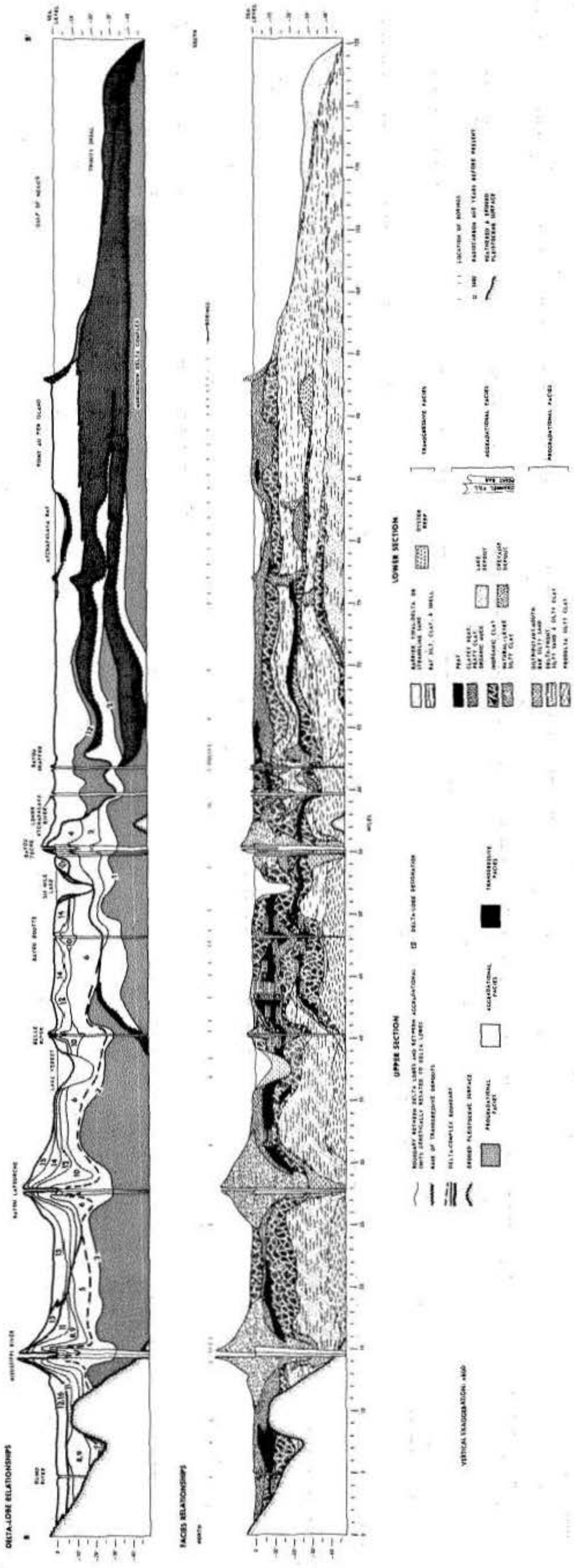


Figure 11. Cross section B-B', deltaic inland and coastal facies (from Frazier, 1967).

and slightly younger initial St. Bernard peats (4,650 to 4,600 years before present) on the third delta lobe, which filled the eastern portion of the estuary past New Orleans, indicates that the time of their progradations were also penecontemporaneous. Also during this interval, occupation of Bayou Cypremort affected the progradation of the third and last Teche delta (lobe 4).

After abandonment of Bayou Crepremort, full flow of the Mississippi River occupied the eastern course as far south as the bifurcation into Bayou Laforche. The Mississippi River was then shared intermittently by Bayou Laforche from that time (approximately 4,200 years before present) until it was artificially dammed at its upstream end in 1904. Aggradational deposits represent the remaining coastal lobes of the St. Bernard delta complex (miles 2 to 25) and by lobes of the Lafourche complex (miles 28 to 52). Sediments of the third discrete coastal delta lobe of the Lafourche complex (lobe 12) between miles 53 and 95, form the only complete sequence of deltaic facies in this area deposited in the past 4,000 years. Development of the third Laforche delta (lobe 12) occurred when Bayou Terrebonne was reoccupied. Bayou Terrebonne was also responsible for the progradation of the initial Laforche lobe (lobe 6).

Once the natural levees along Bayou Laforche and the Mississippi River limited the flooding, an extensive inland swamp environment was established where woody peat deposits accumulated. These swamp peats, which contained predominantly bald cypress and red gum (*Liquidambar styraciflua*) pollen and fresh-water diatoms, have been dated as old as 3,475 years before present (mile 43). Accumulation of this peat has continued throughout the development of the St. Bernard and Lafourche delta complexes and is continuing to form at the present time. The thickest peat is in the vicinity of mile 43 and represents a rate of accumulation of approximately ¼ ft per century. Laterally from this "thick" the accumulation of peat was halted approximately 1,800 years ago by the choking of vegetation by "splits" due to floodwater deposition adjacent to the secondary drainage streams and "cut outs" by Belle River (mile 40) and Bayou Boutté (mile 48). The peat lenses and other carbonaceous deposits between miles 58 and 93 accumulated in a broad peripheral marshland supporting brackish water grasses and sedges very similar to those presently found in this area. The youngest deposits are those contributed by the Atchafalaya River presently prograding a delta lobe into Six Mile Lake which supports a cypress-gum inland swamp.

COASTAL FACIES SEQUENCE

Section D—D′ (fig. 12) extends from Lake Pontchartrain southward across the delta plain to the Gulf of Mexico. Represented on this section are coastal deltaic facies sequences of the Lafourche, St. Bernard, and Plaquemines-Modern complexes. Also shown, between miles 0 and 5, is the transgressive sand buildup of an ancient barrier island, Pine Island, described by Saucier (1963). This barrier island formed during the late phase of the Holocene sea-level rise.

The oldest coastal sequence on this section is that of the initial St. Bernard progradation (lobe 3), represented between miles 6 and 14. These prodelta and delta-front facies were deposited approximately 4,600 years ago and extend 30 miles farther eastward.

The second St. Bernard delta lobe (lobe 5) which was also prograded to the east by both the Mississippi River and Unnamed Bayou (miles 14 and 18) offlapped the drowned distal portion of lobe 3 when the full flow of the Mississippi River was diverted into the eastern course and the Teche delta complex was abandoned. The peripheral marsh peats on this second St. Bernard Delta lobe have been dated as old as 4,050 years before present.

A broad delta lobe extending southward from mile 21 to mile 71 formed approximately 3,500 to 2,500 years ago. Bayou des Families, which diverted a large portion of Mississippi River discharge to the south, was the main distributary of this delta (lobe 7). The peripheral clayey peat began accumulating in a slightly brackish water marsh environment more than 3,000 years ago in the inland portion of this delta plain and 2,875 years ago at mile 48.

Aggradational deposits only of the fourth and fifth St. Bernard deltas (lobes 8 and 9) were penetrated by borings between miles 8 and 30. These delta lobes were prograded consecutively 80 miles eastward.

After subsidence of delta lobe 7, the second Lafourche delta sequence (lobe 10, miles 62 to 68) was prograded over its drowned distal portion. A radiocarbon age of 1,975 years before present was determined for the brackish marsh peat which developed on this coastal delta plain. As lobe 10 sub-

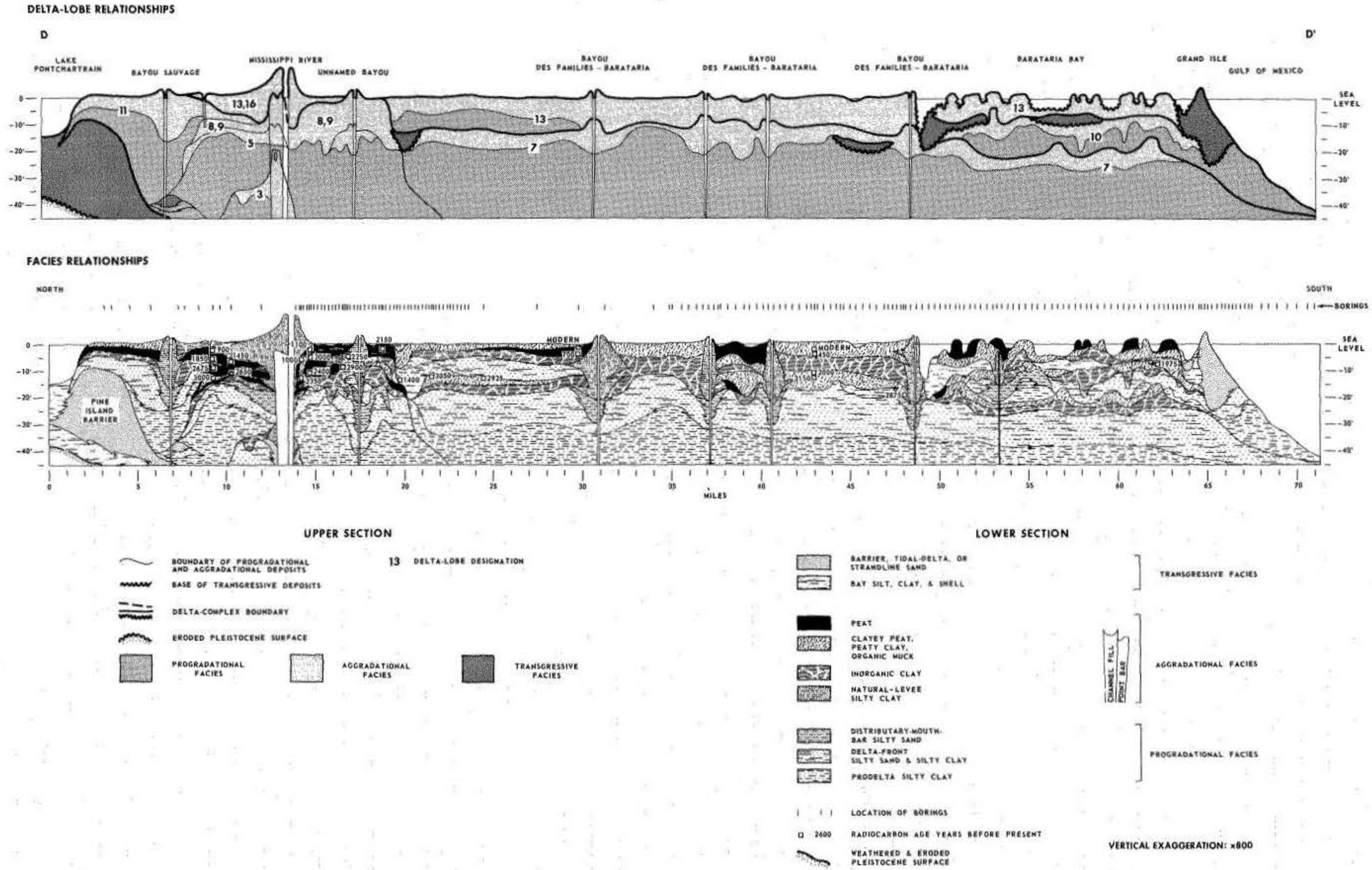


Figure 12. Cross section D-D', coastal facies, (from Frazier, 1967).

sided, transgressive bay sediments accumulated on top of the peat and carbonaceous deposits. Grand Isle, a delta margin island at mile 75, formed during the transgression.

The Bayou Sauvage delta (lobe 11) was the last lobe of the St. Bernard complex and was prograded into a depression between the older St. Bernard lobe to the south (lobe 7) and Pine Island to the north. The Bayou Sauvage delta developed in response to the Mississippi River shifting a portion of its discharge into a steeper gradient course while the distributary networks of an older St. Bernard delta (lobe 9) to the east and the Lafourche delta (lobe 10, miles 62 to 68) to the southeast were undergoing abandonment. The oldest peats on this minor delta plain developed approximately 2,000 years ago.

Approximately 1,400 years before present, Bayou Barataria, a distributary of the Mississippi River, *reoccupied the abandoned* des Familles course. South of mile 20, Bayou Barataria flowed within the older Bayou des Familles natural levees. The sand in fluvial transport was carried downstream into Barataria Bay east of the line of section. Deposition of clay and silt from floodwaters, however, built up the old des Families delta plain (lobe 7), and, in addition, the silt and clay flushed into Barataria Bay aggraded the shallow portions of the bay floor until vegetation could again take hold. The peats on the peripheral marsh of the Barataria delta plain began forming approximately 700 years ago and are still accumulating. Subsidence again is allowing transgression, and the carbonaceous deposits of the saline marsh are being eroded as Barataria Bay is enlarging.

INTERDELTAIC SEQUENCE

The facies sequence cross section G—G′ (fig. 13) is through interdeltaic coastal deposits located to the west of the Mississippi River's deltaic progradations. A similar section to the west (H—H′, fig. 14) was published in a study by Byrne and others (1959) (see also Gould and McFarlan, 1959). The sediments that formed these interdeltaic deposits were derived from the deltaic deposits to the east and were transported westward

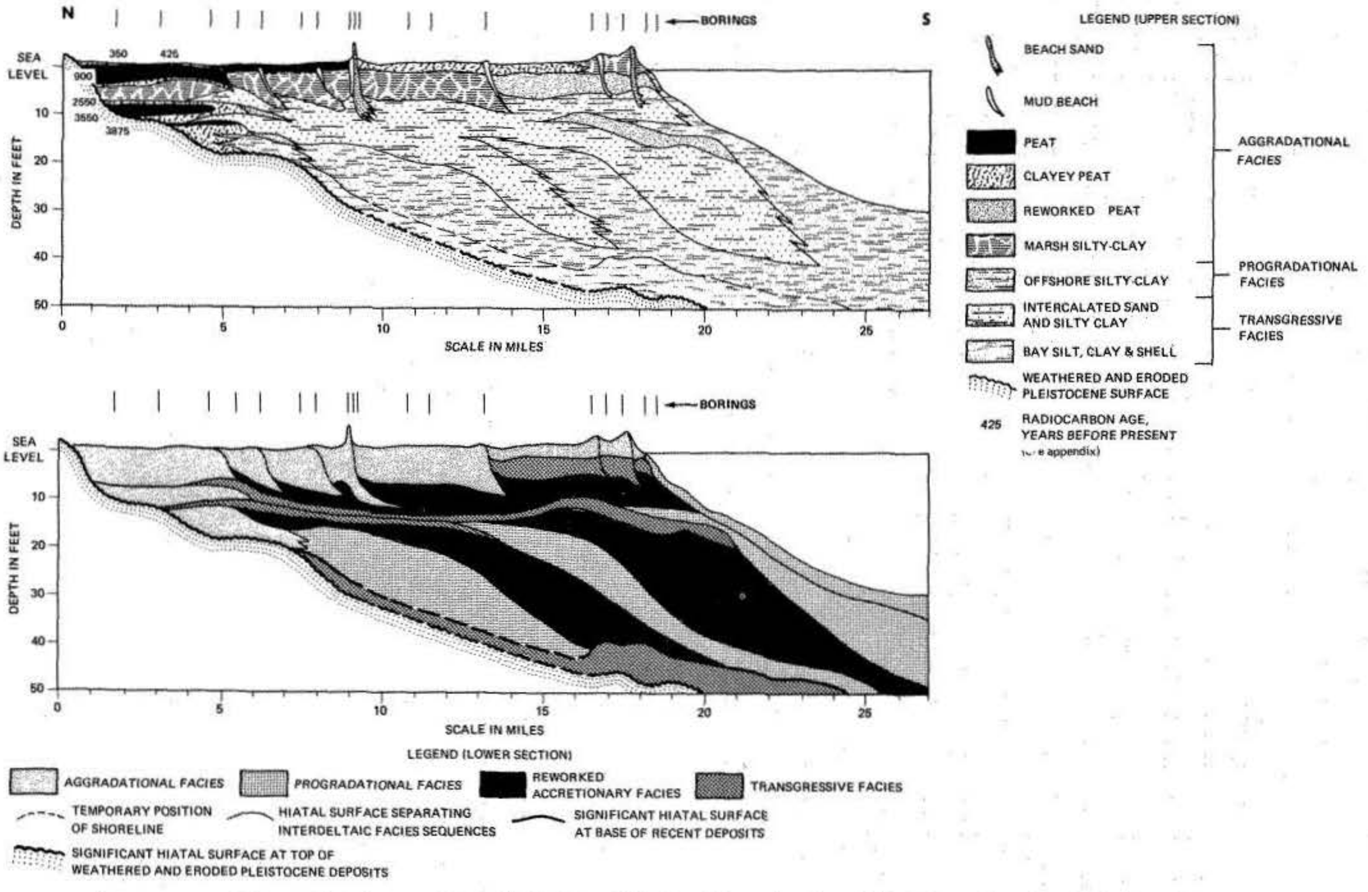


Figure 13. Cross section G-G′, interdeltaic offlap, chenier plain (from Frazier, 1974).

along the coast to this location. The silty clays of the interdeltaic offshore and marsh facies are the suspended sediments deposited penecontemporaneously with the prodelta silty clays; they were transported westward by nearshore surface currents during the deltaic progradations. In contrast, the interdeltaic sandy facies were derived from the delta front sands during destructional transgressive phases; they were transported westward in the longshore drift. The repetitive interdeltaic facies sequences, therefore, reflect the repetitive progradations of the delta lobes to the east from which the sediments were derived. The underlying transgressive bay deposits in this region overlie the hiatal surface represented by the Pleistocene soil zone. There is also a hiatal surface atop the transgressive bay deposits.

The interdeltaic coastal deposits represent an area of minor sediment influx compared with that of the deltaic region; consequently, progradation of the interdeltaic shoreline is slower than that of the delta. The contrasts in shoreline configuration are evident in figure 1.

At approximately 20 ft below sea level, clayey peats and peats began to accumulate on the oxidized Pleistocene surface. There are three thin repetitive peat layers. The lowest is not dated but is presumed to be approximately 4,300 to 3,940 years before present and related to lobe 4 (last Teche delta). The middle layer ranges from 3,875 to 2,550 years before present and is related to lobe 6 (initial Lafourche delta lobe). The uppermost surficial brackish-water layer began to form 900 years ago and is presently forming to mile 9 where it changes to a thin, brackish-water clayey peat. From mile 14 to the coast it has been choked out by storm deposits. Finely comminuted organic debris is present along the tops of lobes 4 and 6, derived sediments attesting to coastal destruction.

MANGROVE SWAMPS: CHANDELEUR ISLANDS

Kolb (1958) notes the transgressive nature of the Chandeleur Islands, which are pivoting at the north end (fig. 15). Mangrove swamps occur

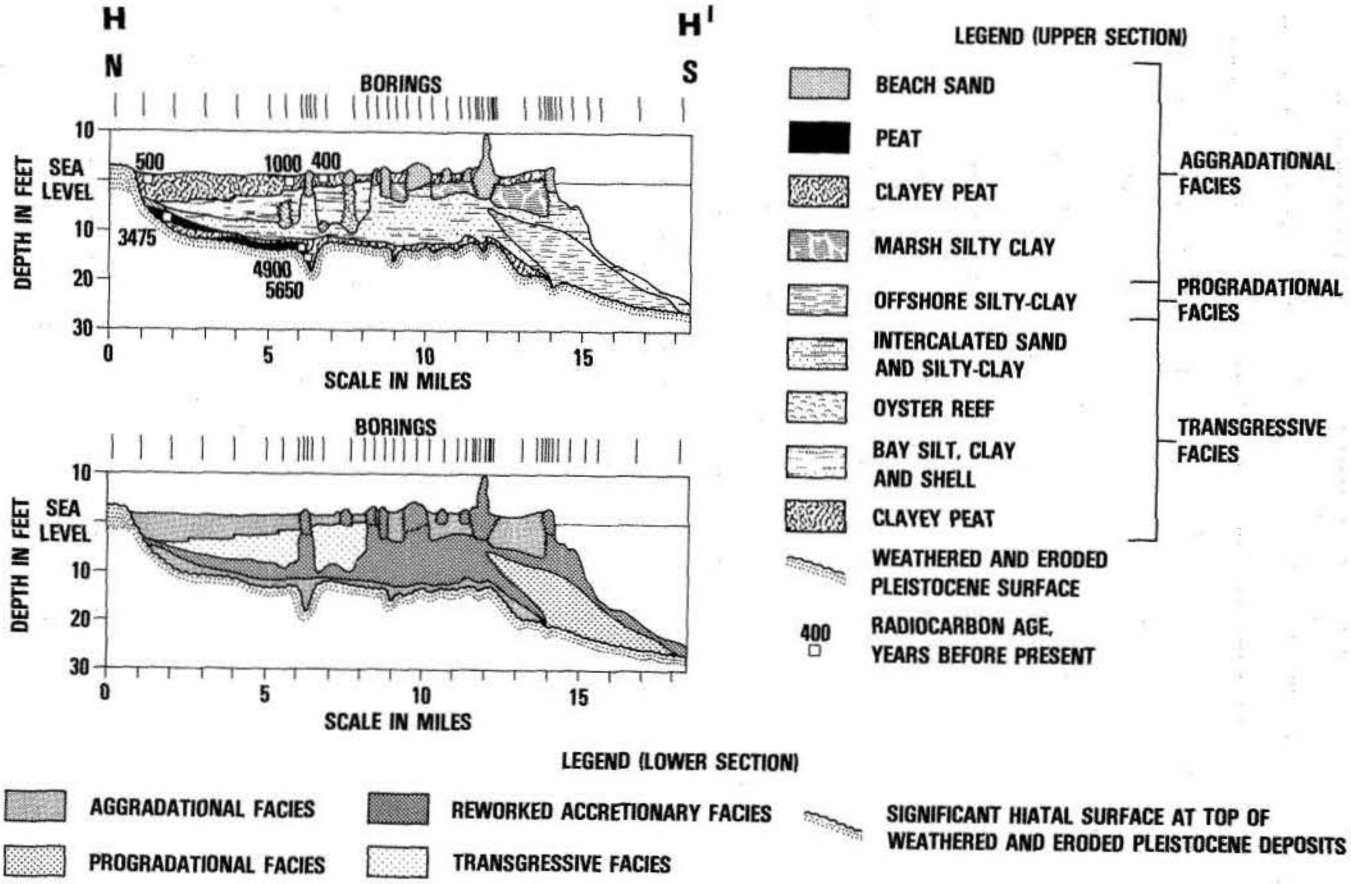


Figure 14. Cross section H-H', interdeltaic offlap, chenier plain; modified from Byrne and others (1959).

on the washover backside of the island and are the sites for minor peat formation. Cores taken along the Chandeleur Islands show only very thin and impure (clayey) peats (fig. 16).

OFFLAP SEQUENCE

Figure 17 represents a dip section across the repetitive peripheral unstable coastal sequences described previously. Note the decrease in quality of the peat as the prodelta deposits thicken. Good peats inland near New Orleans become poorer and clayey coastward. Just coastward of the Pearl River Trench the surface blanket peats of Coleman and Smith (1964), which are accumulating at a greater rate than 1.5 ft per century, are also being destroyed by tidal channels (fig. 18) as Fisk (1960) suggested due to subsidence.

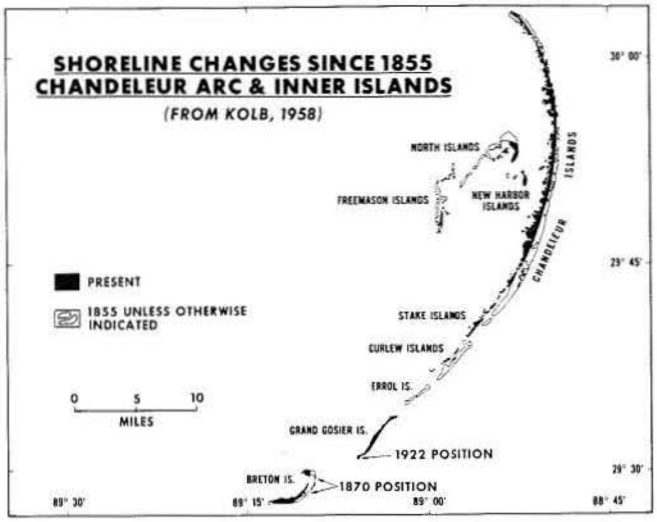


Figure 15. Shoreline changes since 1855, Chandeleur Islands and inner islands (from Kolb, 1958).

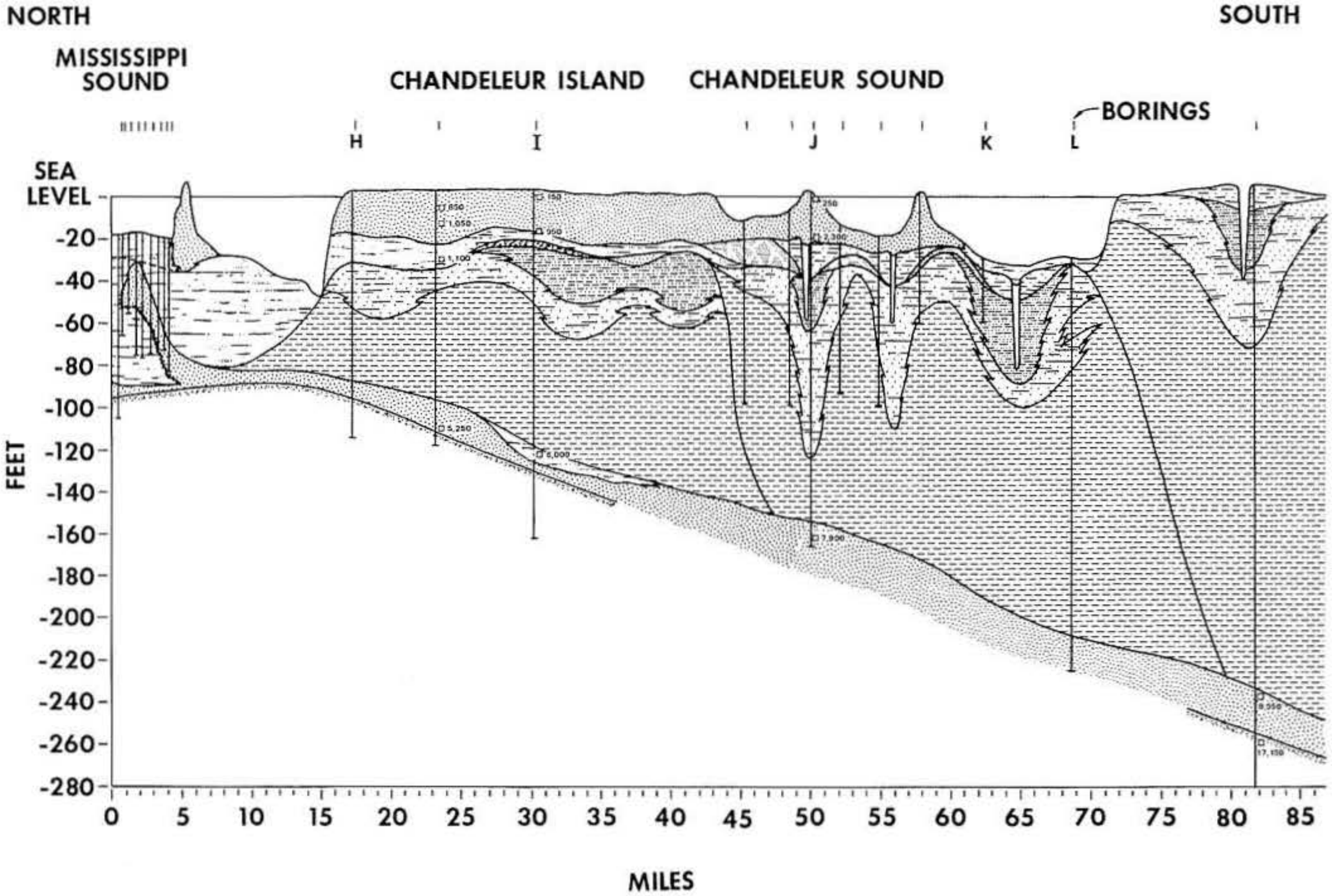


Figure 16. Cross section F, longitudinal section through Chandeleur Islands.

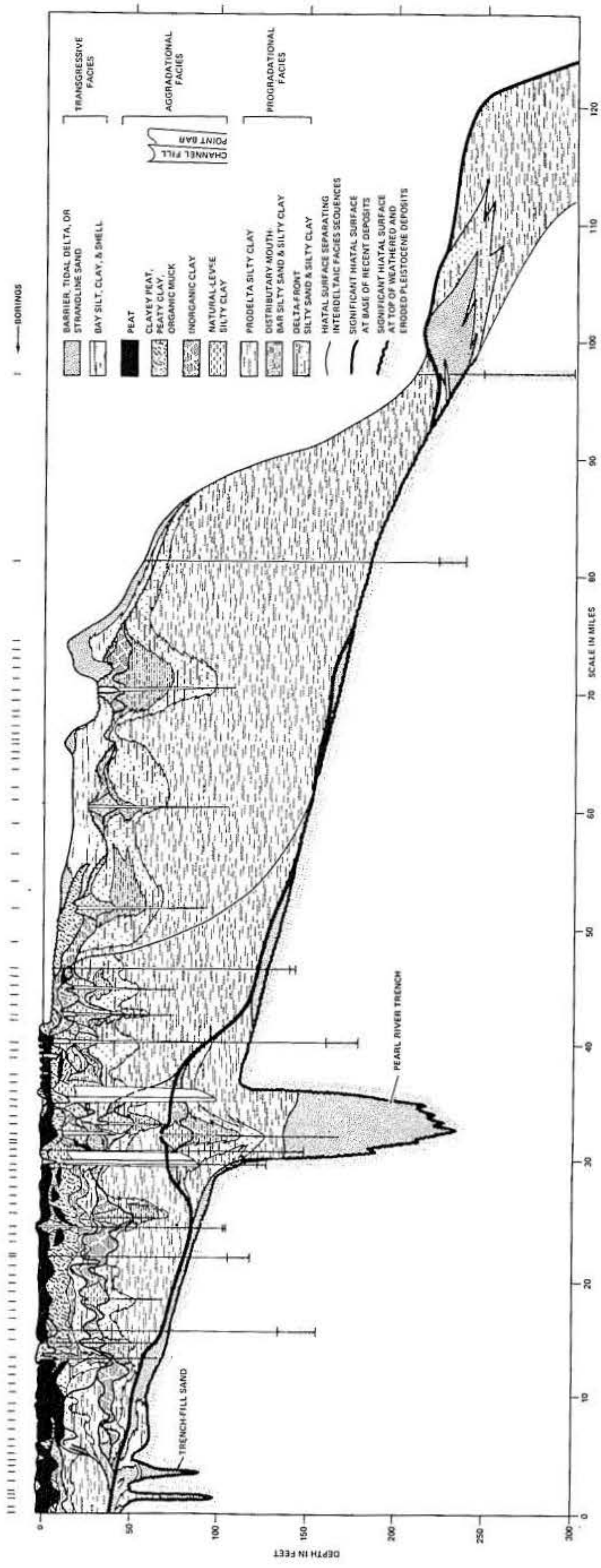


Figure 17. (left) Cross section J, deltaic offlap, St. Bernard delta complex (from Frazier, 1974).

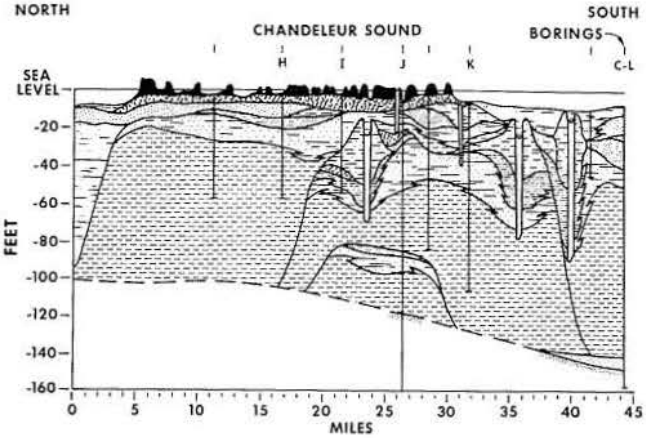


Figure 18. Cross section B across foundering distal St. Bernard delta.

CONCLUSIONS

Although many modern environments of peat accumulation have been described, those of the stable inland swamps which possess the best quality and thickest peats are the most prospective environments for ancient lignites and coals. Best quality refers to least clay-silt-sand admixture.

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PALYNOLOGY OF GULF COAST LIGNITES: THE STRATIGRAPHIC FRAMEWORK AND DEPOSITIONAL ENVIRONMENTS

W. C. Elsik[1]

ABSTRACT

Economic deposits of lignite occur in Texas in the Calvert Bluff Formation, Wilcox Group (Paleocene - early Eocene); the Yegua Formation, uppermost Claiborne Group (late middle Eocene); and the Manning Formation, Jackson Group (late Eocene). Lignites occur in these and other formations of the Wilcox, Claiborne, and Jackson Groups throughout the Gulf Coast and reflect various depositional settings.

The general nonmarine nature of the lignite-enclosing sediments requires correlation with nonmarine fossils. Pollen and spores are well suited for this purpose. A combination of species occurrence and relative abundance techniques allows for the differentiation of Wilcox from other sediments on the ubiquitous presence of *Thomsonipollis*. The uppermost Calvert Bluff Formation and Carrizo Sand and equivalents carry an abundance of *Platycarya* pollen. The Calvert Bluff Formation and its equivalents yield the distinctive *Sernapollenites*. Upper Claiborne sediments are characterized by an abundance of *Polypodium*, *Engelhardia*, *Amanoa*, and *Nudopollis terminalis* but can be differentiated on the presence of *Yeguapollis*, *Nuxpollenites*, and *Enopadios*. Jackson sediments are characterized by an extreme abundance of *Engelhardia* and common *Anemia* and sapotaceous pollen. Post-Eocene sediments yield increasing amounts of *Quercus* and *Carya* pollen and correspondingly less *Engelhardia*.

Allowing for changing conditions with time, the lower Tertiary lignites can be characterized as follows: Calvert Bluff lignites were sourced by a variety of trees mainly of the Betulaceae-Myricaceae, *Nyssa* type and/or the extinct plant represented by *Thomsonipollis*. Yegua and Manning lignites yield an abundance of pollen of the trees of *Engelhardia* and *Nyssa*. Yegua lignites may also carry sparse to common pollen of *Amanoa*. Manning lignites may yield an abundance of the extinct *Pollenites laesius*. All lignites examined to date lack the characteristic abundance of *Taxodium* seen in Mississippi delta swamp peats. Accessory palynomorphs of shrubs and herbaceous plants present in all the lignites include a variety of fern spores: *Anemia* and unidentified psilate, monolete, and trilete spores. In addition, the Calvert Bluff lignite may yield common *Sphagnum*, and Yegua or Manning lignites may yield common *Polypodium*.

The pollen of grasses is absent from most early Tertiary marsh sediments. Instead, in the Calvert Bluff marsh a predominance of *Calamuspollenites-Arecipites* and a sparse amount of *Liliacidites* (Liliaceae-Amaryllidaceae) and *Carex* occur. Yegua and Manning marsh sediments may yield either common *Calamuspollenites-Arecipites* or *Liliacidites*. Fern spores and pollen of the dominant tree vegetation may also occur in the marsh lignites. Manning marsh lignites yield an abundance of finely divided amorphous organic material as contrasted to structured (unaltered) woody tissue in the Yegua and Wilcox swamp lignites.

INTRODUCTION

Gulf Coast lower Tertiary lignites occur in continental to marginally marine strata from Texas across the Mississippi embayment to the western edge of Georgia. Principal lignites (fig. 1) occur in the upper Paleocene - lower Eocene Calvert Bluff Formation (Wilcox Group), in the upper middle Eocene Yegua Formation (Claiborne Group), and in the upper Eocene Manning Formation (Jackson Group) and their Gulf Coast equivalents (Fisher, 1963; Kaiser, 1974; and McNulty, Roland, Self, and Williamson, respectively, this volume). Thinner lignites and lignitic partings may be found throughout the lower Tertiary of the Gulf Coast in various facies, but the principal lignites are found in fluvial-deltaic sequences deposited during major regressions of the lower Tertiary shoreline (fig. 29 of Plummer, 1932).

The lower Tertiary strata generally thicken across the Mississippi embayment. This thickening is especially obvious in the Wilcox Group in the area of Louisiana and Mississippi where the

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AGE	GROUP	FORMATION
OLIGOCENE?		FRIO
		CATAHOULA
LATE EOCENE	JACKSON	WHITSETT
		MANNING*
		WELLBORN
		CADDELL
MIDDLE EOCENE	CLAIBORNE	YEGUA*
		CROCKETT
		SPARTA
		WECHES
		QUEEN CITY
		REKLAW
EARLY EOCENE	WILCOX	CARRIZO
		SABINETOWN
		CALVERT BLUFF*
PALEOCENE		SIMSBORO
		HOOPER
	MIDWAY	WILLS POINT
		KINCAID
MAESTRICHTIAN	NAVARRO	KEMP CLAY
		CORSICANA MARL
		NACATOCH SAND
		NEYLANDVILLE MARL

Figure 1. Age of principal lignite-bearing formations in Texas. Asterisk denotes those occurring in Texas.

predominantly nonmarine Wilcox facies are present below the *Ostrea multilirata-Ostrea thirsae* zone (Murray, 1953). A plot of the updip limits of marine Claiborne strata (fig. 2; Murray, 1953) indicates an extensive area in Arkansas, Kentucky, and Tennessee of nonmarine middle Eocene Claiborne strata of the "Wilcox facies."

The principal lignite-forming environments have been outlined and elaborated by numerous studies. Fisher and McGowen (1967) and Fisher (1969) show the Texas Wilcox in a fluvial-deltaic system analogous to that of the modern Mississippi River delta. Fisher (1964) earlier characterized Eocene cyclic deposits, diagraming the similarities of Wilcox and Yegua deltaic sediments and Fisher and others (1970) described at least portions of the Manning as delta plain.

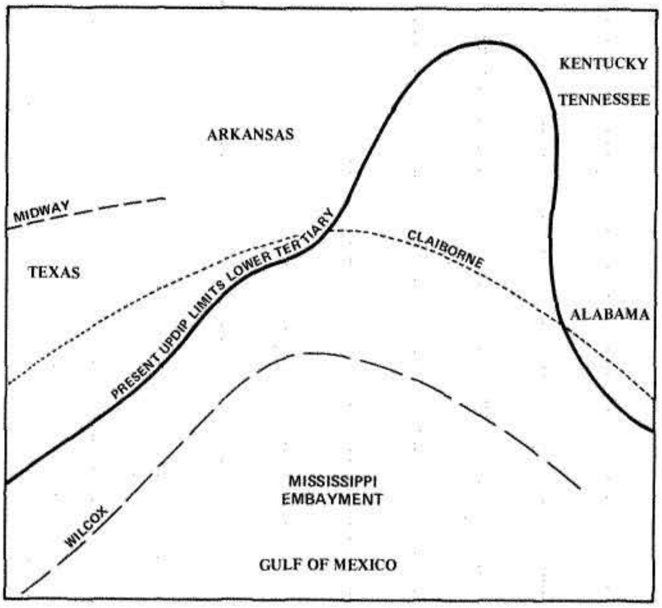


Figure 2. Average position of Lower Tertiary shorelines across the Mississippi Embayment (modified from Murray, 1953, and later sources; Elsik, 1974).

Fisher and McGowen (1967) mapped along the strike and into the subsurface several depositional systems for the Wilcox in Texas: in South Texas, the South Texas shelf system, an updip Cotulla barrier-bar system, and an even more updip Indio bay-lagoon system; in south-central Texas, the San Marcos strandplain-bar system; and in east-central and East Texas, the Mount Pleasant fluvial system, and downdip Rockdale delta system, with a portion of Pendleton bay-lagoon system along the Texas-Louisiana border. Galloway (1968) extended the depositional systems eastward: the Pendleton bay-lagoon system as well as the Mount Pleasant fluvial system and Rockdale delta system into western Louisiana; the Holly Springs delta system across the axis of the Mississippi embayment in Louisiana and Mississippi with an updip unnamed fluvial system in the northward trending Mississippi trough; and an unnamed restricted shelf system in Alabama.

Deltaic and interdeltaic environments recurred through the lower Tertiary in much of the Gulf Coast. A lower Oligocene Vicksburg delta was described for southeast Texas by Gregory (1966). Deltaic systems in the middle Oligocene Frio of Texas were described by Gernant and Kesling (1966) and Martin (1969). Additional deltaic settings were described for the Louisiana lower Miocene by Glowacz and Horne (1971) and for the Gulf Coast Miocene in general by Rainwater (1964).

Frazier and Osanik (1969) have demonstrated the inland swamp facies as being the most prospective area for the origin of thicker lignites in a deltaic system. What is the palynologic evidence from the lower Tertiary lignites?

The principal lower Tertiary lignites occur in a fluvial-deltaic setting lacking marine fossils. Therefore, age dating and correlation must be done with land-derived plant microfossils, pollen, and spores (palynomorphs). The palynomorph assemblages contained in the lignites also allow an interpretation of the origin of the lignite-forming peat environment. Objectives of this paper are therefore twofold: (1) a general review of Gulf Coast lower Tertiary palynologic stratigraphy and (2) a status report of lignite paleoenvironments based on palynologic content.

PALYNOSTRATIGRAPHY

Fairchild and Elsik (1969) summarized the status of Midway and Wilcox palynology in the Gulf Coast. Midway and Wilcox strata are characterized by a predominance of pollen of the Normapolle type and *Engelhardia* and related extinct Juglandaceae. *Engelhardia dilatus, Sernapollenites,* and *Thomsonipollis* are especially distinctive pollen. A summary chart (Fairchild and Elsik, 1969) was presented showing a comparison of Gulf Coastal and western European occurrences. A dramatic floral change between the Wilcox and Claiborne Group at the surface was noted, and it was apparent that palynology supported a Paleocene-lower Eocene boundary much higher in the Wilcox, perhaps within the Calvert Bluff Formation of Central Texas. This is higher in the section than the classic Paleocene-Eocene boundary marked by the *Ostrea multilirata-Ostrea thirsae* zone. Berggren (1965) had earlier suggested that in Alabama the Tuscahoma Formation is Paleocene, and the Hatchetigbee Formation is lower Eocene based on the lowest occurrence there of the lower Eocene planktonic foram, *Globorotalia rex.*

The occurrence (fig. 3) of the more useful Wilcox palynomorphs was summarized (Atlee and others, 1968; Elsik, 1974) with ascending tops for *Engelhardia dilatus, Choanopollenites, Sernapollenites,* and *Thomsonipollis.* The occurrences were plotted against Central Texas surface exposure terminology circa 1968. Currently the use of the Rockdale Formation has been dropped by the Texas Bureau of Economic Geology; Calvert Bluff, Simsboro, and Hooper Members have been raised to formation rank; and the Buter clay is the lower part of the Calvert Bluff Formation (fig. 4). *Sernapollenites* does not occur in the exposure of the Butler clay at the clay pits of the Elgin-Butler Brick Company near Butler, Texas. It appears that the earliest occurrence of *Sernapollenites* is a useful datum within the Calvert Bluff Formation in Texas.

The Wilcox in the subsurface thickens coastward. The thickening is especially obvious in East to south-central Texas in the Mount Pleasant fluvial-Rockdale deltaic facies across growth faults (Fisher and McGowen, 1967). The thickening is also reflected in the uppermost occurrences of the index palynomorphs named in the preceding paragraph. At the surface their occurrence tops are separated by tens of feet, in the subsurface by hundreds of feet.

Thomsonipollis marks the top of the Wilcox (includes Carrizo Sand) throughout the Gulf Coast. *Sernapollenites* is also known from equivalent strata in Mississippi (Stewart, 1971). The occurrence of *Choanopollenites* (fig. 3) may be controlled by environment; not regionally as noted by Nichols and Traverse (1971) but locally, for example, two out of four wells in Central Texas (DeWitt County).

The distinctive pollen of *Platycarya* are common to abundant in the uppermost Calvert Bluff and Carrizo Sand in Central Texas where these units measure in tens of feet at the outcrop. The subsurface zone of *Platycarya* approaches 5,000 ft in South Texas, and the pollens, although highly carbonized, are identifiable. This lower Eocene zone may be largely lacking updip at the surface due to a hiatus similar to that shown between the Wilcox and Claiborne Groups in Alabama (Self, this volume) and may explain the distinct floral change at the base of the Claiborne.

The Wilcox strata are also amenable to the palynomorphic relative-abundance technique (fig. 5). In particular, *Thomsonipollis* is seen to be common throughout most of the Wilcox with at least three correlatable abundance peaks marked by an arrow in figure 5. All relative abundances

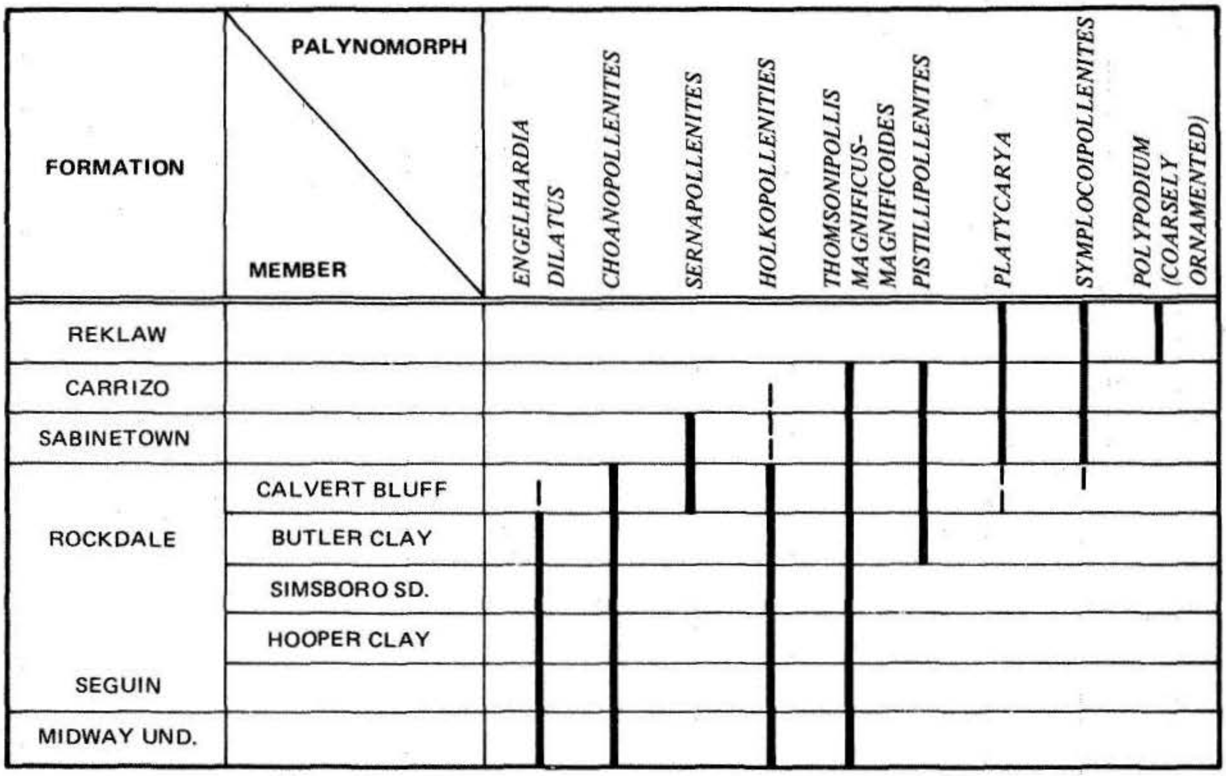


Figure 3. Significant palynomorphs of the Lower Tertiary in the Gulf Coast; Central Texas terminology (Elsik, 1974).

shown in figure 5 are computed to the total palynomorph population except the curve for *Thom./* Adjpol, which is the relative abundance of *Thomsonipollis* to the pollen sum.

Our knowledge of Claiborne and Jackson palynology is based mainly on the study of surface samples. Tschudy (1973) summarized a study of a few samples of the Wilcox, Claiborne, and Jackson from the Mississippi embayment, noting the dramatic floral change at the Wilcox-Claiborne boundary. Elsik and Dilcher (1974) summarized the Gulf Coast occurrence of characteristic palynomorphs, noting the occurrence of most of the forms generally through both the Claiborne and Jackson Groups.

The Claiborne is characterized by *Nuxpollenites, Amanoa,* large *Nyssapollenites, Bombacacidites claibornensis, Yeguapollis, Enopadios,* and other palynomorphs. These occurrences were first noted in 1972 with a later elaboration on relative abundance (fig. 6; Elsik, 1974). *Thomsonipollis* was noted to be common to abundant in the Paleocene and lower Eocene but very rare in the uppermost Maestrichtian and to occur only as rare reworked specimens in the middle Eocene.

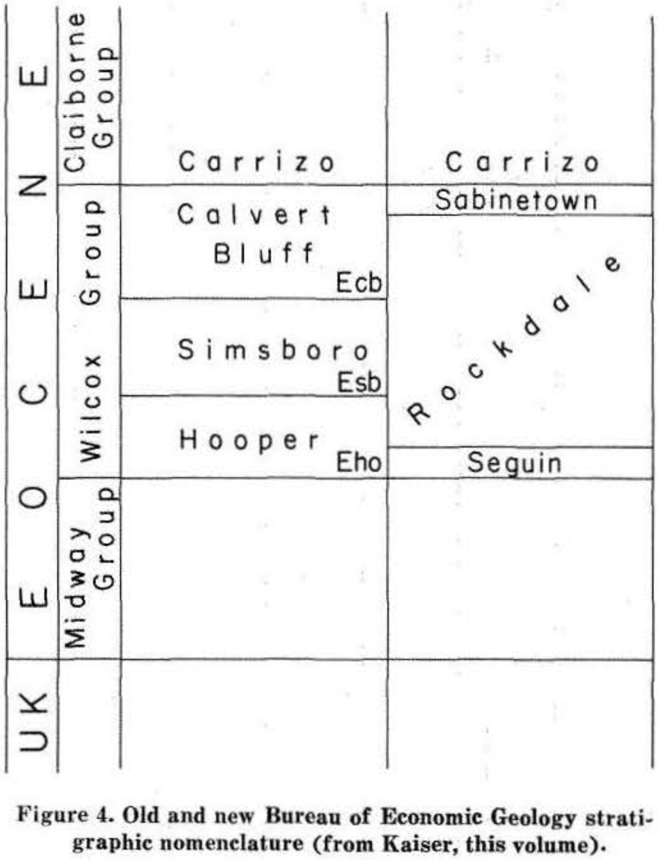


Figure 4. Old and new Bureau of Economic Geology stratigraphic nomenclature (from Kaiser, this volume).

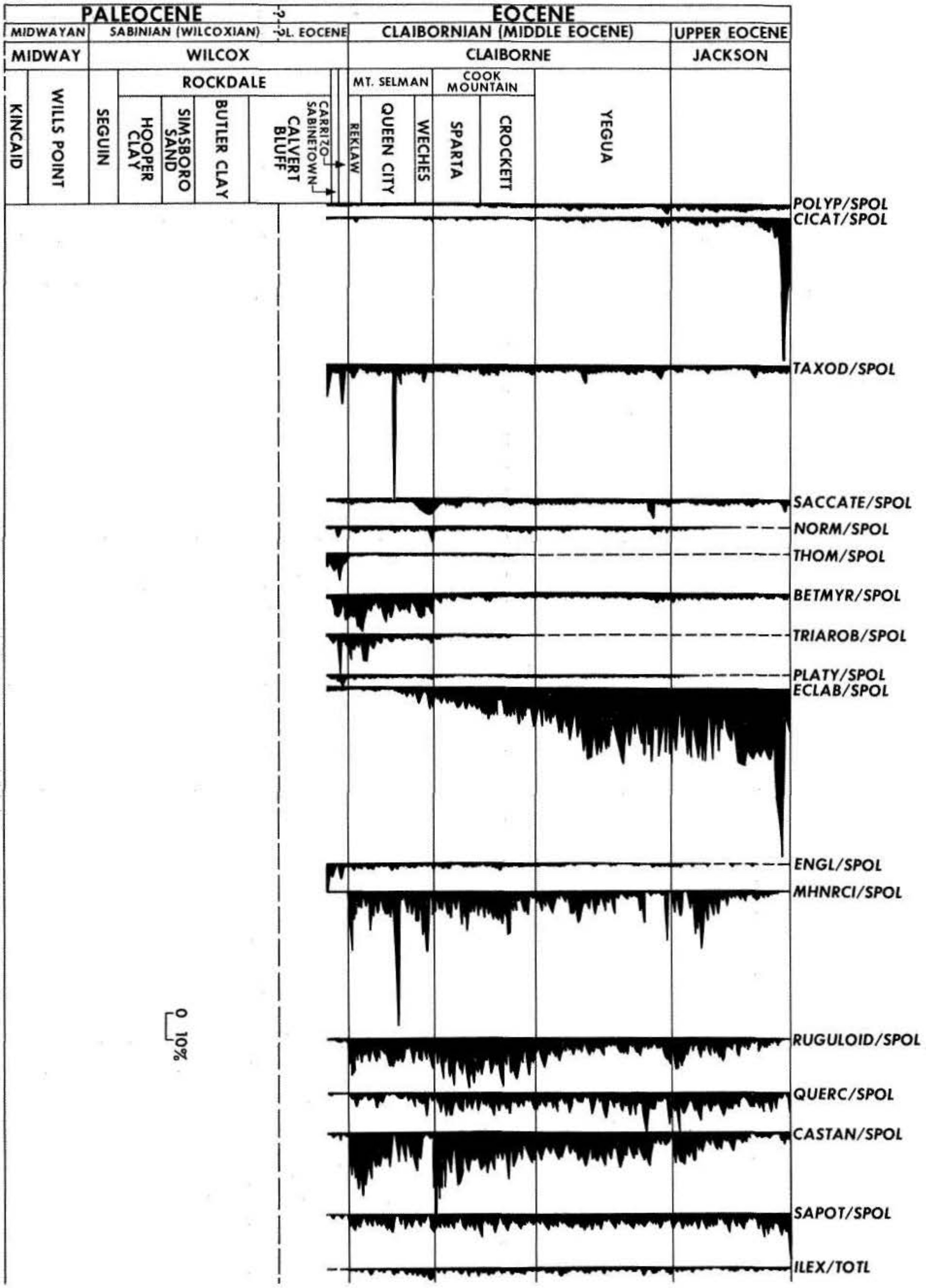


Figure 5. Palynologic correlation of subsurface Wilcox, Central to East Texas.

The differentiation of upper and lower Claiborne sediments is now possible on relative abundance (fig. 7). Common triporate pollen of the Betulaceae-Myricaceae (BETMYR/SPOL in fig. 7) occur in the Reklaw, Queen City, and Weches Formations. *Engelhardia* of the modern type (ECLAB/SPOL) is common to abundant in the Yegua. *Engelhardia* is common to extremely abundant in the Jackson strata (Elsik, 1974).

A combination of palynomorph occurrence and relative abundance also allows identification and differentiation of Claiborne strata in the updip "Wilcox facies" of both Arkansas and Tennessee (fig. 8). This refinement of Claiborne palynology has led to more precise placement of unknown samples from the updip area. Lignite and clays near Malvern, Hot Springs County, Arkansas, were first dated as middle Eocene on palynomorphs (Saunders and others, 1973, 1974). Likewise, clay from a pit near Lawrence, Henry County, Tennessee, was dated as middle Eocene (Elsik and Dilcher, 1974). Later it was possible to show (Elsik, 1974, 1975) that the Tennessee samples were latest middle Eocene, Yegua (Cockfield) Formation equivalent on the occurrence of *Enopadios* and common *Amanoa* and *Nudopollis terminalis*. The palynomorph assemblage from Arkansas ap-

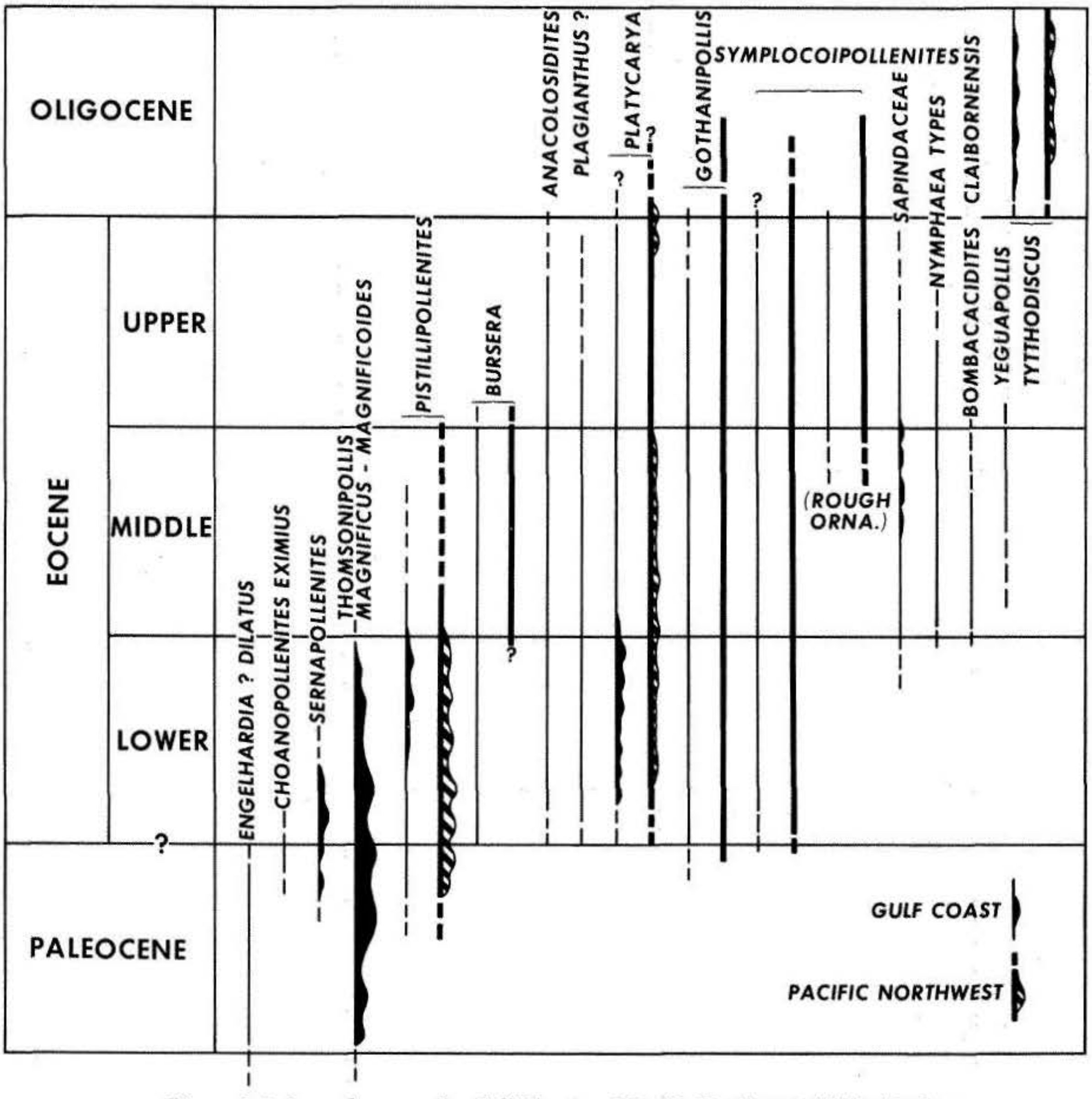


Figure 6. Index palynomorphs, Gulf Coast and Pacific Northwest (Elsik, 1974).

parently is older, with *Nuxpollenites* and common large *Nyssapollenites* (probably *Alangium* of the Alangiaceae).

The Jackson is characterized by an abundance of *Engelhardia* in most strata including the lignites. Near the end of the Eocene, *Engelhardia* pollen became less common and was replaced by an abundance of *Quercus* (oak). The example given in figure 9 is from samples taken at Little Stave Creek, Clarke County, Alabama. An extreme abundance of *Engelhardia* is characteristic of Jackson strata, especially in the upper portion, throughout the Gulf Coast. Samples higher in the Oligocene, for example the Frio Formation of Liberty and Chambers Counties, Texas, yield continuing abundance of *Quercus* and lesser amounts of *Engelhardia* (Ebtehadj, 1969, figs. 13, 19). *Engelhardia* apparently remains an inconspicuous part of the palynomorph spectrum throughout the rest of the Tertiary of not only the Gulf Coast but also the Atlantic Coast, as in the Brandon lignite (Traverse, 1955).

Jackson strata do not appear to contain diagnostic palynomorphs other than an abundance of *Engelhardia*. The general palynomorph assemblage is much like that of the upper Claiborne Group, especially the Yegua Formation. The palynologic differentiation of Jackson from Claiborne strata is therefore contingent upon more detailed study; pending that study, Jackson strata are tentatively identifiable on negative palynologic evidence.

PALEOENVIRONMENTS

Nichols and Traverse (1971) attempted in an early study to differentiate Fisher and McGowen's (1967) Wilcox depositional systems on the palyniferous content of lignite and clay samples. Interpretations of their data were made without benefit of stratigraphic control. *Sernapollenites* was listed as part of a pollen group indigenous to East Texas, and *Choanopollenites* was noted to be indigenous to Central Texas. *Sernapollenites*, as has been noted, has a much more widespread geographic occurrence, including lignites of central Texas. *Choanopollenites* occurs in the subsurface of East Texas (fig. 4), but it may be in the same environmental setting (Rockdale delta system) as in east-central Texas.

Nichols' and Traverse's most widespread lignite assemblage is dominated by Betulaceae-Myricaceae pollen and the spores of *Sphagnum*. This is indeed part of the most typical Calvert Bluff lignite assemblage and is indicative of a swamp environment (Atlee and others, 1968, p. 21). The Betulaceae-Myricaceae and *Sphagnum* assemblage is also seen in the principal Alabama lignites, especially near the top of the seam (Robert Q. Gutzler, personal communication, 1976).

Engelhardia types are also common in Calvert Bluff lignites. Nichols (1973) contrasts the abundance of *Engelhardia tenuipolus* in lignite and clays at a Central Texas mine to an abundance of *Engelhardia triradiatus* in lignites and clays of an East Texas mine, noting that the lignite occurrences reflect local environmental conditions. The distributional significance is not clearcut, however, as it appears *E. triradiatus* is more abundant in the upper part of the Wilcox, especially in the area of the Pendleton bay-lagoon system, suggesting stratigraphic as well as geographic control.

What are the basic characteristics of organic residue of the lignites? Organic residues are prepared by crushing the lignite and maceration-demineralization in HCL, HF, and flotation in zinc bromide with a specific gravity of 1.9. After a slide of this preparation is made, pollen and spores

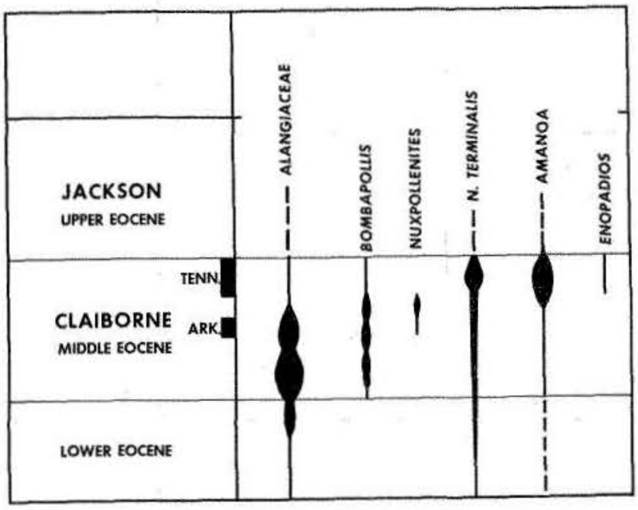
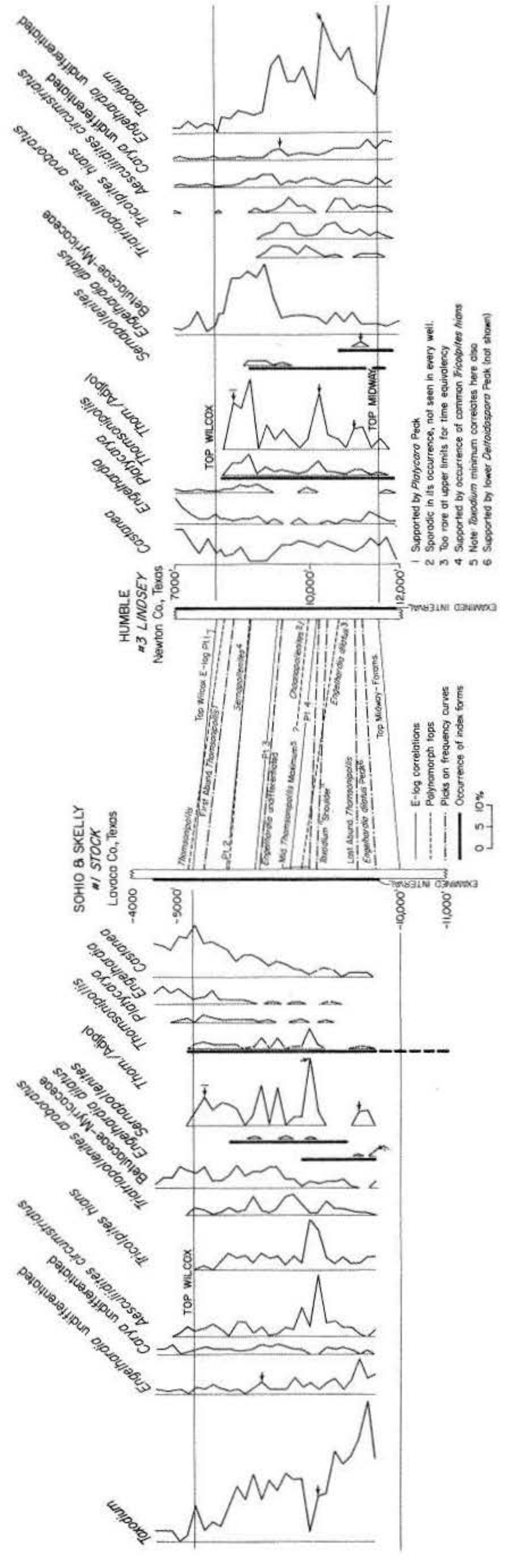


Figure 7. Generalized relative abundance of Middle and Late Eocene palynomorphs, Texas Gulf Coast (Elsik, 1974).



are further concentrated by removal of less resistant organics with HNO_3 followed by concentrated ammonia.

Residues of Calvert Bluff lignites from the Alcoa and Darco mines and from near Fairfield and Winfield generally consist of an obvious mixture of structured woody tissue, sparse to common palynomorphs, and occasionally lighter cellular plant material suggestive of epidermal tissue. A variety of swamp tree pollen may dominate the pollen assemblage at any one level: Betulaceae-Myricaceae, *Nyssa*, or the extinct plant represented by *Thomsonipollis*. This interpretation is consistent with an interpretation of the Calvert Bluff lignite at the Aluminum Company of America (ALCOA) mine as being a swamp deposit in the transition area between the lower alluvial plain and high on the delta plain (Kaiser, 1976).

Yegua lignites contain common structured woody tissue, but coarse, amorphous material also can be common. Arboreal pollens of *Engelhardia* and *Nyssa* are common to abundant, and *Amanoa*, a tropical plant of the Euphorbiaceae (not a mangrove as noted in the original abstract to this paper), may be sparse to common. The common *Nyssa* are indicative of a swamp environment. The Yegua lignite sample came from a core in Madison County, Texas, where the Yegua strata are dominantly fluvial (W. R. Kaiser, personal communication, 1976).

At least one fluvial lignite can be demonstrated for the Claiborne Group of Tennessee. Prospective drilling for the associated clay lenses resulted in a plot pattern suggesting the presence of ancient oxbow lake deposits (Dilcher, 1973). The clays and overlying lignite at one locality were examined by Potter (in press). The lignite contains common arboreal pollen at the base and an increasing abundance of herbaceous pollen upward indicating that, as the clastic source to the oxbow lake was cut off, the lake began to fill in with organic debris from the surrounding wooded area. Herbaceous plants were established around the

Figure 8. Diagnostic Claiborne palynomorphs (Elsik, 1974).

margins of the lake and gradually began to dominate the flora as the lake filled.

Manning lignites from Brazos and Grimes Counties, Texas, yield much more finely divided organic debris, mostly degraded to the amorphous state. Arboreal pollen of *Engelhardia* and *Nyssa* are abundant, and occasional samples yield an abundance of the extinct *Pollenites laesius*. The general lack of structured woody material, but especially the finely comminuted size of the organic particles, may prove to be significant for a marsh origin of these lignites. The Manning is lower on an ancient deltaic plain than either the Calvert Bluff or Yegua lignites (W. R. Kaiser, personal communication, 1976).

Amorphous material is present at various levels in Calvert Bluff and Yegua swamp lignites. The macerated particles are generally coarser than those of the Manning, with the exception of finely comminuted amorphous material from the underclay of the main Calvert Bluff lignite exposed at the Alcoa mine in Milam County, where initial accumulation of organic material apparently began under more open, marshy conditions (Atlee and others, 1968) but culminated in a swamp.

The presence of amorphous residue-yielding layers of swamp lignite may be explained through detailed sampling of the Calvert Bluff lignite at the Alcoa mine (fig. 10). There is abundant structured plant material except at those levels containing abundant fungal material. Evidently water level fluctuated during deposition (Traverse and Nichols, 1967). Low water level allowed the growth of fungi in the plant litter resulting in the degradation of plant material in those layers.

All major lignites lack the characteristic abundance of *Taxodium*, cypress, seen in Recent Mississippi delta inland swamp peats. Also lacking is the pollen of red gum, *Liquidambar*, which is present in levee flank peats of the Mississippi delta (Frazier and Osanik, 1969). Although rare, *Liquidambar* does occur in the lower Tertiary of the Gulf Coast (Atlee and others, 1968, p. 12). *Taxodium* is abundant in many marine and nonmarine clastic sediments of Paleocene-lower Eocene of the Gulf Coast. The distribution of *Taxodium* and reworked Mesozoic palynomorphs is apparently closely associated with water transport. *Taxodium* is found in the Calvert Bluff lignites, but apparently is associated with clay partings.

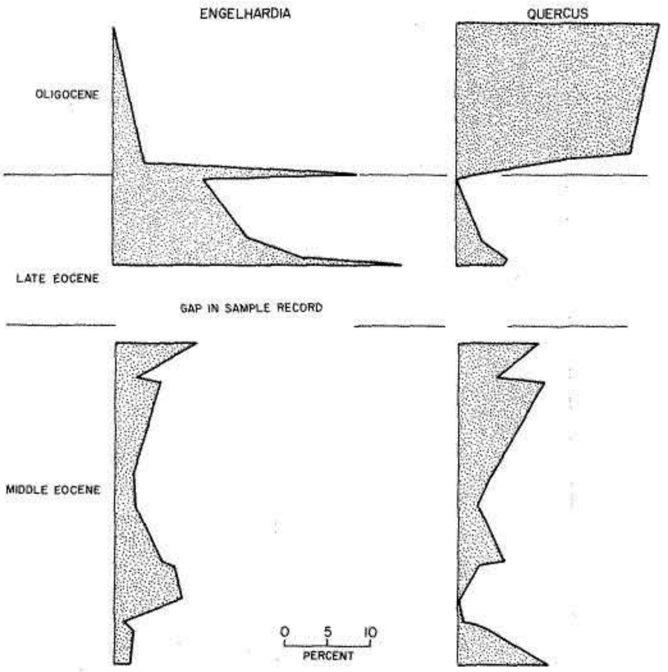


Figure 9. Relative abundance of Engelhardia and Quercus pollen across the Eocene-Oligocene boundary at Little Stave Creek, Clarke County, Alabama.

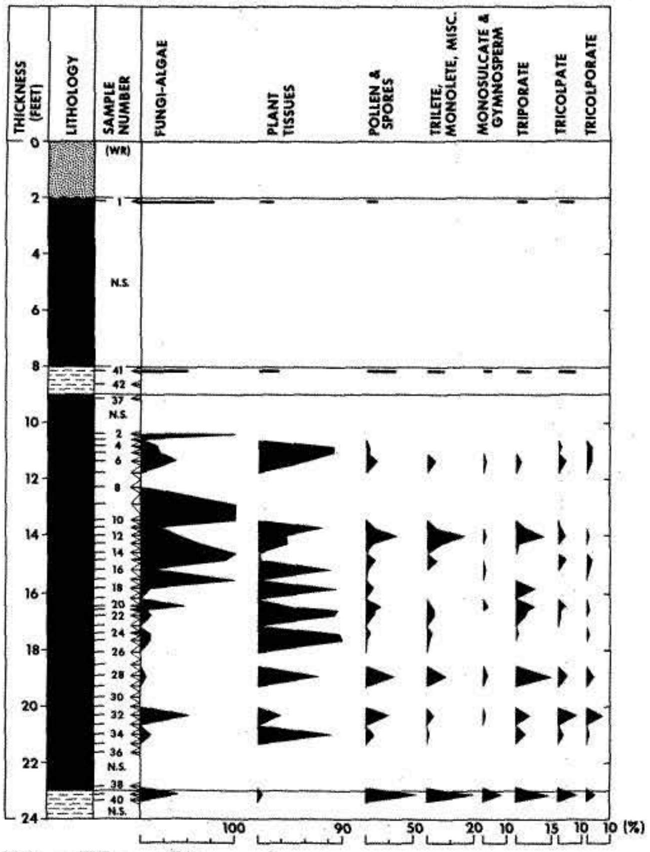


Figure 10. Relative abundance of microscopic organic remains in Calvert Bluff lignites exposed at the Alcoa mine, Milam County, Texas.

Accessory palynomorphs of shrubs and herbaceous plants present in all the lignites examined include a variety of fern spores: *Anemia* and unidentified psilate, monolete, and trilete spores. In addition, the Calvert Bluff lignite may yield common *Sphagnum* and Yegua or Manning lignites may have common *Polypodium*. Wilcox sediments may carry common *Polypodium* spores, but only of the *Verrucatosporites* type. These ferns may have grown in the more open swamp or on lake fringes. They may also be indicative of marsh conditions in tropical areas.

Presently lignite floras can be differentiated only as swamp or marsh and then occasionally with difficulty as herbaceous plants other than grasses evidently filled that ecological niche during the lower Tertiary. The pollen of grasses are absent from early Tertiary marsh sediments. Rather, in the Calvert Bluff marsh, a preponderance of *Calamuspollenites-Arecipites*, sparse *Liliacidites* (Liliaceae-Amaryllidaceae) and rare *Carex* occur. In the typical Calvert Bluff lignite, however, the "marsh assemblage" is only a short episode at the beginning or infrequently repeated through the history of the deposit. Yegua and Manning marsh lignites may yield either common *Calamuspollenites-Arecipites* or common *Liliacidites*. Fern spores and airborne pollen of trees may also occur in the marsh lignites.

It appears that principal lignites of the Calvert Bluff originated in a swamp environment located adjacent to levee flanks in a distributary network. Yegua lignites may be primarily swamp or marsh. Manning lignites, although lacking an abundance of pollen of herbaceous plants, do contain abundant pollen of *Engelhardia*, a tree in modern times growing in upland areas. The Manning lignites after preliminary study also appear to have less diversity of arboreal pollen types, suggesting a marsh environment.

PROJECTIONS

The following palynologic studies are proposed for future utilization in geologic exploration for lignites in the Gulf Coast basin.

1. Regional studies of depositional systems using palynostratigraphy for time datum points.
2. Detailed palynomorph assemblage study through lignites and enclosing strata for environmental interpretations. This study can be expanded to include lateral changes in the lignites. It is impossible at the present time, for example, to pinpoint a deposit in the detail possible for modern swamp-marsh complexes (Cohen, 1975) or to differentiate the local variation of marsh plant communities (Spackman and others, 1969).
3. Detailed palynologic study across the Claiborne-Jackson boundary to age date South Texas Yegua-Jackson lignites.
4. Palynologic study of Webb County, Texas, Eocene cannel coal (Evans, 1974) to determine age and environmental indicators.

ACKNOWLEDGMENTS

Many of the Calvert Bluff lignite samples and most of the Yegua and Manning lignite samples upon which paleoenvironmental remarks are made were furnished by W. R. Kaiser, Bureau of Economic Geology, The University of Texas at Austin. This paper is published with the permission of Exxon Company, U.S.A.

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DEPOSITIONAL SYSTEMS IN THE WILCOX GROUP (EOCENE) OF EAST-CENTRAL TEXAS AND THE OCCURRENCE OF LIGNITE

W. R. Kaiser[1]

ABSTRACT

Between the Colorado and Trinity Rivers, the Wilcox Group (lower Eocene) is divided into three formations; upsection they are the Hooper, Simsboro, and Calvert Bluff. The most important commercial lignite deposits occur in the Calvert Bluff Formation. Lignite of lesser importance occurs in the upper Hooper Formation.

The Calvert Bluff is a dip-oriented channel system 500 to 2,000 ft thick, dipping southeast at ½ to 2°. Major rivers flowed from the northwest to the southeast. Updip is a straight or slightly dendritic channel geometry. This geometry, based on analogy with modern deltas, is representative of the transition between the bifurcating distributary channel facies of the lower delta plain and the dendritic fluvial channel facies of the high alluvial plain. The outcrop is positioned at the transition zone between the lower alluvial plain and the upper delta plain. Southward there is a convergence of depositional and structural strike. In the deep subsurface is a bifurcating channel geometry.

Lignite in the Calvert Bluff occupies an interchannel position. In interchannel basins, fresh-water swamps and marshes were the sites of greatest organic accumulation. The relationship of swamps and marshes to channels on the Mississippi delta system is similar to that of Calvert Bluff lignite and channels. Modern analogues of Calvert Bluff interchannel basins are the Atchafalaya and Des Allemands-Barataria basins. These basins lie between the alluvial ridges formed by the modern Mississippi and older Mississippi river courses. Peat is best developed far from the contaminating influence of active channels and inland from the destructive effects of the Gulf, at the junction of the delta and alluvial plains. Infilling of the basins by crevassing and overbank flooding generates coarsening-upward sediment sequences. An ideal Calvert Bluff coarsening-upward sequence is approximately 15m thick and begins with lignite, then passes into clay, mud, interlaminated mud and very fine-grained sand, and finally beds of flat-bedded fine sand.

Exploratory drilling in the Calvert Bluff should concentrate on the interchannel areas (low sand-percent areas) coincident with a high lignite count. All the major near-surface deposits can be identified using the model outlined. Once drilling starts, log patterns might be a guide to future drilling. Scant data suggest that inverted Christmas-tree patterns, representing coarsening-upward interchannel basin cycles, are the best guide to commercial deposits.

INTRODUCTION

PREVIOUS WORK

The regional framework of Wilcox deposition was established by Fisher and McGowen (1967). They defined in east-central Texas, or the area between the Colorado and Trinity Rivers (fig. 1), a fluvial channel system updip merging downdip with a high-constructive delta system. Their work revealed the presence of extensive lignite in the deep basin, pointing out the relative abundance in various depositional systems. Fisher (1969, fig. 12, p. 253) mapped in broad outline the principal sand trends in the upper Wilcox of east-central Texas. In these studies, no specific attempt was made to outline the occurrence of lignite. Lignite was placed in an overall facies context as equivalents of marine delta destruction or constructional interdistributary environments.

McGowen (1968, fig. 10, p. 167) published the first generalized map of Wilcox deep-basin lignite in eastern Texas, but he did not relate the occurrence of lignite to the sand geometry or outcrop stratigraphy. Kaiser (1974) published the first statewide isopleth maps of deep-basin lignite. He did no lithofacies mapping in presenting a generalized exploration model relating lignite to depositional systems and stratigraphy. The importance of the Calvert Bluff Formation as a lig-

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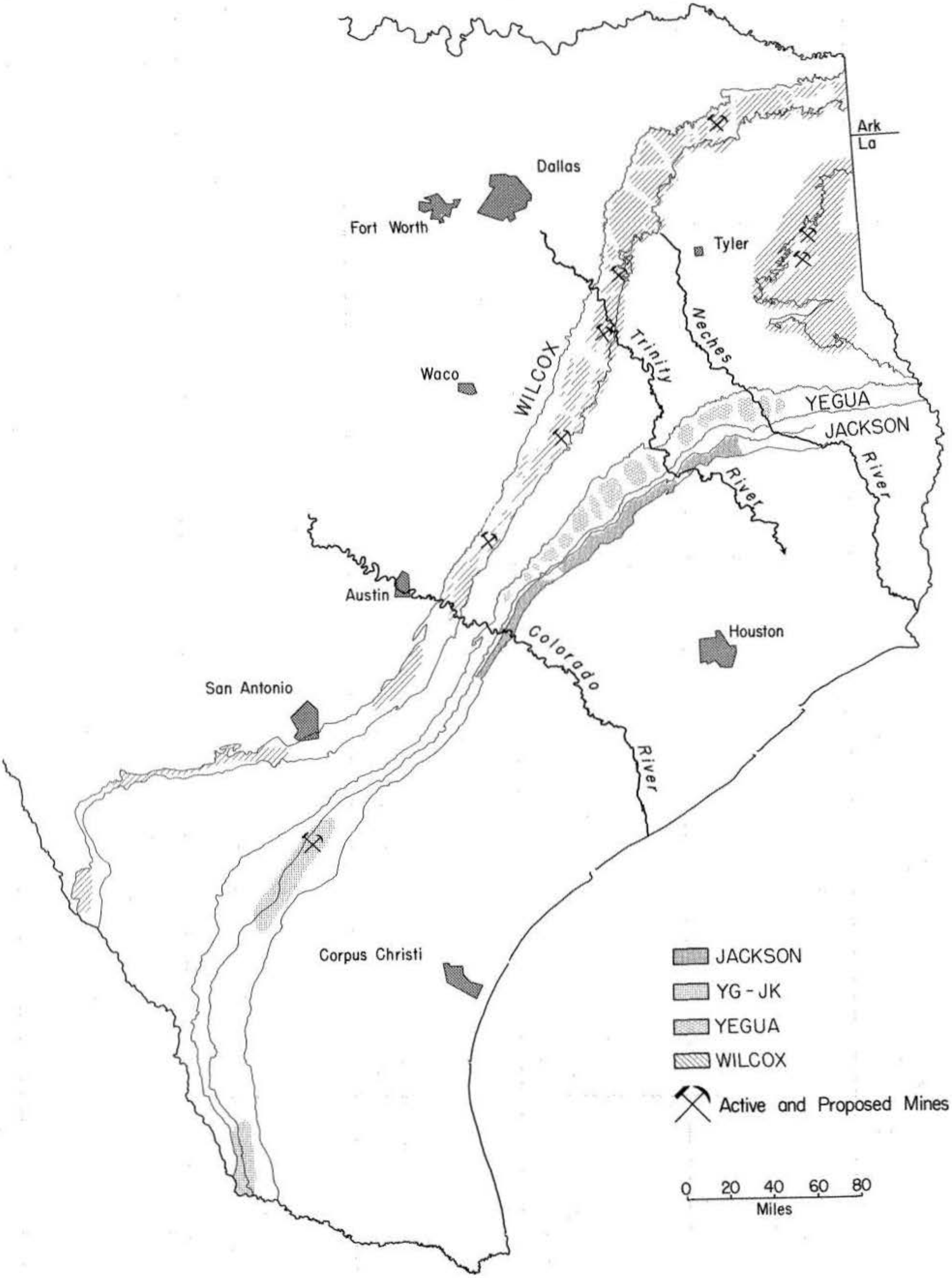

Figure 1. Distribution of Texas near-surface lignite.

nite-bearing interval in east-central Texas was recognized. Lignite in the Hooper Formation is of lesser importance though not commercially insignificant as originally thought by Kaiser.

OBJECTIVE

The east-central Texas Wilcox lignite is being mined from two large-scale strip mines; a third has been announced, and additional mines are planned for the future. Furthermore, with the development of in situ gasification, deeper lignite will become an exploration target. The objective of this study was to develop an exploration model for shallow subsurface lignite (0 to 2,000 ft), using available electric and induction logs, to identify areas of relatively highest potential for reserves. Exploratory effort could then be concentrated in those areas. The relationship of lignite occurrence and sand geometry was expected to be the model's essential element and was meant to serve as a guide for exploratory drilling. Identification and delineation of deposits of specific tonnage was not intended and was not an objective.

APPROACH

This paper is based on a subsurface study of a 15-county area between the Colorado and Neches Rivers (fig. 1). From a data base of 603 electric and induction logs, a series of lithofacies, lignite occurrence, and structure contour maps were prepared. Cross sections were prepared mainly for illustrative purposes.

Sand and lignite are defined in terms of their log response. Sands containing brackish or saline pore waters are easily recognized by their negative spontaneous potential (SP). Unconsolidated sands charged with fresh water are recognized by their high formation resistivity which is directly related to the resistivity of the interstitial water and grain size (Alger, 1966). Close agreement was found among sand values determined from either the SP or resistivity curve.

Coal can be uniquely and easily identified with a porosity log (Bond and others, 1971; Reeves, 1971; Kowalski and Holter, 1975; Davis, 1977). The density log is best in the unconsolidated sediments of the Gulf Coast; low density is characteristic of lignite (fig. 2). In this study without porosity logs, lignite is operationally defined to be those beds with a sharp resistivity spike and baseline SP (Kaiser, 1974, p. 32). Lignite is highly resistive because it is a hydrocarbon and lacks appreciable free or gravitational water (Davis, 1977). Baseline SP is a function of the

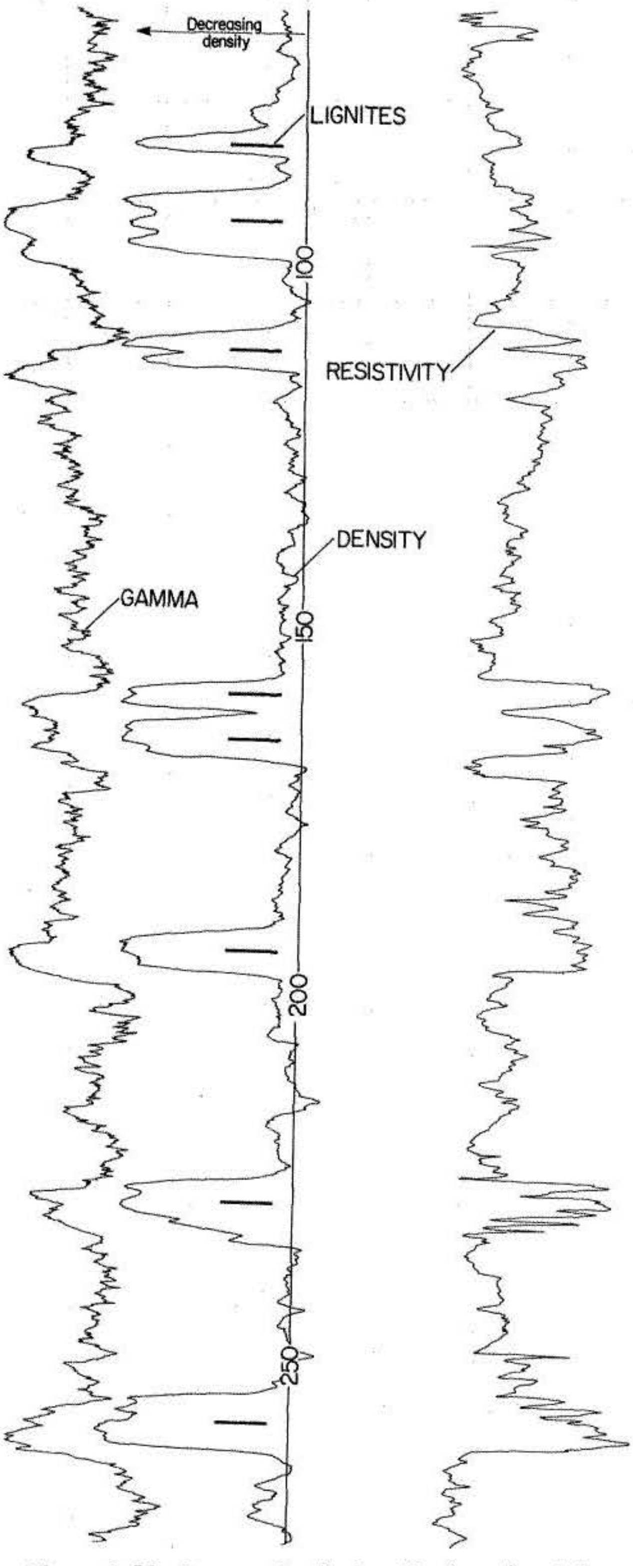

Figure 2. Lignite on a density log (Bastrop County).

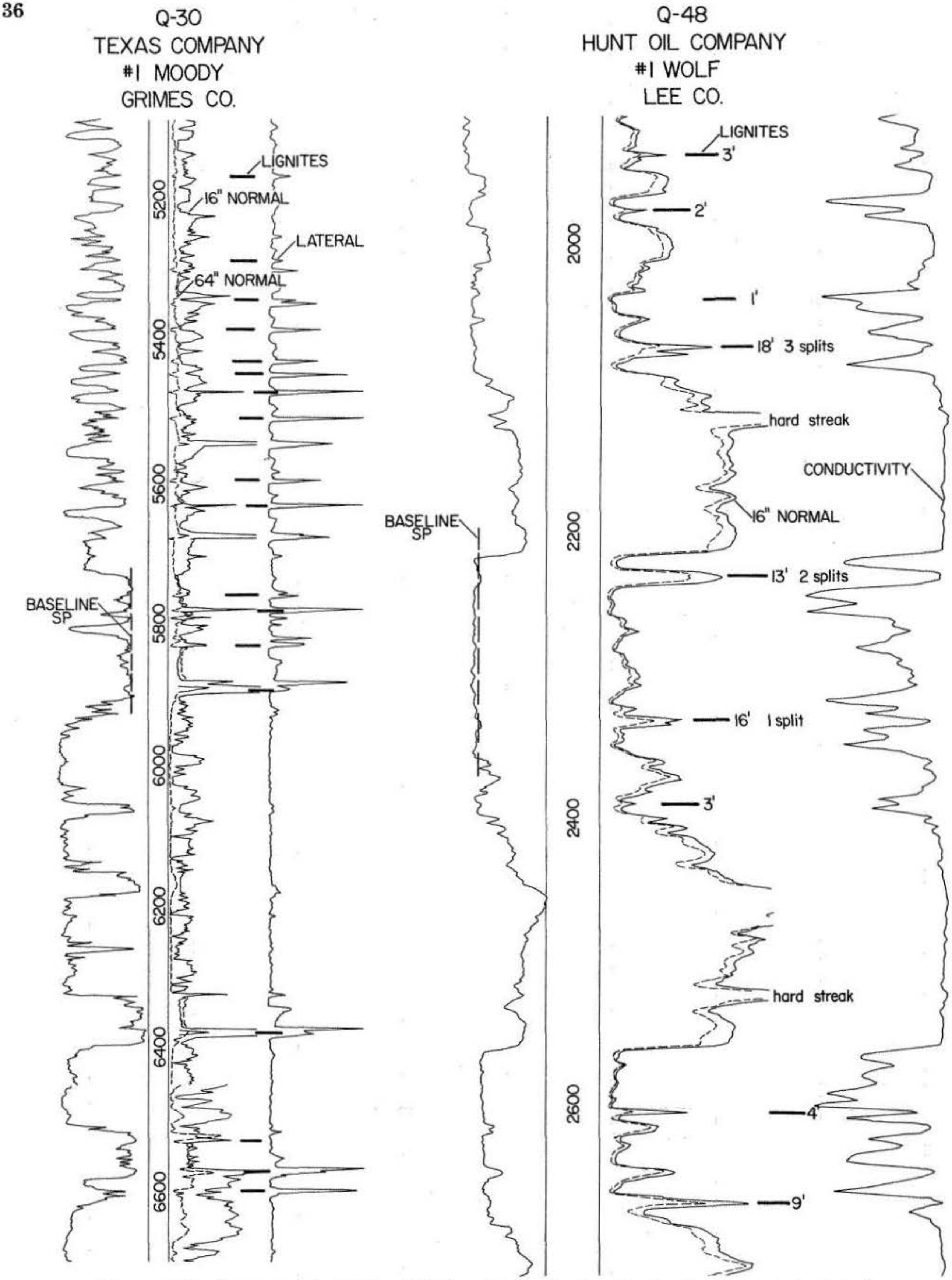

Figure 3. Lignite on an electric log (Q-30) and induction log (Q-48). See figure 9 for location. Lignites on Q-48 identified from a companion neutron log.

low water content (low chemical activity), high resistivity, bed thickness, and shaliness or dispersed mud content. The operational definition becomes increasingly more difficult to apply as formation water becomes fresher and the SP less and less well defined. Lignites cannot be distinguished easily from thin fresh-water sands. Thus picking lignites close to the outcrop depends largely on the worker's experience and intuition.

Lignites are best picked on electric logs. Opposite a lignite seam, the long lateral curve (18 ft 8 inch spacing) has a resistivity kick of extreme peakedness. This curve will identify lignites as thin as 1 ft. The long normal curve (64-inch spacing) displays a reversal back toward the baseline in beds thinner than 64 inches (fig. 3, well Q-30). A sequence of thin, closely spaced lignites complicates the interpretation. The induction log is not well suited to the identification of lignite beds less than 4 ft thick. Thicker beds can be picked reasonably well based on curve peakedness. Figure 3 (well Q-48) illustrates the response to lignites on an induction log.

STRATIGRAPHY

In east-central Texas the Wilcox Group is 1,200 to 3,500 ft thick and is divided into three formations; upsection they are the Hooper, Simsboro, and Calvert Bluff (fig. 4). North of the Trinity River and south of the Colorado River the Simsboro is absent. Therefore, only in east-central Texas can the tripartite division of the Wilcox be made.

The Hooper is composed of mud and sand, conformably overlies the Midway marine muds, and normally is 400 to 1,000 ft thick. The Simsboro, a massive, highly resistive sand 0 to 800 ft thick, rests conformably and unconformably on the Hooper. The Calvert Bluff, 500 to 2,000 ft of sand and mud, conformably overlies the Simsboro and is recognized by its finer grain size, as reflected in reduced resistivity on normal curves, and by the first occurrence of lignite (fig. 5). Resting unconformably on the Calvert Bluff is the Carrizo, a massive, highly resistive sand. Older literature often referred to the Calvert Bluff as dominantly mud; however, fine- and very fine-grained sand is a major lithology and commonly conspicuous (fig. 6).

The most important commercial lignite deposits occur in the lower one-third of the Calvert Bluff immediately above the Simsboro (fig. 5). Lignite occurs persistently at this stratigraphic position throughout the area at the outcrop and in the subsurface. Seams are 2 to 22 ft thick. Deposits of secondary importance occur less persistently in the upper Calvert Bluff. Lignite of lesser importance occurs in the upper Hooper just below the Simsboro. Seams are 2 to 7 ft thick.

DEPOSITIONAL SYSTEMS

Interpretation of depositional systems rests on sand geometry as revealed by sand percent, net sand, and maximum sand maps. All of these maps were made of the Calvert Bluff. Only a net sand map was made of the Simsboro. No lithofacies mapping was done of the Hooper. Mapping was extended downdip until the Simsboro was lost as a mappable unit or to the limit of recognition of the Wilcox tripartite stratigraphy. Where the Simsboro is poorly developed or absent updip, a correlative horizon was used. The north and south ends of the study area were mapped first where well control was best. The area of poorest control, at the center, was mapped last to reflect patterns developed north and south.

CALVERT BLUFF FORMATION

Sand Geometry

The Calvert Bluff is named for exposures at Calvert Bluff on the Brazos River 5.5 miles west of Calvert, Texas. In the subsurface, ribbons and dendroids of dip-oriented sand merge downdip with deltoid depocenters of sand flaring basinward (400 and 600 versus 800 and 1,000 ft isoliths). All are geometric elements of a delta system (fig. 7). The basinward increase of sand is due to formational thickening in that direction. Major sand inputs, sand maximums extending to the outcrop as shown by the 400 and 600 ft isoliths, are located in central Anderson, southwest Freestone, northeast Robertson, central Milam,

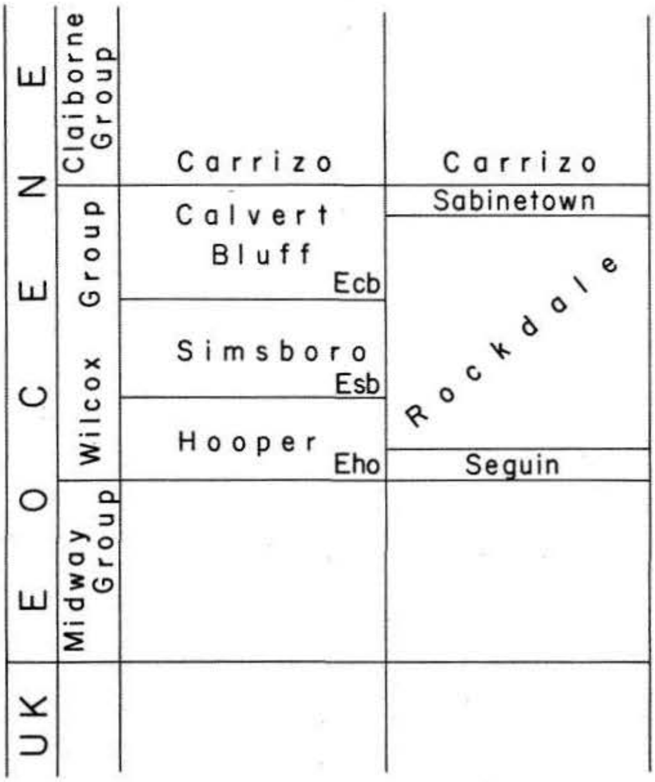

Figure 4. **Stratigraphic terms, current and past Bureau of Economic Geology usage, from Barnes, 1970, 1974, and Plummer, 1932.**

and northern Bastrop Counties (fig. 7). In central Milam County, the site of maximum Wilcox sand input, fluvial facies are dominant and in places comprise the entire Wilcox (fig. 8).

The sand-percent map defines a dip-oriented channel system dipping southeast at ½ to 2° (fig. 9). Major river systems flowed from west-northwest to east-southeast at the south of the study area, from northwest to southeast northward, and from north to south at the northern edge in Anderson County. Updip is a straight or slightly dendritic channel geometry. This geometry, based on analogy with modern deltas, is representative of the transition between the bifurcating distributary channel facies of the lower delta plain and the dendritic fluvial channel facies of the high alluvial plain. At this physiographic position active and abandoned alluvial belts of the major river courses diverge little and are subparallel (Smith, 1966). The Calvert Bluff outcrop is placed in the transition zone between the lower alluvial plain and the upper delta plain. Major sand bodies are composed of multistory and multilateral fine- to course-grained meanderbelt deposits.

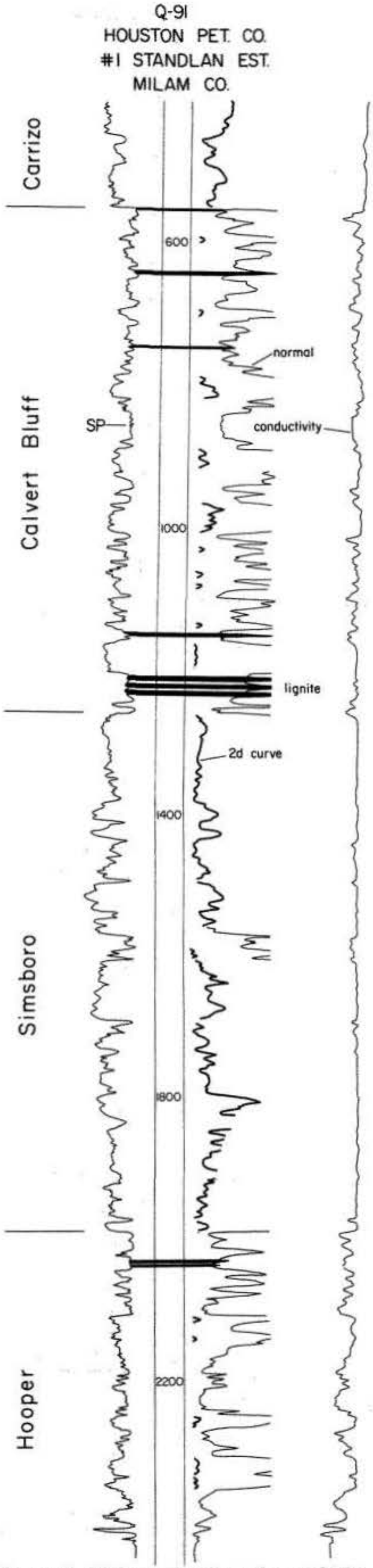

Figure 5. **Wilcox stratigraphy and the occurrence of lignite.**

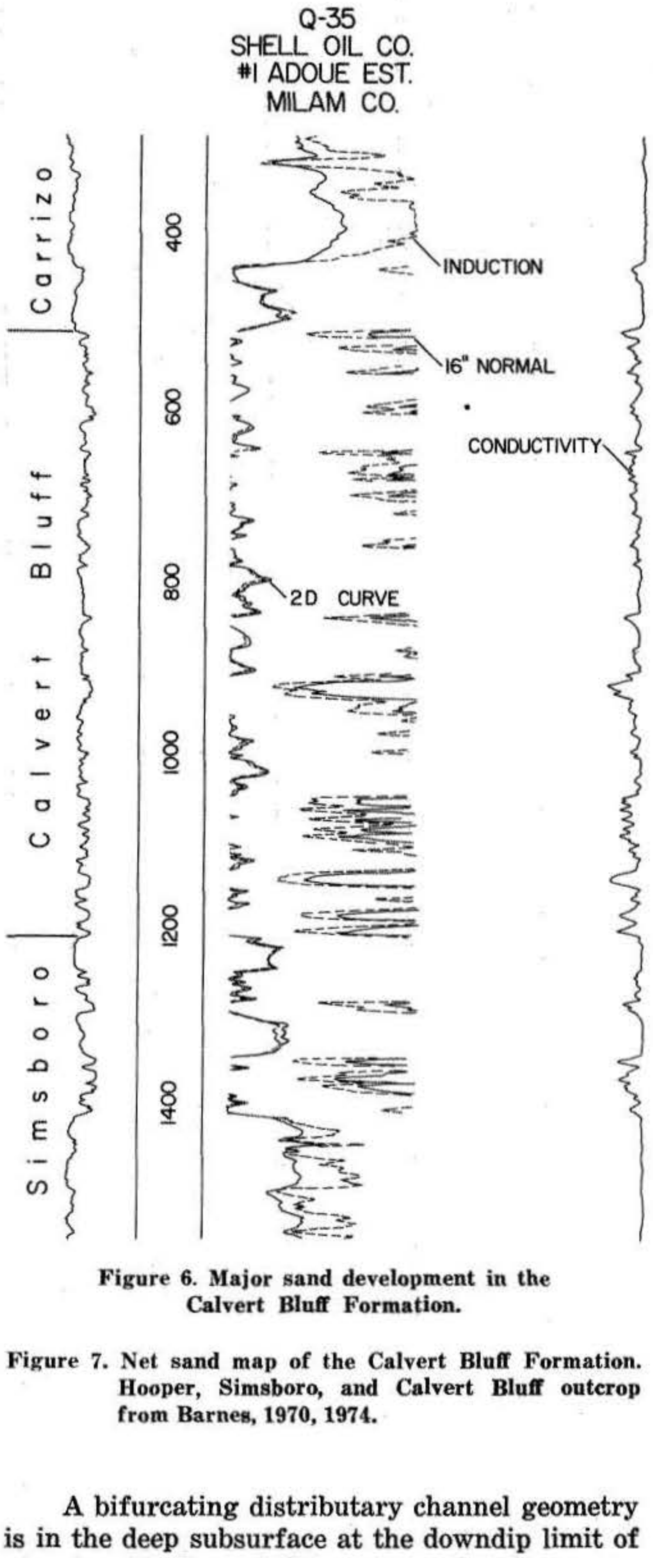

Figure 6. Major sand development in the Calvert Bluff Formation.

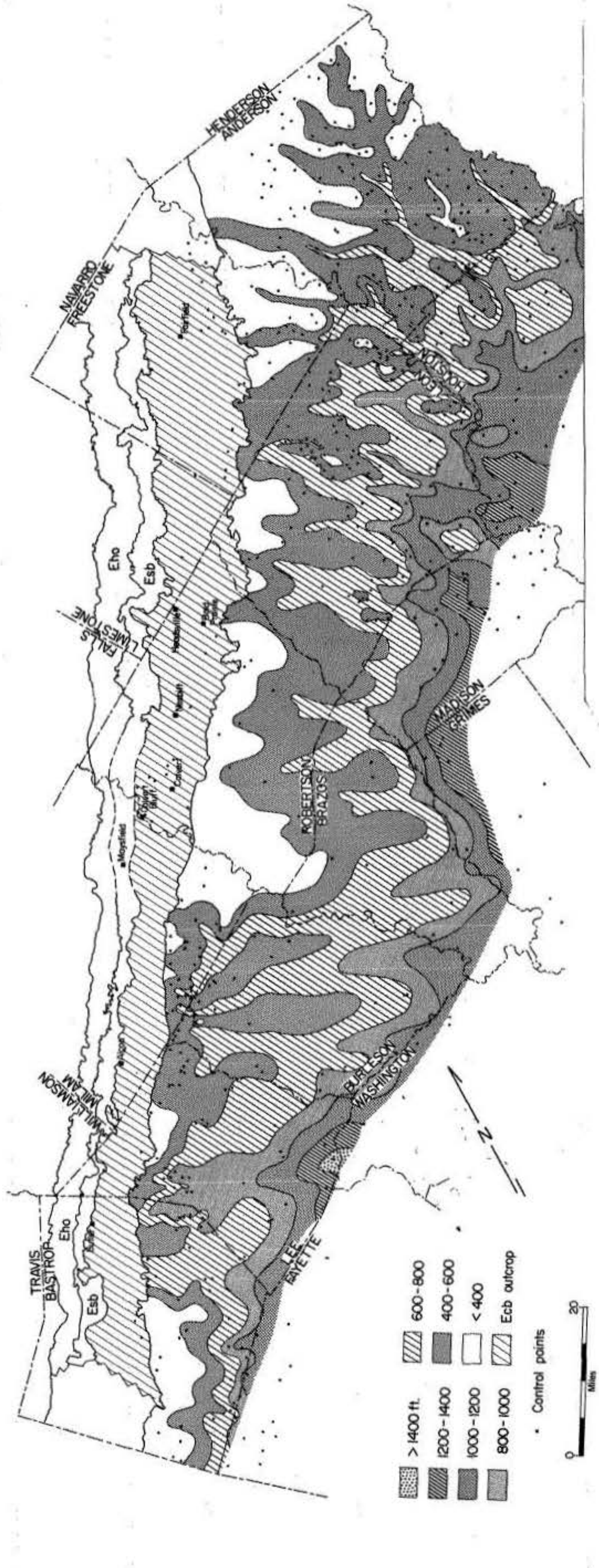

Figure 7. Net sand map of the Calvert Bluff Formation. Hooper, Simsboro, and Calvert Bluff outcrop from Barnes, 1970, 1974.

A bifurcating distributary channel geometry is in the deep subsurface at the downdip limit of mapping. Southward this geometry is closer to the outcrop, indicating convergence of depositional and structural strike (fig. 9). As the edge of the delta system is crossed in southern Bastrop County, a change to marine sedimentation occurs (fig. 8). Thus to the south the outcrop occupies a position lower on the ancient delta system.

Upper Calvert Bluff

Marine processes played a role in upper Calvert Bluff sedimentation. Glauconite is locally present and in some places the uppermost Calvert Bluff (Sabinetown of older literature) contains a molluscan fauna (Plummer, 1932, p. 601–606; Harris, 1957). To evaluate the marine influence in the upper Calvert Bluff, a maximum sand map was made, the intent being to determine the relative importance of strike sands versus dip-oriented sands. Between the last lignite of the lower Calvert Bluff and the Carrizo, the single thickest or maximum sand was picked irrespective of stratigraphic position. The resulting isopleth map reveals a dip-oriented channel system with a geometry very similar to that of the sand-percent map of the total formation (fig. 10). Major channel complexes, as shown by the isopleth pattern of sands greater than 75 ft thick, closely approximate the positions occupied by the highest sand percent and net sand values for the formation as a whole. Thus, marine processes played at most a secondary role in upper Calvert Bluff sedimentation.

Delta Classification

Fisher (1969) in his study of the upper Wilcox concluded that the upper Wilcox was a high-destructive delta system. Apparently his upper Wilcox embraced the middle and upper Calvert Bluff plus the Carrizo (Fisher, unpublished Bureau of Economic Geology cross sections). Fisher showed downdip depocenters in a belt roughly parallel to regional depositional strike fed by sand updip with axes perpendicular to depositional strike.

The author's study involves a stratigraphic interval different from Fisher's; hence, interpretations cannot be directly compared. Furthermore, mapping by this author was not carried far enough basinward to conclusively determine delta classification. Therefore, the Calvert Bluff as here defined is tentatively classified as a high-constructive delta system or one which is dominantly fluvial or fluvially influenced (Scott and Fisher,

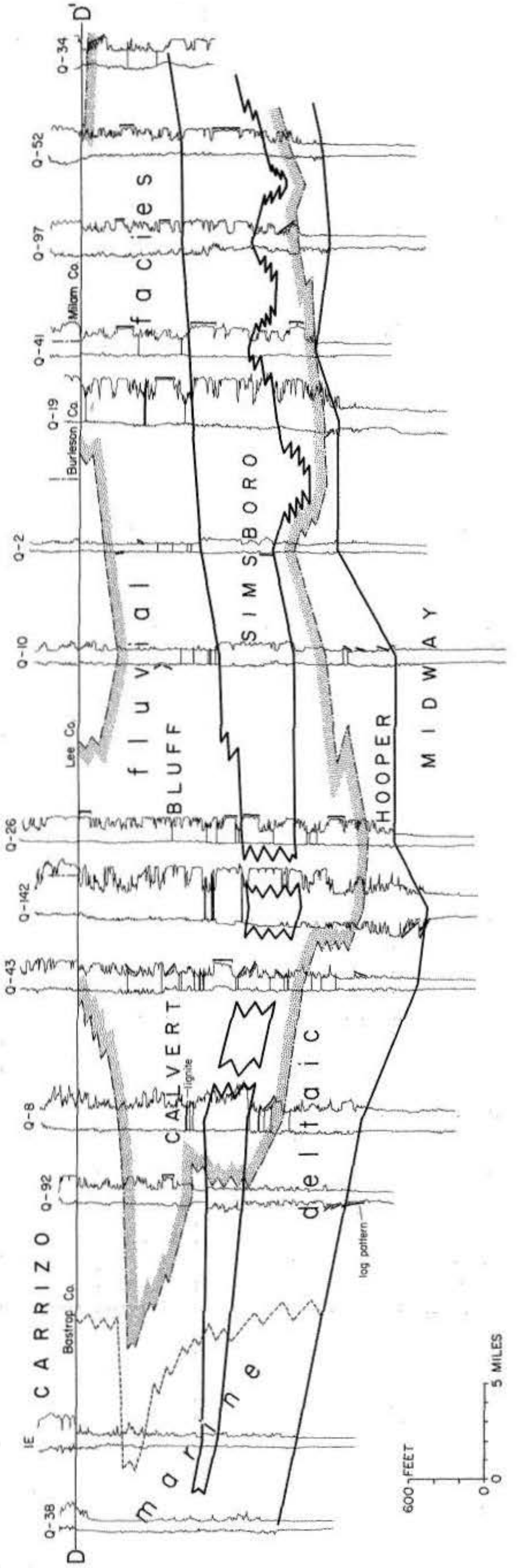

Figure 8. Strike cross section. See figure 9 for location.

1969; Fisher, 1969). At the limit of mapping, 20 to 50 miles into the subsurface, dip-oriented channel sands still dominate. Marine processes played a minor role in Calvert Bluff sedimentation. Rare marine units are thin and vertically distinct. The system is regional in extent (5,000-square-mile minimum) with thick aggradational facies containing numerous lignites.

SIMSBORO FORMATION

The Simsboro is named for exposures at Simsboro, Texas, 4 miles north of Teague and can be mapped from central Bastrop County to northern Freestone County (fig. 11). The Simsboro underlies some of the most important deposits in Texas. A net-sand map was made to evaluate the relationship between Simsboro sand geometry and distribution and Calvert Bluff lignite occurrence. For the exploration of deep-basin lignite, a structure contour map of the top of Simsboro was made.

Maximum development of the Simsboro sand centers about Milam County, secondarily in Robertson and Lee Counties, and southeastward into the subsurface. At the north in Anderson County are multistory sand bodies displaying an excellent dendritic channel geometry characteristic of the high alluvial plain. Southward are thick multilateral sand belts with a straight or slightly dendritic channel geometry. Downdip in the deep basin, a bifurcating channel geometry is evident (fig. 11).

The Simsboro thins, breaks up, and changes facies to the south and north (figs. 8 and 11) and is actually a facies equivalent of the Calvert Bluff in these areas. Southward there is a change to marine sedimentation. At the extreme southern edge of the study area in Bastrop County, Simsboro equivalents are strike-oriented, nearshore marine units.

McGowen and Garner (1970), in an outcrop study in Milam and Limestone Counties, interpreted the Simsboro as coarse-grained meanderbelt deposits. Sand geometry, as revealed here, indicates the presence of fine-grained meanderbelt and braided stream deposits as well.

LIGNITE OCCURRENCE

The areal occurrence of lignite in the Calvert Bluff and Hooper is shown on an isopleth map for each formation of the total number of lignites counted. Lignites were identified on electric and induction logs using the aforementioned operational definition. Because of the inherent difficulties in determining bed boundaries of thin resistive beds on the normal and lateral curves, no attempt was made to prepare a lignite isopach map. The number of beds greater than 5 ft thick were recorded but not mapped. Cross sections were prepared to illustrate stratigraphic occurrence.

CALVERT BLUFF

Lignite occurs stratigraphically as a persistent zone in the lower Calvert Bluff just above the Simsboro and less persistently in the upper Calvert Bluff (fig. 12). Note the absence of lignite in the upper Calvert Bluff in several wells of figures 8 and 12. Areally lignite occurs in elongate concentrations roughly perpendicular to the outcrop (fig. 13). Updip areas of low lignite occurrence (< 2 lignites) correlate well with high sand-percent areas (> 55 percent), especially in Milam and Freestone Counties. In central Milam County very high sand-percent values and low lignite counts coincide almost exactly (figs. 9 and 13). Thus lignite occupies an interchannel position as defined by relatively lower sand-percent areas. For example, low sand-percent areas (< 55 percent) are found just downdip from the Alcoa and Big Brown (northeast of Fairfield to Trinity River) deposits. Calvert Bluff lignite deposits are on the order of 100 to 200 million short tons.

Downdip, areas of more than eight lignites coincide with the bifurcating distributary channel geometry or lower delta-plain facies. The positive correlation between low sand percent and lignite occurrence is less definite than on the upper delta/lower alluvial plain updip. A number of factors are involved. (1) At the more seaward position, a higher sand percent may favor peat accumulation. If subsidence is slowed (sandy sediment compacts less than muddy), interdistributary lake formation and marine encroachment are slowed and marsh integrity is maintained. (2) Too many lignites may mask any apparent correlation. The thicker downdip stratigraphic section alone contributes to a high lignite count. Furthermore, sub-

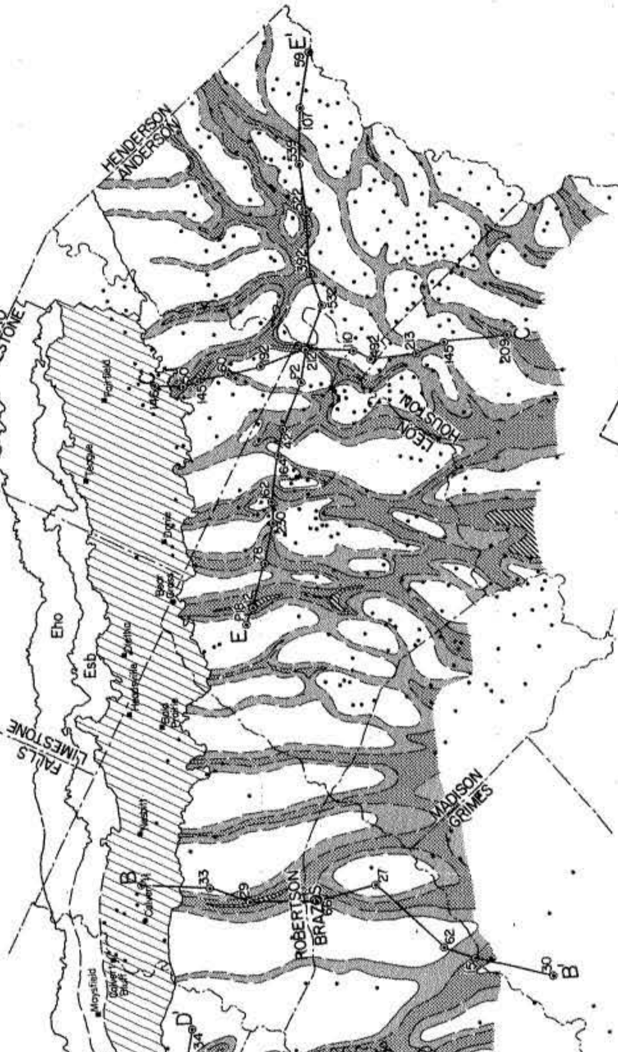

Figure 9. Sand-percent map of the Calvert Bluff Formation. Numbers identify logs for figures 3, 5, 6, 8, and 12.

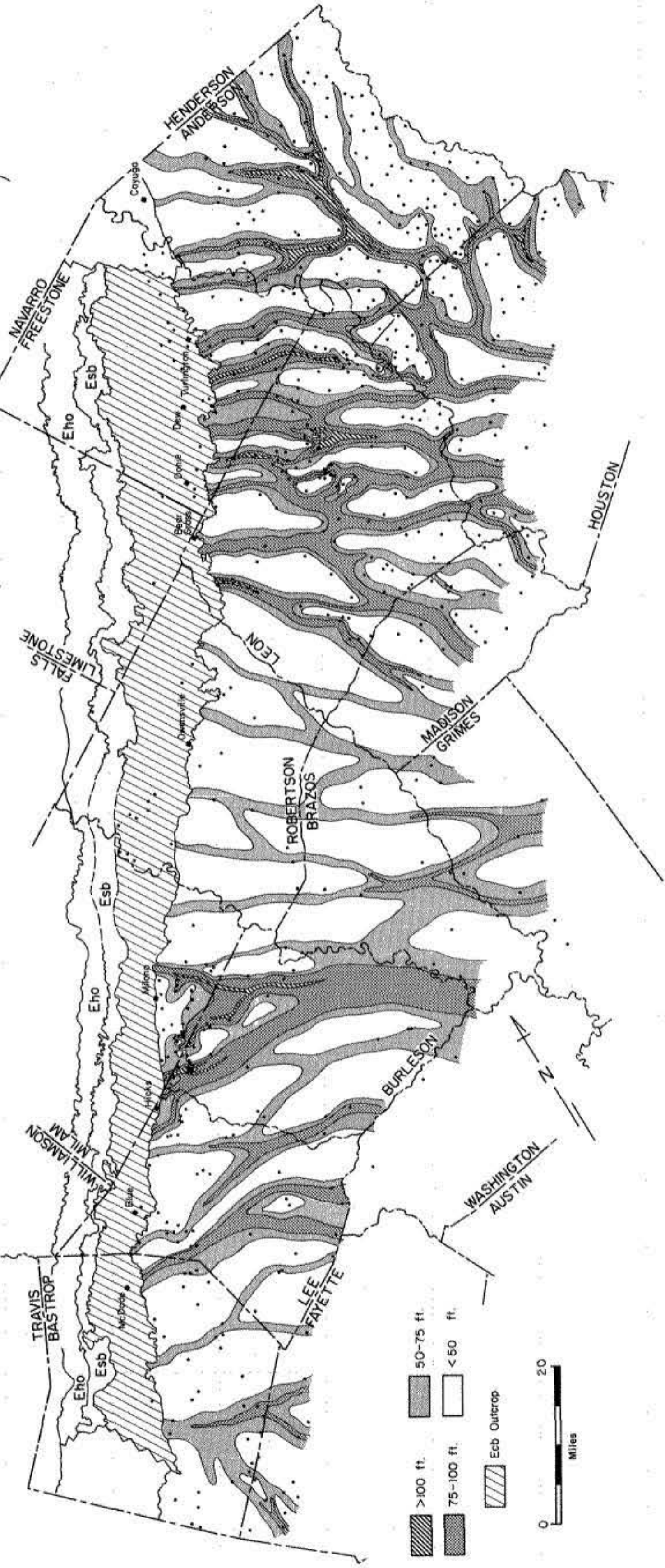

Figure 10. Maximum sand map of the upper Calvert Bluff Formation.

siding marshes generate many more layers of peat in the distal areas. (3) Blanket peats will extend across two or more abandoned distributary channels and obviously will not reflect an interchannel position.

HOOPER

The Hooper is named for exposures at Hooper Bend (now Wilbargers Bend) on the Colorado River (fig. 14). Hooper lignites are most numerous and thickest in the upper Hooper just below the Simsboro (fig. 5). Commercial deposits are expected to be smaller (about 50 million tons) than Calvert Bluff deposits (about 100 to 200 million tons) and widely scattered along trend. Scatter is evident from the cross sections and occurrence map. Note the absence of lignite in the upper Hooper in several wells of figures 8 and 12. Areally lignite is abundant downdip coincident with a deltaic facies. Updip in the shallow subsurface, lignite occurs as widely spaced amoeboid-shaped cells associated with a fluvial facies (fig. 14).

Lignite should be sought in the upper Hooper along the Simsboro contact. Three areas, based on crude projection from the subsurface, are believed to have the best exploration potential. The higher number of lignites nearer the outcrop at the south indicates potential may be highest in Bastrop and Lee Counties (fig. 14).

MODERN ANALOGUE

PHYSIOGRAPHIC SETTING

Modern analogues for Calvert Bluff lignite depositional environments are taken from the Mississippi River delta system, a Holocene high-constructive system (Fisher, 1969). The relationship of swamps and marshes to channels on the Mississippi is similar to that of Calvert Bluff lignite and channels (fig. 15). In interchannel basins, developed between alluvial ridges formed by modern and ancient Mississippi river courses, freshwater swamps and marshes are the sites of greatest organic accumulation. Note the crevasses and crevasse distributaries extending into the basins (on figure 15, protrusions of levee sediment oriented basinward at high angle to major river courses). Gulfward these basins diminish in size and increase in number as trunk streams bifurcate into distributary networks which enclose smaller and smaller interdistributary basins (Frazier and others, this volume).

Peat beds of the upper delta plain and inland areas are thicker and more widespread (Frazier and Osanik, 1969; Gagliano and van Beek, 1970; Frazier and others, this volume). The thickest peats encountered are in inland swamps. Frazier and Osanik report inland swamp peats up to 20 ft thick, composed of cypress-gum vegetation, flanking natural levee ridges (fig. 16). They indicate peat accumulates at a rate of approximately 6 m per 1,000 years.

ENVIRONMENTS OF ACCUMULATION

Analogues of Calvert Bluff interchannel basins are the Des Allemands-Barataria and Atchafalaya basins (fig. 15). The Des Allemands-Barataria basin lies between levee and meanderbelt deposits formed by the modern Mississippi River and an older Mississippi river course now occupied by Bayou Lafourche (fig. 17). Developed is a coastward zonation from cypress-gum swamp to freshwater marsh through saline marsh and an interconnected lake system. Peat is best developed far from the contaminating influence of active channels and inland from the destructive effects of the Gulf. Maximum development is to be expected at the junction of the delta and alluvial plains northwest of Lake Des Allemands (fig. 17). Each thick inland swamp peat may be time correlative with several coastal marsh peats, genetically related to thin overlapped delta lobes (Frazier and others, this volume). Basinward in the Calvert Bluff the number of lignites also increases (fig. 13).

Palynology of Calvert Bluff lignites supports dominantly swamp environments with occasional marsh environments during accumulation (Elsik, this volume). Palynology of the main seam at Alcoa indicates that hardwood swamp and freshwater marsh conditions alternated (Atlee and others, 1968). Southward, at Butler; dominantly marsh conditions are indicated by the palynology where the apparent absence of swamps is consistent with a position lower on the ancient delta system (Kaiser, 1976).

VERTICAL SEQUENCE

Peat accumulation halts when organic accumulation no longer keeps pace with subsidence (averages 1 m per 1,000 years on the Mississippi)

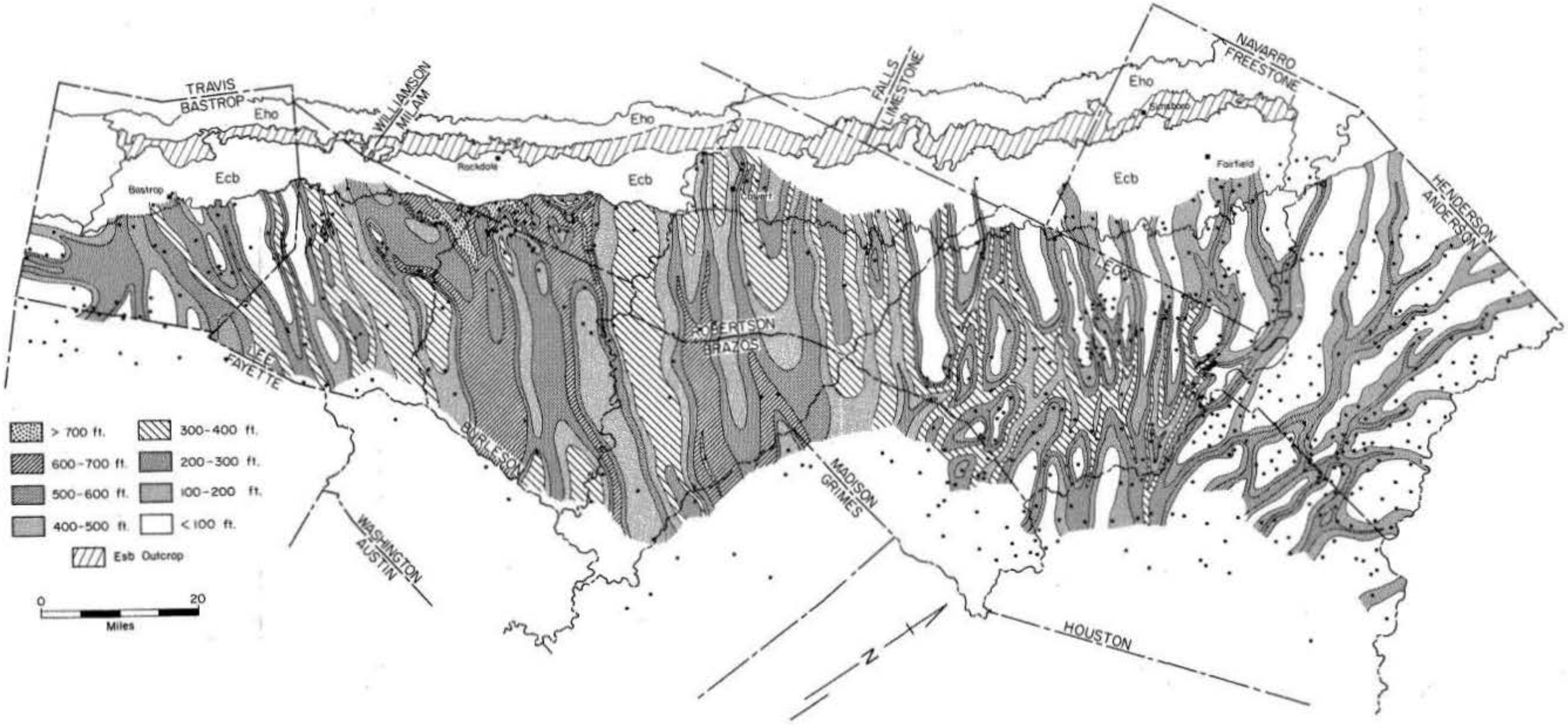

Figure 11. Net sand map of the Simsboro Formation.

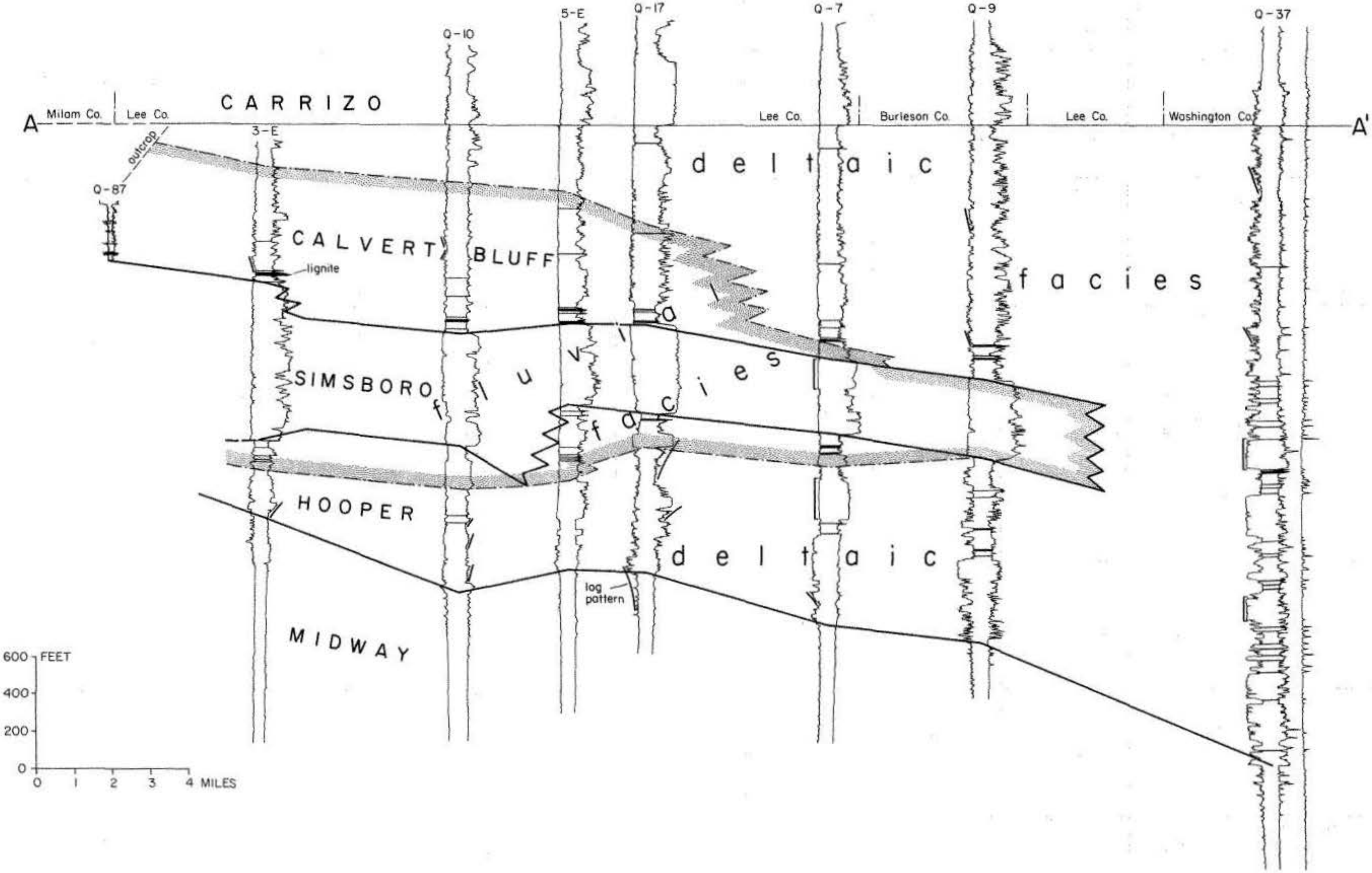

Figure 12. Dip cross section.

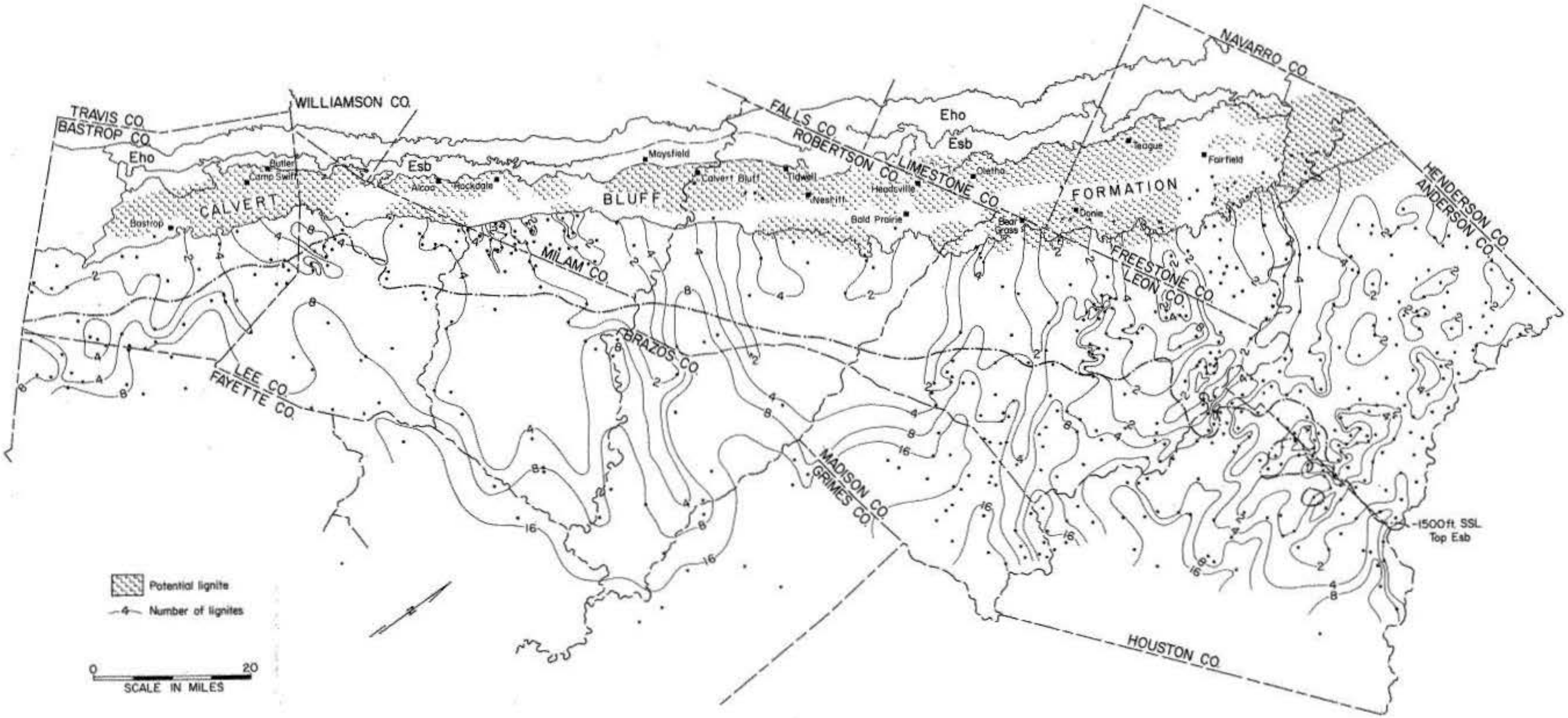

Figure 13. Occurrence of lignite in the Calvert Bluff Formation.

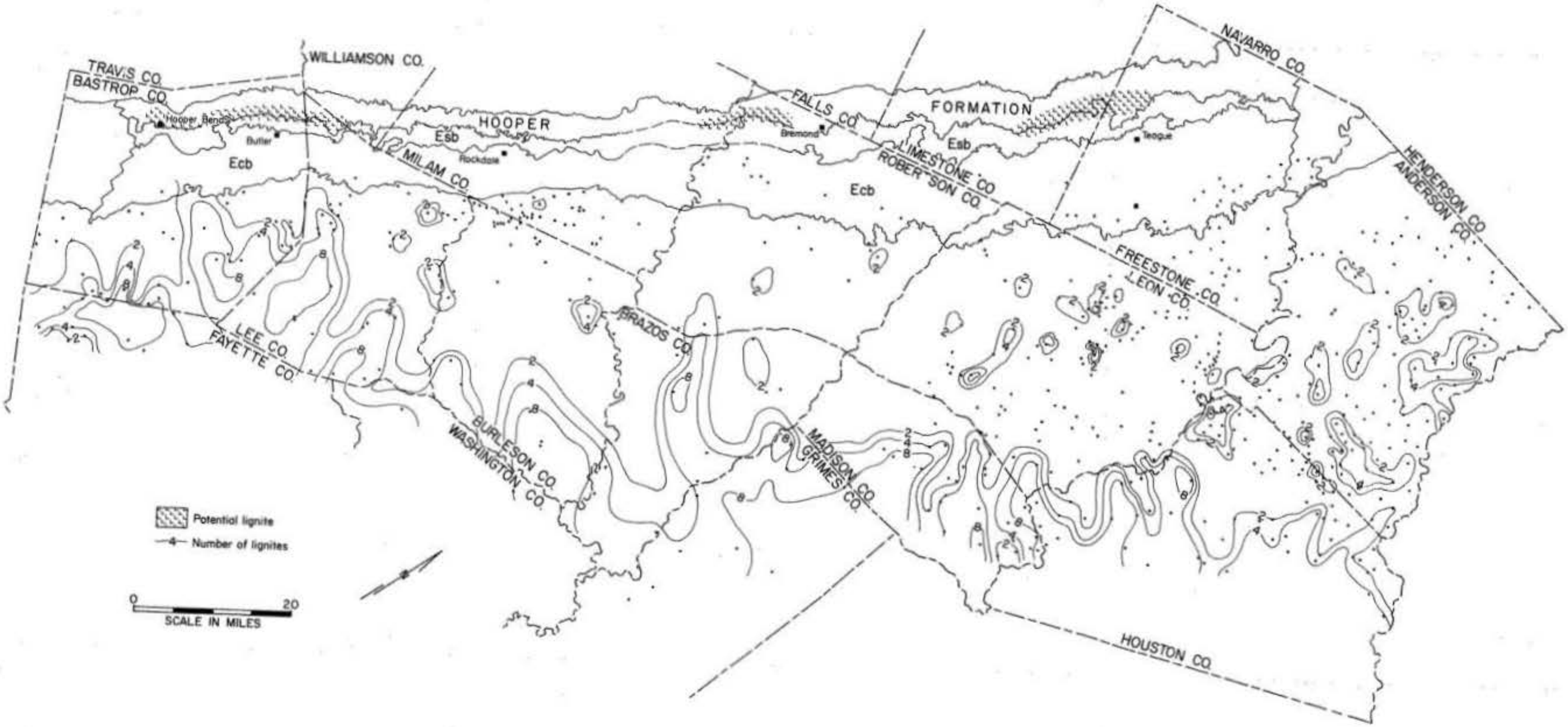

Figure 14. Occurrence of lignite in the Hooper Formation.

or upon major sediment influx. Rapid subsidence triggers the growth of interchannel lakes which drown out the peat-forming vegetation. Deposited initially is fine-grained sediment mainly from suspension during overbank flooding. With the advent of extensive crevassing (breaching or topping of the levee), crevasse splays advance toward the lowest part of the interchannel basin depositing upward-coarsening sediment sequences 3 to 10 m thick (Coleman and Wright, 1975, p. 128-129). Infilling is accomplished by the continued progradation of crevasse splays and lacustrine deltas basinward. Upon the joining of advancing splays and their abandonment, swamps and marshes may again reestablish themselves. Reinitiation of crevassing repeats the cycle. In this manner, a cyclic sequence of coarsening-upward interchannel basin cycles bounded by lignites is generated.

An ideal Calvert Bluff coarsening-upward sequence is approximately 15 m thick and begins with lignite, then passes into clay, mud, interlaminated mud and very fine-grained sand, and finally beds of flat-bedded fine sand. Representative sequences are exposed in the pits at Big Brown, Alcoa, and Butler (Lentz, 1975; Kaiser, 1976). At Big Brown, Lentz called these sequences flood-basin cycles and described two, 4.5 and 11 m thick, in detail. They were fed by extended crevasse distributaries from major streams to the south and northeast. Lentz chose the Atchafalaya basin as a modern analogue of the Big Brown interchannel basin. This choice is appropriate because it occurs higher on the Mississippi system than the Des Allemands-Barataria basin. Likewise, Big Brown occurs higher on the Calvert Bluff system than deposits farther south.

PATTERNS OF SEDIMENTATION

Lignite is found associated with four geophysical log patterns: box, inverted Christmas tree, Christmas tree, and sawtooth. They are defined by either the SP or resistivity curves, or both, and represent six different depositional environments. Overall shape and the nature of excursion from baseline (abrupt or gradual) are the definitive characters. The box pattern is defined by box or blocky SP or resistivity which terminates abruptly top and bottom (fig. 18, wells Q-37 and Q-3). The gradual excursion from baseline of the SP or resistivity upward approximates the silhouette of an inverted Christmas tree (wells 3E and Q-92) and vice versa for the (upright) Christmas tree (Q-213). Rapid excursions of the curves from and to baseline outlines sawteeth (P2).

LOG PATTERNS AND ENVIRONMENTS

In wells Q-37 and Q-3 (fig. 18), thick, massive sands alternate with mud, muddy sand, and lignite. Q-3 differs in that its sands are highly resistive. Depositional environments represented are distributary and interdistributary deposits (Q-37) and fluvial channel and interchannel deposits (Q-3). Well Q-37 is located in the bifurcating distributary channel facies of the lower delta plain, whereas Q-3 is updip in the fluvial channel facies of the lower alluvial/upper delta plain and penetrates the Simsboro-Calvert Bluff contact. Distributary channels typically display low sinuosity and experience abrupt abandonment preserving no major vertical grain-size variation, hence the sharp contacts and box log patterns. Coarse-grained meanderbelt deposits, common to the Simsboro and lower Calvert Bluff, also generate box patterns. In neither environment are lignites expected to be laterally extensive except for the occasional blanket lignite.

Sequences of coarsening-upward grain size with mud at the base grading upward into sand occur in wells 3E and Q-92. Represented in 3E is a cyclic sequence of coarsening-upward interchannel basin cycles (stacked crevasse splays) of the lower alluvial/upper delta plain. Several progradational events are recorded. Lignites in this environment are thick and areally extensive. The 15 to 20 ft lignite of 3E indicates long-term deposition in a large, stable basin. Well Q-92 is in the lower delta-plain facies and the sequences represent delta front deposits recording progradation of the lower Wilcox Hooper over Midway marine muds. Sequences without lignites were deliberately chosen to illustrate the relative importance of lignite in the two environments.

In well Q-213 is a fining-upward sequence with sand at the base passing upward into muddy sand and mud. Channel and overbank deposits of the base and top respectively of a fine-grained meanderbelt deposit are represented. Lignites are likely to be less laterally extensive in this environment than in that of well 3E.

In well P2 there is a rhythmic alternation of sand and mud. Deposition is from traction and

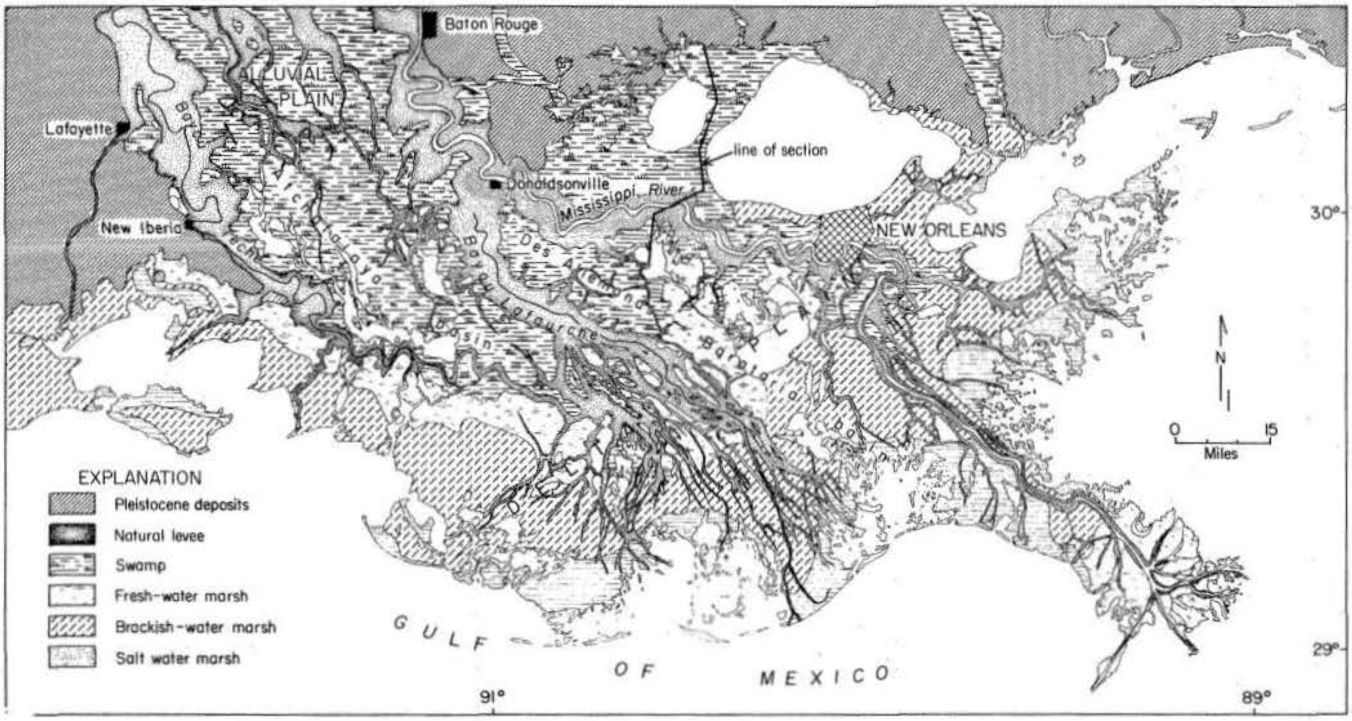

Figure 15. Mississippi delta physiography, from Frazier and Osanik, 1969.

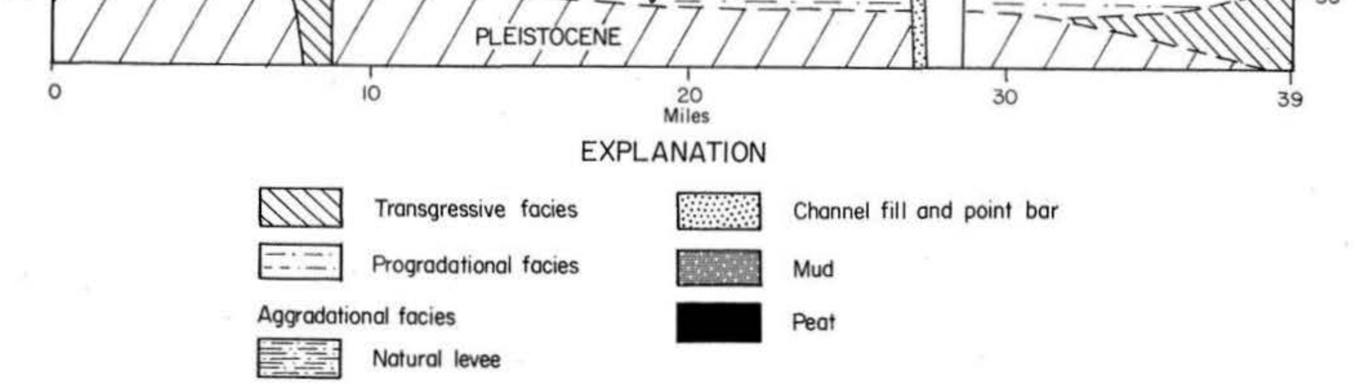

Figure 16. Cross section through Mississippi delta inland swamp peat modified from Frazier and Osanik, 1969. (See figure 15 for location.)

suspension by sand and mud-rich currents generated during repeated overbank flooding. Levee progradation is suggested by thicker sands upward (Elliott, 1974, fig. 1, p. 614). Associated lignites are probably of limited lateral continuity.

APPLICATION

The presence or absence of a particular log pattern is not a reliable way to distinguish between environments. Similar patterns occur in different depositional environments; for example, inverted Christmas trees on the lower alluvial plain and at the delta front. Obviously, to make a correct interpretation, one needs to know the major facies tract—fluvial or deltaic. These tracts are best determined from regional sand geometry. Once facies tracts are established, log patterns become a tool for the reconstruction of ancient environments.

Log patterns are helpful in positioning the imprecise and subjectively drawn boundaries shown between facies tracts on the cross sections (figs. 8 and 12). The boundary between deltaic and fluvial in the Hooper was drawn largely on the change from inverted Christmas tree to box log patterns. Positioning the same boundary in the Calvert Bluff relied heavily on the fact of marine influence in the uppermost Calvert Bluff, hence the implied deltaic facies, and secondarily on log patterns.

EXPLORATION MODEL

On the Mississippi delta system, the Calvert Bluff's modern analogue, the thickest and most extensive peats occur inland at the junction of the alluvial and delta plains. Almost all the Calvert Bluff outcrop and shallow subsurface is similarly located. Only the area south of the Colorado River

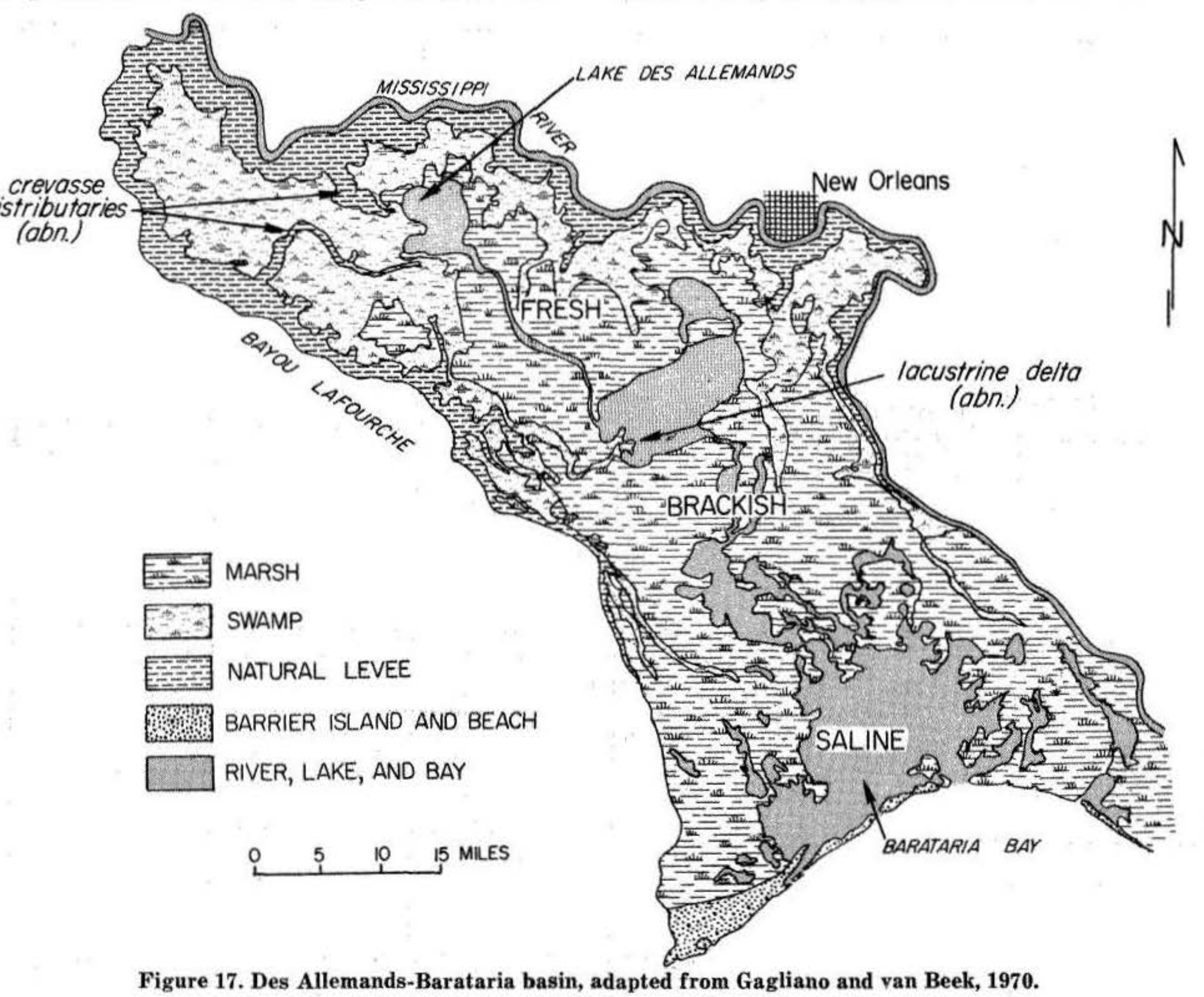

Figure 17. Des Allemands-Barataria basin, adapted from Gagliano and van Beek, 1970.

in southern Bastrop County, off the ancient delta system, is nonprospective.

Exploration for Calvert Bluff lignite should concentrate on low sand areas (low sand percent, low net sand, thin maximum sands) coincident with high lignite count. There is good positive correlation of areas with less than 55-percent sand and more than four lignites (figs. 9 and 13). Deep-basin lignite is prospective to the minus 1,500 ft contour on top of the Simsboro (fig. 13). These areas when projected to the outcrop identify known near-surface (0 to 200 ft) lignite deposits (table 1). Note that central Milam County is not included. Except for the Milano area and a small area north of Rockdale, its potential is relatively lower because it sits astride the highest sand-percent area (values up to 73 percent) in the Calvert Bluff. Regionally three large low-sand areas are shown on the net-sand map: western Anderson–eastern Freestone, northwest Leon, and Robertson–northern Milam Counties (fig. 7). Updip from each of these areas are known lignite deposits; especially large reserves lie in Robertson County from Nesbitt to Headsville (fig. 13).

Exploratory effort in the upper Calvert Bluff should concentrate on those areas where the maximum sands are less than 50 ft thick (fig. 10). Promising areas appear to be McDade, Blue, Milano, Owensville, Turlington, and Cayuga (fig. 10). Upper Calvert Bluff lignite was mined in the past at Hicks, Bear Grass, and Donie. The maximum sand map is a useful exploration tool and

Table 1. Identification of near-surface lignite deposits.

Coincident Areas ($< 55\%$ sand and > 4 lignites)	Projected Areas (Near-surface deposits)
Western Anderson-eastern Freestone	Trinity River alluvial plain, Big Brown (Fairfield northeast)
South-central Freestone	Donie northeast, Teague
Northwest Leon	Bear Grass
Southwest Robertson	Calvert Bluff, Tidwell
Northwest Milam	Maysfield-Calvert Bluff
Southwest Milam	Alcoa
Lee-northern Bastrop	Butler northeast
Northern Bastrop	Bastrop-Camp Swift

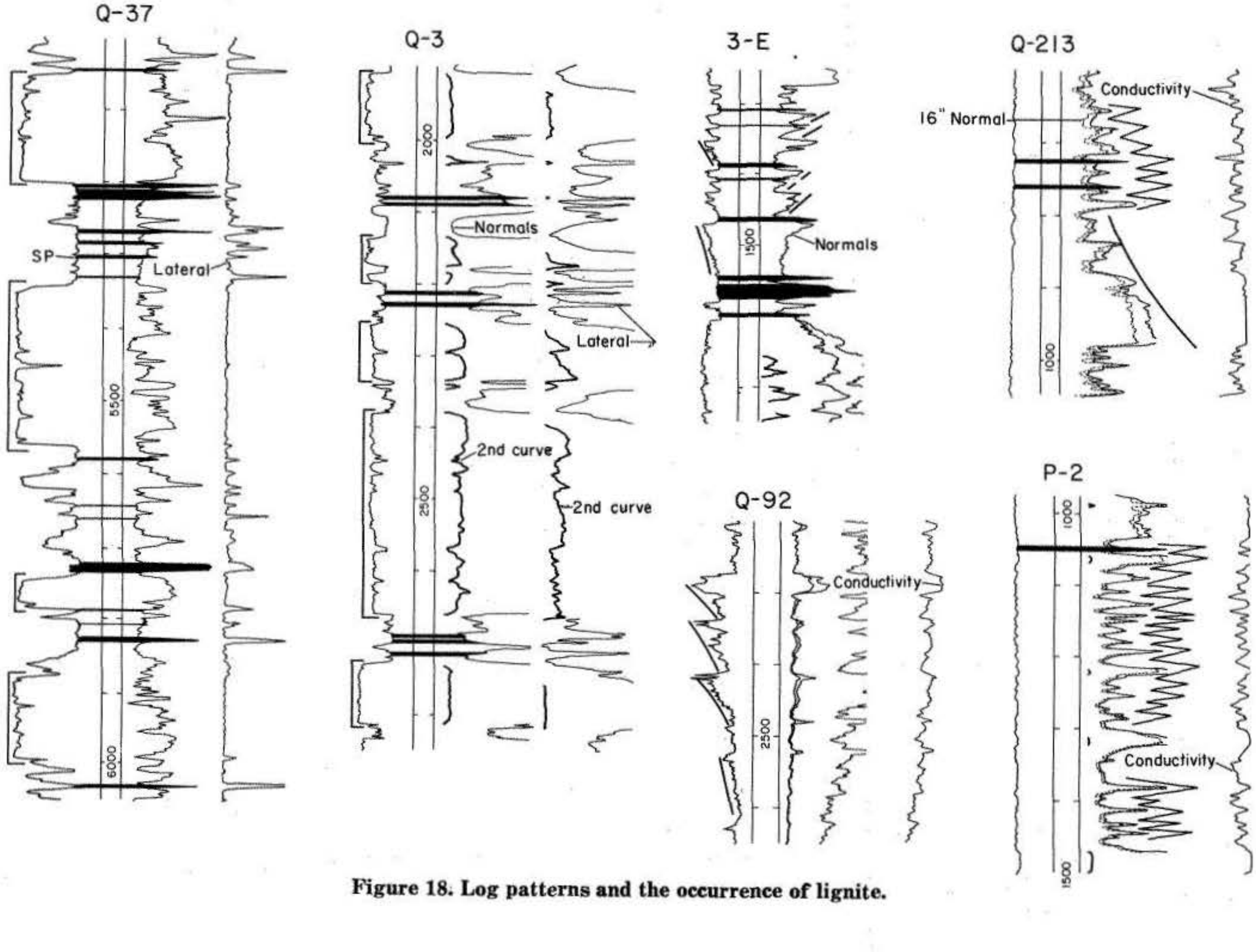

Figure 18. Log patterns and the occurrence of lignite.

should be made routinely; it can be quickly made because time-consuming sand calculations and detailed stratigraphic correlation are not necessary.

Once drilling starts, log patterns might be a guide to future drilling. Scant data suggest that inverted Christmas trees, representing coarsening-upward interchannel basin cycles, are the best guide to commercial deposits (fig. 19). It might even be useful to map the distribution of the four log patterns (fig. 18).

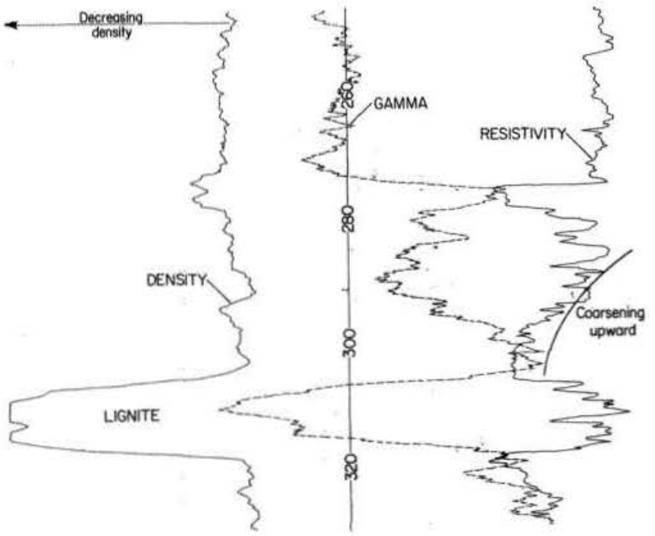

Figure 19. Juxtaposition of an inverted Christmas tree and a commercial lignite seam on an exploration log (Robertson County).

All major near-surface deposits can be identified using the model outlined. Significantly this was done with almost no logs specifically used for lignite exploration such as shallow density logs, but with old logs to be found in the files of every major energy company. In this study the sand-percent map gave the best correlation of sand geometry and lignite occurrence. This map minimizes the effect of downdip thickening. There was a poorer correlation of Calvert Bluff net sand and no apparent correlation of Simsboro net sand and lignite occurrence.

Finally, good resource estimates can be made without data from extensive shallow drilling (density logs) by combining knowledge of depositional systems, stratigraphic occurrence, location of major sand bodies at the surface and in the subsurface (fig. 20), regional dip, and geologic intuition (Kaiser, 1974).

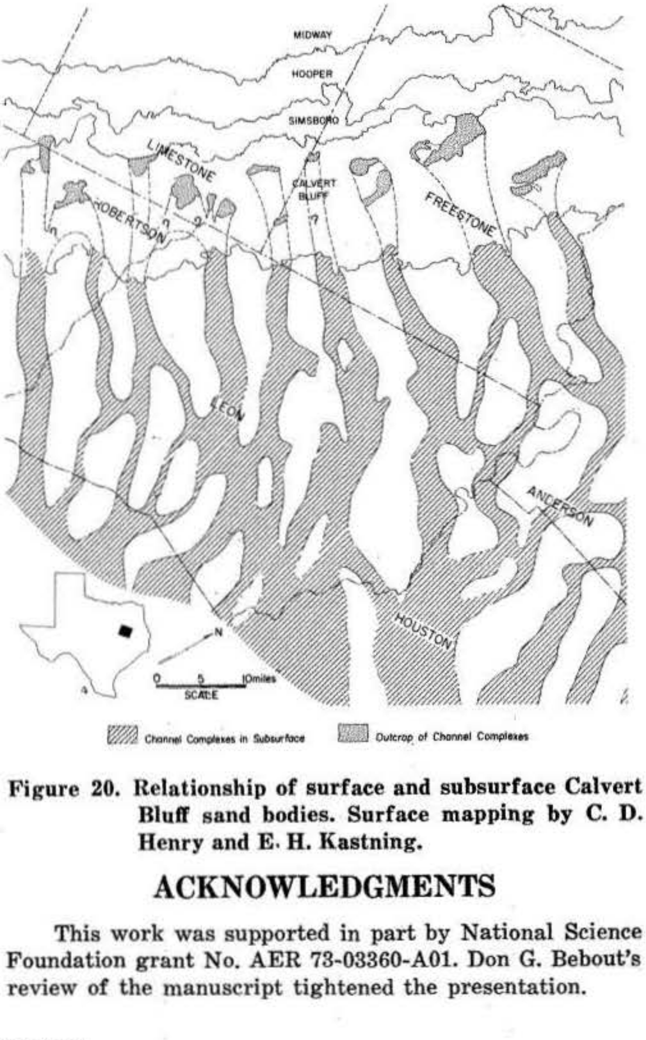

Figure 20. Relationship of surface and subsurface Calvert Bluff sand bodies. Surface mapping by C. D. Henry and E. H. Kastning.

ACKNOWLEDGMENTS

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THE TERTIARY LIGNITES OF MISSISSIPPI

D. R. Williamson[1]

ABSTRACT

Lignite is present in the Tertiary sediments of Mississippi in potential commercial quantity and quality. The Mississippi Tertiary lignites are found principally in two geologic horizons of the Eocene series—the Wilcox Group and the Claiborne Group.

The sediments of the Wilcox and Claiborne Groups crop out in narrow arcuate bands through north-central and east-central Mississippi. The area of outcrop occupies all or portions of 33 of the State's 82 counties and covers an area of approximately 12,578 square miles.

The lignites are present, at strippable depths, as tabular, discontinuous, irregularly shaped deposits overlain by unconsolidated sands, silts, and clays. Lignite seam thicknesses vary from a few inches along the margins of deposits up to 10 to 12 ft at the center of really restricted basins. Lignite seams 4 to 7 ft in thickness are more common.

The quality of Mississippi lignites is generally good. Moisture content is high, varying from 40 to 45 percent; sulfur content is usually less than 1 percent in cored samples; ash content is variable, but averages about 16 percent. Mississippi lignite samples generally vary from 4,800 to 5,500 Btu/lb on an as-received basis.

Lignite apparently has a future in the economic growth of Mississippi as a potential energy source. To date at least six energy-producing companies have conducted lignite exploration programs in Mississippi, concentrating on the Wilcox trend. Since mid-1973 approximately 450,000 acres have been leased for lignite in Mississippi.

INTRODUCTION

Lignite deposits have been reported in sediments of the Cretaceous and Tertiary Systems of Mississippi (Williamson, 1976). These deposits are best developed in the Tertiary sediments where they occur principally in two stratigraphic horizons of the Eocene Series—the Wilcox Group and the Claiborne Group (fig. 1). This discussion is primarily concerned with the near-surface occurrence of Wilcox and Claiborne lignites because of their potential commercial importance.

LOCATION AND EXTENT OF OUTCROP AREA

The outcrop belts of the Wilcox and Claiborne Groups form narrow arcuate bands in Mississippi (fig. 2). The area of outcrop extends from the Mississippi-Tennessee State line in the north, through the central part of the State to the Alabama-Mississippi boundary on the east. The outcrop area encompasses all or portions of 33 of the State's 82 counties and covers approximately 12,578 square miles.

LIGNITES OF THE WILCOX GROUP

The Mississippi lignites of greatest apparent economic value are associated with the interbedded sands, silts, and clays of the Wilcox Group. Wilcox sediments crop out in 21 counties in the State and cover nearly 4,075 square miles. The outcrop belt varies from 1 to 10 miles in width in the northern part of the State. Its width increases to approximately 25 to 30 miles near the Alabama-Mississippi State line.

In Mississippi, the outcropping Wilcox is composed predominantly of nonmarine sediments deposited on a broad, flat coastal plain. These sediments are about 700 ft thick in Lauderdale County near the Alabama line but thin rapidly to less than 100 ft at the Tennessee line. Downdip

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[1] South Louisiana Production Company; Lafayette, Louisiana 70505.

from the outcrop, the Wilcox becomes deltaic and lagoonal and thickens to approximately 3,500 ft in southwestern Mississippi where it is a prolific oil producer.

The Wilcox, according to Rainwater (1964), can be subdivided in Lauderdale and Kemper Counties where the marine Nanafalia (lower Wilcox) and the Bashi Marl (upper Wilcox) crop out as follows:

1. Hatchetigbee Formation: Nonmarine; 200 ft thick.
2. Bashi Member: Shallow marine; 20 ft thick.
3. Tuscahoma Formation: Nonmarine; 400 ft thick.
4. Nanafalia Formation: Shallow marine; 100 ft thick.

However, in the north-central and northern portions of the State, the use of Wilcox undifferentiated is preferred due to the complexity of the fluvial and transitional sedimentary sequences that are present.

Evidence indicates a low-lying, near-coastal depositional environment for the lower Wilcox lignites. The occurrence of dinoflagellates and acritarchs and their restriction to the carbonaceous underclays of a Nanafalia lignite from Kemper County have been reported (Stewart, 1971). A low-lying, near-coastal position has been suggested for the depressions in which these underclays originated due to the interpretation of the microfossils as representing cysts of certain marine plankton.

Interpreting the palynology of a Tuscahoma lignite from Kemper County, Warter (1965) stated that

> the pollen and spore assemblage supports the theory that the lower Eocene Mississippi embayment area was a subtropical, humid, coastal plain occupied by a strand and lowland swamp flora, whereas the inland foothills of the southern Appalachians supported an upland forest of more temperate aspect.

The Wilcox of Mississippi is characterized by small, multiple (stacked) lignite deposits of erratic seam thickness rather than thick, blanketlike seams of large areal extent and uniform thickness. Lignites of the Wilcox Group appear to be irregular in shape, varying from narrow sinuously elongate fluvial deposits to roughly elliptical deposits of deltaic origin. Individual lignite seams are tubular, discontinuous, and unpredictably irregular in extent.

Seam thicknesses vary from a few inches along the margins of deposits to as much as 10 to 12 ft at the center of downwarped basins. The presence of lignite seams thicker than 10 ft ap-

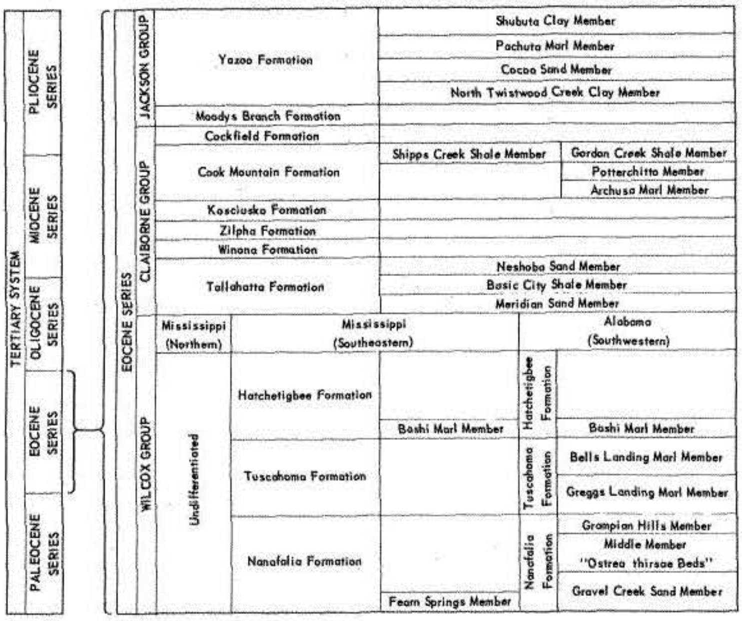

Figure 1. Generalized geologic column of the Eocene stratigraphy of Mississippi.

parently is exceptional and represents basin lows of limited areal extent. Lignites 4 to 7 ft in thickness are more common. These thicknesses are based on the study of near-surface (0 to 300 ft) lignites. Also, the possibility of thicker lignites at greater depths should not be ignored.

It is not unusual to find lignite seams grading laterally into carbonaceous clays within short distances. Splits and channel washouts are also common. Occasionally channel features developed in the Wilcox and the associated lignitized plant matter are observed (fig. 3).

Wilcox lignites were sampled by Hughes (1958) in Kemper County for petrographic analysis (fig. 4). The following comments concerning the composition of the lignites were made.

> Four thin sections of lignites of Kemper County were examined in the Special Coal Research Sections of the U. S. Bureau of Mines. The representative thin section [fig. 4] was thoroughly examined and found to be very similar to that of humic attrital coal. The predominant petrographic constituent is finely divided, translucent humic matter. In the thin section this appears as a light-brown to black ground mass, depending on the degree of translucency. The particles comprising the ground mass are generally without distinct structural form, but some thin fibrous particles with residual cellular details are recognizable . . . . The lignite . . . has its origin from woody plant remains subjected to intense biochemical decay, resulting in extreme maceration of plant debris during the peat stage.

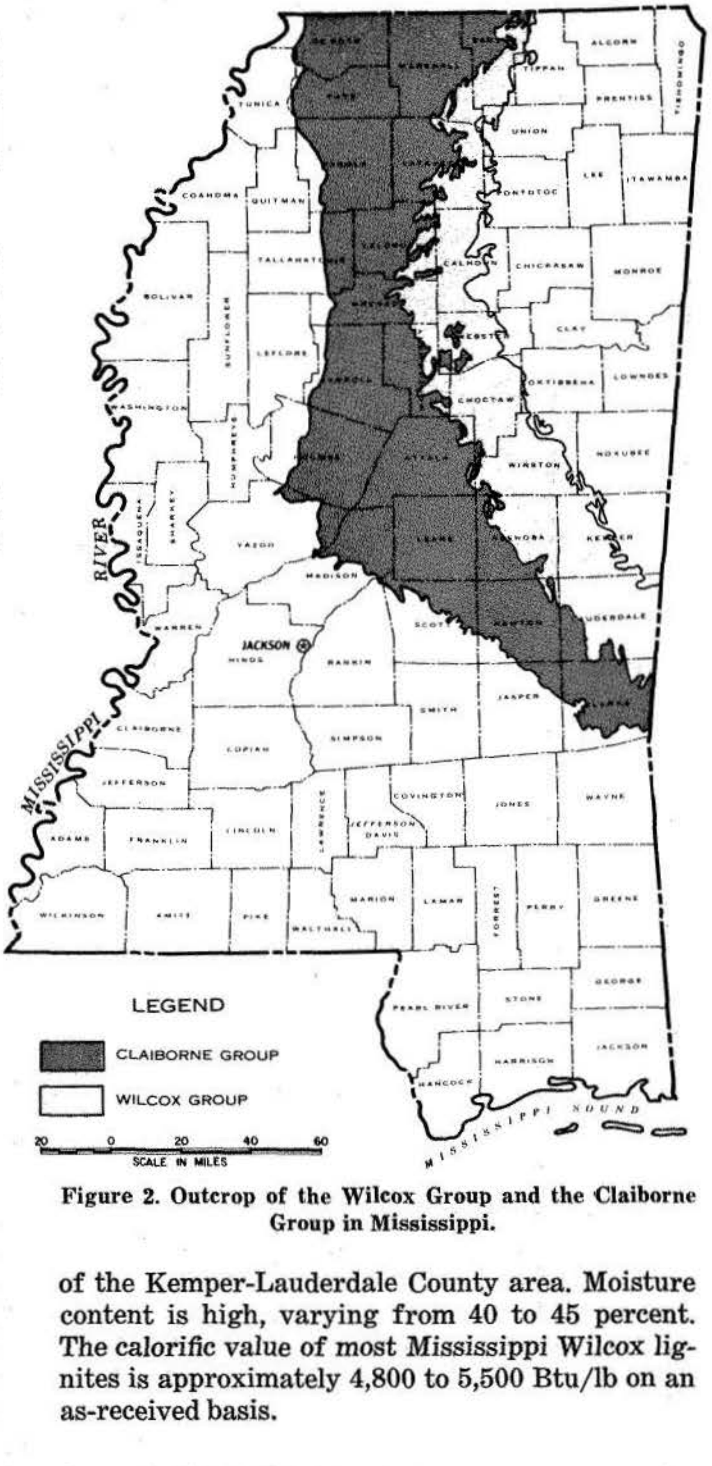

Figure 2. Outcrop of the Wilcox Group and the Claiborne Group in Mississippi.

The quality of Mississippi Wilcox lignites is generally good. Ash content is variable but averages about 16 percent. Sulfur content, on an as-received basis, is usually less than 1 percent in cored samples. The sulfur content appears to increase from the northern part of the State southeast toward the increasingly marine environments of the Kemper-Lauderdale County area. Moisture content is high, varying from 40 to 45 percent. The calorific value of most Mississippi Wilcox lignites is approximately 4,800 to 5,500 Btu/lb on an as-received basis.

LIGNITES OF THE CLAIBORNE GROUP

The outcrop of the Claiborne Group covers approximately 8,503 square miles in Mississippi. The outcrop belt varies from 65 to 45 miles in width in the northwestern part of the State, thins to 15 miles in width in the central part, bulges to the southwest to a width or 60 miles, and thins to a width of approximately 15 to 20 miles near the Alabama-Mississippi State line (fig. 1).

The Claiborne lignites are similar in nature to those of the Wilcox Group and are found principally in sediments of the Cockfield (Yegua) Formation. Fewer lignites are reported in the Zil-

Figure 3. A small channel feature developed in the Wilcox and the associated lignitized plant matter. SW/4, SE/4, Sec. 33, T.7N., R.17E., Lauderdale County, Mississippi.

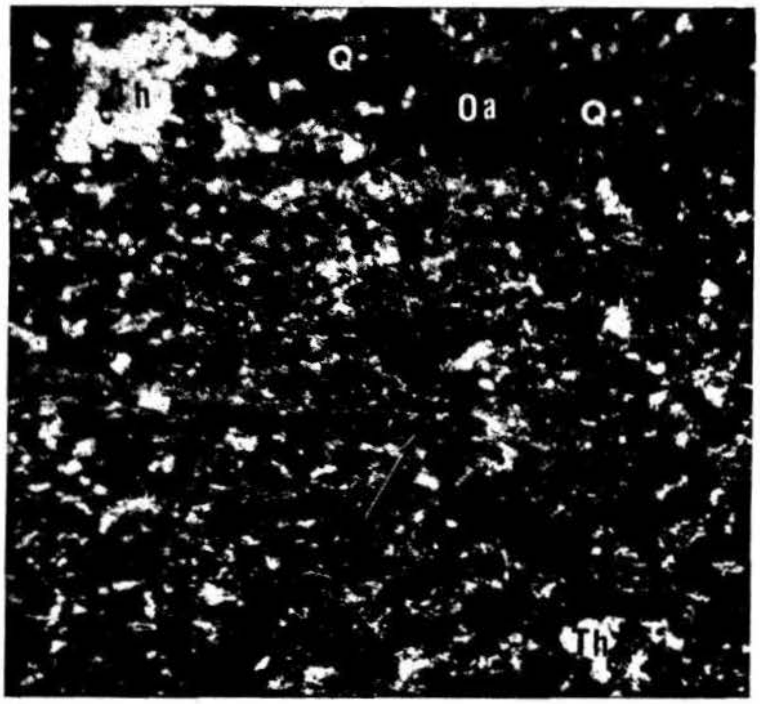

Figure 4. Photomicrograph of lignite showing: small quartz grains (Q), opaque attritus (OA), and small masses of translucent humic matter uncrossed nicols, X63. SE/4, NE/4, Sec. 4, T.9N., R.17E., Kemper County, Mississippi (From Hughes, 1958).

pha, Kosciusko (Sparta), and the Cook Mountain Formations.

Depositional conditions during Claiborne time were much like those of the Wilcox, but perhaps on a smaller scale. The Claiborne sediments are the result of at least two cycles of deposition (Bornhauser, 1947). The first (lower) of these cycles is represented by a basal transgressive phase, the Tallahatta and Winona Formations; a middle *inundative shale, the Zilpha Formation;* and a regressive unit, the Kosciusko Formation.

The second (upper) sedimentary cycle is characterized by a basal transgressive unit, the Cook Mountain limestones; an inundative phase, the shales of the Cook Mountain; and a regressive phase, the Cockfield Formation.

The Mississippi Claiborne lignites are best developed in the sediments of the Cockfield Formation. Payne (1970) studied the pattern of sand concentration and thickness in the Cockfield Formation of the Louisiana-Mississippi-Texas area. He noted lineal distribution patterns trending north and northeast, generally normal to the presumed Cockfield (Yegua) strandline. Payne interpreted the sediment-distribution pattern to be that resulting

> from deposition in the intricate system of channels and intervening swamps, marshes, and lakes developed in the delta and fluvial plain area of an ancestral Mississippi River.

Lithologically the Cockfield is similar to the Kosciusko Formation. Generally the basal section of the formation is composed of massive to cross-bedded sands. The upper part of the section becomes more and more shaley through a gradual transition until carbonaceous lignitic shaley clays predominate. Lignite is abundant in the Cockfield. Sands are frequently lignitic, and lenses of lignitic leaf-bearing clays are often observed. Lignite seams as thick as 5 ft have been noted. Cockfield lignites, like others of the Claiborne Group, are black to brown, impure, and generally thought to be of small areal extent.

Compared to the Wilcox lignites, the Claiborne lignites are not as well developed. They are frequently high in ash and subsequently low in heating value. The Claiborne lignite trend has not been investigated in sufficient detail to provide the necessary control data for a reliable evaluation of its lignite potential.

CONCLUSION

To date at least six energy-producing companies have conducted lignite exploration programs in the State. These exploration efforts have concentrated on the Wilcox trend, although at least one company has begun evaluation of the Claiborne lignites. The Mississippi Geological Survey estimates that approximately 450,000 acres have been leased in the State for lignite since mid-1973. Lignite as a potential energy source apparently has a future in the economic growth of Mississippi.

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LIGNITE RESOURCES OF THE ALABAMA-TOMBIGBEE RIVERS REGION, ALABAMA

D. M. Self[1]

ABSTRACT

The lignite resources of the Alabama-Tombigbee Rivers Region of southwest Alabama exceed 4.7 billion short tons (4.3 billion tonnes). Near-surface deposits having economic potential occur in the Oak Hill Member of the Naheola Formation (Paleocene) and the upper unnamed member of the Tuscahoma Formation (lower Eocene). Demonstrated reserves in the near-surface amount to approximately 562 million short tons (510.9 million tonnes).

The near-surface lignite in the Oak Hill Member generally occurs as a single tabular bed which ranges from 1 to 14 ft (0.3 to 4.3 m) in thickness. Moisture and sulfur content are high; however, ash content is low, and the calorific value may exceed 11,200 Btu/lb (6,222 kcal/kg) on a moisture-free basis.

The lignite of the Tuscahoma Formation occurs in from one to six lenticular beds and is generally inferior to the Oak Hill lignite. The ash content is very high, and the calorific value is correspondingly low.

Deep-basin deposits occur in the Midway and Wilcox Groups; however, only the Midway lignites appear to have economic potential. Demonstrated and inferred resources in deep-basin deposits total over 4.1 billion short tons (3.7 billion tonnes). The lignite of the Midway Group occurs in one to three beds which are apparently equivalent to the near-surface lignite of the Oak Hill Member.

INTRODUCTION

The purpose of this paper is to describe the lignite resources of the Alabama-Tombigbee Rivers Region in southwest Alabama (fig. 1). This region is composed of 10 predominantly rural counties located within the drainage basins of the Alabama and Tombigbee Rivers. Near-surface lignite deposits, located at depths of less than 250 ft (76.2 m) and available to conventional surface-mining methods, occur in the central part of the region, whereas deep-basin lignite deposits occur in the southern half of the region. These deep-basin deposits occur at depths greater than 250 ft (76.2 m) but less than 6,000 ft (1,828 m) and are exploitable only through underground mining or in situ recovery methods.

PREVIOUS INVESTIGATIONS

Since lignite was first reported by Tuomey in 1858, several reports concerning the occurrence and quality of lignite in Alabama have been published. Barksdale (1929) was first to compile a comprehensive report of known lignite occurrences in the State. This report included detailed outcrop descriptions and chemical analyses. Barksdale concluded that the lignite located at the base of the Nanafalia Formation (Oak Hill lignite) was the most important lignite in the State and that the lignite in the Bashi Formation (Tuscahoma lignite) was second in importance. Pallister and Morgan (1950) revised the earlier work of Barksdale (1929) and included previously unpublished data from southeastern Alabama.

Between the years 1964 and 1968, the Geological Survey of Alabama made three surveys of lignite in south Alabama. The results of these studies were published in a series of county mineral resources maps (Daniel, 1969a, 1969b, 1969c, and 1969d) and in *A Strippable Lignite Bed in South Alabama* (Daniel, 1973). Daniel (1973) estimated that there were approximately 2 billion short tons (1.8 billion tonnes) of lignite in near-surface deposits of the Oak Hill lignite bed in Alabama.

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[1] Consolidation Coal Co.; Meridian, Mississippi 39301.

GEOLOGY

Lignite is rather widely distributed in several lower Tertiary (Paleocene and Eocene) formations of the Alabama Gulf Coastal Plain. The principal lignite deposits of the Alabama–Tombigbee Rivers Region occur in the Midway, Wilcox, and Claiborne Groups (fig. 2). Formations of these groups consist mostly of terrigenous clastic sediments which were deposited primarily in transitional and fluvial depositional environments. Several marine transgressions resulted in the deposition of sandy limestones and marls, which are useful as marker beds in this otherwise monotonous clastic sequence.

The Midway Group of Paleocene age is composed of, in ascending order, the Clayton, Porters Creek, and Naheola Formations. Lignite deposits of the Midway Group occur in the Oak Hill Member of the Naheola Formation.

The Naheola Formation is divided into the lower Oak Hill Member and the upper Coal Bluff Marl Member. The lower member, which consists primarily of brownish-gray laminated sandy silt, silty clay, and beds of greenish-gray fine-grained sand, is generally 80 to 150 ft (24.4 to 45.7 m) thick in southwest Alabama. Lignite, ranging in thickness from 1 to 14 ft (0.3 to 4.3 m) is present at or near the top of the member. The Coal Bluff Marl Member disconformably overlies the Oak Hill Member and consists of glauconitic sand and sandy marl with thin-bedded silty clay in the upper part. The Coal Bluff is variable in thickness, ranging from 15 to 30 ft (4.6 to 9.1 m). The Naheola thins rapidly toward the east, and east of Wilcox County, it is included in the Porters Creek Formation.

The Naheola Formation is undifferentiated in the deep subsurface of southwest Alabama. Deep-basin lignite deposits, apparently equivalent to the near-surface Oak Hill lignite, were previously interpreted as marking either the top of the Midway or base of the Wilcox Group. In this report, these deposits are considered to mark the top of the Midway Group.

The Wilcox Group is considered to be early Eocene in age and disconformably overlies the Coal Bluff Marl Member of the Naheola Formation. The Wilcox Group is divided into three formations which are, in ascending order, the Nanafalia Formation, the Tuscahoma Sand, and the Hatchetigbee Formation. Lignites of the Wilcox Group are found primarily in the upper, unnamed, nonmarine member of the Tuscahoma Sand; however, thin, less continuous deposits of lignite also occur in the lower part of the Nanafalia Formation and in the Hatchetigbee Formation.

The Nanafalia Formation, the lowest formation in the Wilcox Group of Alabama, has been divided into three members: the Gravel Creek Sand Member at the base, the *"Ostrea thirsae* beds," and the Grampian Hills Member at the top. The Gravel Creek Sand Member consists of as much as 40 ft (12.2 m) of coarse-grained cross-bedded fluvial and beach sand containing fine quartz gravel and clay pebbles. This member is thicker updip, pinches out downdip, and is locally absent.

The middle unnamed member of the Nanafalia Formation is referred to as the *"Ostrea thirsae* beds." This member consists of 30 to 60 ft (9.0 to 18.0 m) of glauconitic quartz sand and glauconitic sandy marl containing the guide fossil, *Odontogryphaea thirsae* (Gabb). The overlying Grampian Hills Member ranges from 10 to

Figure 1. Index map of the Alabama-Tombigbee Rivers Region of southwest Alabama.

150 ft (3.0 to 45.6 m) in thickness and consists of marine glauconitic sandy clay and dark-gray massive clay with lenses of glauconitic sand.

The Tuscahoma Sand ranges from 250 to 350 ft (76.2 to 106.4 m) in thickness and consists primarily of nonfossiliferous gray interlaminated and interbedded fine-grained sand and clayey silt. The lower half of the formation is marked by two or more thin zones of fossiliferous glauconitic sand and marl. These zones are considered to be separate members of the Tuscahoma Sand and are termed the Greggs and Bells Landing Marl Members. One to six relatively thin seams of lignite occur in the upper nonmarine member of the Tuscahoma Sand.

The Hatchetigbee Formation, the uppermost formation of the Wilcox Group in Alabama, is composed of the Bashi Marl Member and an upper unnamed member. The Bashi Marl Member, which ranges from 2 to 25 ft (0.6 to 7.6 m) in thickness, consists of very fossiliferous, glauconitic, calcareous sand in which large calcareous sandstone concretions occur.

The upper unnamed member of the Hatchetigbee Formation is composed of gray to olive interlaminated and interbedded fine-grained sands and silty clays, and some lighter colored loose sand, all of which are similar to beds of the underlying Tuscahoma Sand. The Hatchetigbee Formation is 250 ft (76.2 m) thick in the extreme western part of the region and thins to the east. Several thin seams of lignite occur within this upper member.

The Tallahatta Formation, the lowermost formation in the Claiborne Group of middle Eocene age, disconformably overlies the Hatchetigbee Formation. In western Choctaw County, the Hatchetigbee and the Tallahatta Formations are separated by a thin wedge of the Meridian Sand which extends eastward from Mississippi into Alabama.

The Tallahatta Formation is typically composed of 100 to 125 ft (30.4 to 38.0 m) of pale-green marine siliceous claystone with some interbedded glauconitic sand and sandstone. East of Clarke County, Alabama, the middle and upper parts of the formation become more sandy and fossiliferous. The claystone of the Tallahatta Formation, termed "buhrstone" in early reports, is resistant to erosion and forms a prominent cuesta which has been dissected into a range of rugged hills.

The Lisbon Formation conformably overlies the Tallahatta Formation and throughout most of the area consists of about 200 ft (60.8 m) of very fine- to coarse-grained glauconitic, fossiliferous sand with indurated calcareous layers, sandy clay, and marl. This marine sequence intertongues in western Choctaw County, Alabama, with a predominantly nonmarine sequence of sands and clays. Lignite and lignitic clay occur in some of these terrestrial deposits.

The Lisbon Formation is disconformably overlain by the Gosport Sand, which is the uppermost formation in the Claiborne Group. The Gosport Sand is composed of 17 to 30 ft (5.2 to 9.2 m) of fine- to coarse-grained glauconitic, very fossiliferous sand and lenses of carbonaceous shale. At least two very thin lenticular beds of lignite

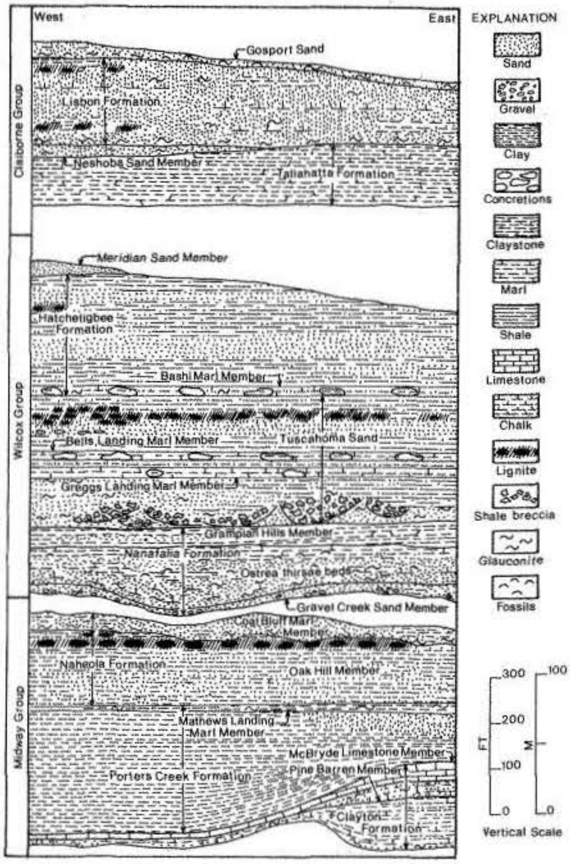

Figure 2. Generalized diagram showing the thickness and lithology of the lignite-bearing formations of the Alabama-Tombigbee Rivers Region (modified from La Moreaux and Toulmin, 1952).

have been reported in the Gosport in Monroe County, Alabama. The formations of the Claiborne Group are, in turn, overlain by formations of the Jackson (Upper Eocene) and Vicksburg (Oligocene) Groups and various formations of the Miocene and Pliocene Series.

LIGNITE RESOURCES

Although lignite is rather widely distributed in the lower Tertiary formations of southwest Alabama, lignite deposits possessing economic potential occur only in the Oak Hill Member of the Naheola Formation, in the upper nonmarine member of the Tuscahoma Formation, and in their subsurface equivalents. Since the formations composing the Midway and Wilcox Groups are not easily differentiated in the subsurface, the lignites occurring in the deep subsurface will be referred to as either Midway or Wilcox lignites (fig. 3). The lignite which occurs in the Hatchetigbee and Lisbon Formations in the western part of the region and the Gosport Sand in the central part of the region is either too thin or discontinuous to be of economic significance.

NEAR-SURFACE DEPOSITS

One seam of lignite (or rarely two) occurs in the upper few feet of the Oak Hill Member of the Naheola Formation. Where present, the upper seam averages about 0.5 ft (0.1 m) in thickness and is separated from the lower seam by approximately 3 ft (0.9 m) of laminated, carbonaceous sand, silt, and clay (Newton, Suttcliffe, and LaMoreaux, 1961). The lower seam ranges from 1 to 14 ft (0.3 to 4.3 m) in thickness and is the most continuous lignite seam in Alabama. The near-surface reserves and resources of this bed occur in a belt that extends from Mississippi southeastward across Sumter, Choctaw, Marengo, and Wilcox Counties in Alabama. The belt may be as wide as 8 miles (12.8 km). East of the Alabama River in Wilcox County, the bed thins and pinches out. The lignite is apparently not present east of Camden, Wilcox County (LaMoreaux and Toulmin, 1959; Daniel, 1973). The Oak Hill lignite lies atop a nonmarine laminated to thinly bedded carbonaceous sand, silt, and clay sequence (MacNeil, 1946; Rainwater, 1964). The lignite is generally overlain by a similar nonmarine clastic sequence; in some areas of Marengo County, subsequent erosion has removed these uppermost beds of the Oak Hill Member and marine glauconitic sands and marls of the Coal Bluff Marl Member are in direct contact with the underlying Oak Hill lignite.

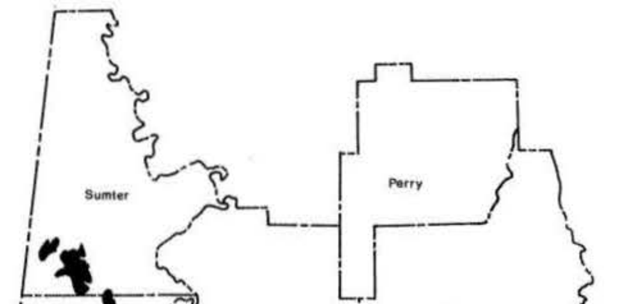

Figure 3. Distribution of lignite in the Alabama-Tombigbee Rivers Region, Alabama.

The lignite of the Oak Hill Member is classified as lignite A, nonagglomerating. Samples obtained by Daniel (1973) and as a part of the present study indicate that the calorific value of the Oak Hill lignite in southwest Alabama ranges from 4,020 to 11,240 Btu/lb (2,233 to 6,244 kilogram-calories per kilogram [kcal/kg]) and averages 8,992 Btu/lb (4,996 kcal/kg) on a moisture-free basis. The calorific value is generally high throughout most of the region; however, in western Wilcox County, the heating value shows a marked decrease just before the lignite pinches out. This decrease in heating value is directly related to an increase in ash toward the eastern end of these deposits. Throughout most of it, however, the Oak Hill lignite averages less than 16-percent ash. Its free-swelling index number is zero.

Moisture content is high, ranging from 45.2 to 53.3 percent on an as-received basis; however, Daniel (1973) indicates that air drying of samples of Oak Hill lignite reduced moisture content to less than 10 percent. The sulfur content is also high, ranging from 1.6 to 6.28 percent on a moisture-free basis (Daniel, 1973). Sulfate (SO_4^{2-}) averages 12.3 percent of the total sulfur, whereas organic and pyritic sulfur comprise 45.8 and 41.9 percent, respectively. The overburden, which consists primarily of unconsolidated sand, sandy silt, and clay, may also have a high sulfur content. The pH of composite overburden samples submitted to Auburn University Soil Testing Laboratory for analysis ranged from 2.4 to 3.6 and averaged 3.1. Major and minor oxide and trace-element analyses performed on the lignite ash and "whole coal" indicate that there are no anomalous concentrations of potentially harmful trace metals.

Assuming a recovery rate of 85 percent, demonstrated reserves of the Oak Hill lignite total approximately 282 million short tons (256 million tonnes[2]). Demonstrated subeconomic resources total more than 226 million short tons (205 million tonnes). The variability of the shape and thickness of the Oak Hill lignite precludes the estimation of inferred reserves; however, they would probably equal several times the demonstrated reserves and subeconomic resources.

The presence of nonmarine sediments above and below the lignite and the physical characteristics of the lignite suggest a nonmarine origin. The low-ash content, moderate to high sulfur content, general tabular shape, and large areal extent indicate that deposition occurred in a low-energy environment away from the contaminating effects of active streams or distributaries and inland from the destructive effects of the Gulf of Mexico. The relatively high sulfur content, however, indicates the apparent presence of brackish water. Such an environment is found on an abandoned, inactive delta lobe in which peat accumulation keeps pace with delta foundering (Coleman and Smith, 1964). Fisher and McGowen (1967) and McGowen (1968) interpreted similar extensive lignites in the Wilcox Group of Texas to be a regional, landward facies of marine delta destruction.

The near-surface deposits of the Tuscahoma lignite occur in a belt that generally parallels the outcrop of the Oak Hill lignite and occurs approximately 17 miles (20.4 km) to the south. The Tuscahoma lignite occurs in a zone located approximately 50 ft (15.2 m) below the Tuscahoma-Hatchetigbee contact. The lignite occurs in from one to six relatively thin lenticular seams; however, in Choctaw, Clarke, and western Wilcox Counties, the Tuscahoma lignite is apparently continuous under relatively large areas and, at least locally, may exceed 60 inches (152.4 cm) in thickness.

The calorific value of the Tuscahoma lignite is rather low, ranging from 2,400 to 9,270 Btu/lb (1,333 to 5,150 kcal/kg). The average calorific value on a moisture-free basis is 5,818 Btu/lb (3,232 kcal/kg). The ash content of the lignite of the Tuscahoma Formation is uniformly high, averaging 40.6 percent. The sulfur content averages 2.9 percent and ranges from 2.0 to 6.05 percent. Sulfate comprises approximately 24.8 percent of the total sulfur, and organic sulfur makes up 44.6 percent. Pyritic sulfur accounts for the remaining 30.6 percent of the total sulfur. The overburden of the Tuscahoma lignite is apparently rather high in sulfur content, as indicated by its generally low pH which ranges from 3.3 to 6.0 and averages 4.1. Trace-element analyses of the Tuscahoma lignite indicate that these lignites are more variable in their trace-metal content than that of the Oak Hill. Possible anomalies were noted in copper, thorium, arsenic, and selenium; however, concentrations of these elements were quite low with only copper exceeding 20 parts per million (ppm). The free-swelling index number of all samples was 0.

Demonstrated reserves of lignite total 7.3 million tons (6.6 million tonnes) using a recovery factor of 85 percent. Demonstrated subeconomic resources total approximately 47 million tons (42.7 million tonnes). Inferred estimates were not made because of the very limited lateral extent of these lenticular beds.

The Tuscahoma lignite generally occurs within a sequence which Fisher (1964) has interpreted as regressive nonmarine, laminated to very thinly bedded carbonaceous sands, silts, and clays. These sediments are generally unfossiliferous; however, locally they may contain abundant fragments of

[2] Tonne or metric ton equals 2204.62 lb.

silicified wood. At least one probable paleo-soil horizon was penetrated during exploratory drilling, and several relatively clean fine sands, which are here interpreted as channel sands, were also penetrated. The sulfur content of the lignite is somewhat lower than that of the Oak Hill (2.9 percent as opposed to 4.4 percent). The stacked lignite beds, lenticular form, high ash content, and lower sulfur content, coupled with the presence of silicified wood and fossil soils, are indicative of deposition between the distributary channels of an actively prograding delta lobe. The presence of silicified wood, relatively lower sulfur content, and variable nature of the lignites indicate a relatively higher position on the delta plain than that of the Oak Hill (Fisk, 1960; Fisher, 1969).

DEEP-BASIN DEPOSITS

Deep-basin lignite deposits occur beneath the southern half of the Alabama-Tombigbee Rivers Region. These deposits are generally overlain by 2,000 ft (609.6 m) or less; however, in Washington County, Alabama, in the southwestern corner of the region, the Midway lignite is buried beneath 3,000 to 4,000 ft (914.4 to 1,291.2 m) of overburden.

An operational definition of lignite was adopted for use with deep-basin deposits; its three elements are the presence of lignite in well cuttings, a sharp resistivity peak, and near-baseline spontaneous potential. The presence or absence of lignite in well cuttings was used to determine the general horizon at which lignite occurs, whereas the geophysical logs were used in determining the number, depth, and thickness of the lignite seams.

The largest and most extensive deposits of deep-basin lignite in southwestern Alabama occur in the Midway Group in Choctaw, Washington, Clarke, and Monroe Counties. No data are available on the quality or physical characteristics of this lignite. The lignite occurs as one to three seams in the upper part of the Midway Group. These seams may exceed 14 ft (4.3 m) in thickness and, where adequate well control is available, appear to resemble near-surface deposits of the Oak Hill in their areal extent. Demonstrated resources total more than 470 million short tons (427 million tonnes), whereas inferred resources exceed 3.7 billion short tons (3.4 billion tonnes). At this time, the lack of adequate well control and apparent irregular shape of these deposits preclude the estimation of inferred resources and undiscovered resources.

Sedimentation patterns interpreted from geophysical logs indicate that the Midway lignites occur in association with probable overbank or delta-plain facies sediments. These sedimentary sequences are characterized by generally baseline spontaneous potential curve and numerous S-shaped resistivity peaks. Progradation (coarsening upward) is apparent on a scale of several hundred feet.

The deep-basin lignite deposits in the Wilcox Group of southwestern Alabama are known only from occurrences in scattered oil and gas wells. On the basis of these limited data, it appears that these lignites rarely exceed 5 ft (1.5 m) in thickness and are less extensive than deep-basin lignites in the Midway Group. Nothing is known of their quality or chemical characteristics. Geophysical and sample logs indicate that these lignites occur in interdistributary and valley fill or overbank deposits (Fisher, 1969; Kaiser, 1974). Lignites occurring in these depositional environments are characteristically lenticular and therefore limited in extent. The generally thin nature and lenticularity of the beds render any estimate of these deposits suspect.

CONCLUSIONS

The near-surface lignite deposits of southwest Alabama constitute a significant energy resource that can be readily utilized to overcome short- and intermediate-term energy shortfalls. These deposits can be mined utilizing existing technology. Deep-basin deposits, although incompletely known, appear to represent an even greater energy resource; however, development of these deposits will depend upon advances in in situ recovery technology or the use of more efficient underground mining techniques.

ACKNOWLEDGMENTS

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LOUISIANA LIGNITE

H. L. Roland, Jr.[1]

ABSTRACT

Some of the lignites in northwestern Louisiana have been mapped and evaluated by the Louisiana Geological Survey under the auspices of the Division of Natural Resources and Energy, Louisiana Department of Conservation. Two areas were investigated: one in southeastern De Soto Parish, the other in west-central Sabine Parish. The most significant result of these surveys was determining that the Chemard Lake lignite lentil has consistent thickness and continuity over a rather large area in southeast De Soto Parish and contains estimated reserves of at least 546 million tons of lignite.

The lignite in Sabine Parish is not as thick or as consistent as that in De Soto Parish. The area mapped contains approximately 50 million tons of lignite.

INTRODUCTION

Lignite is defined by the U. S. Bureau of Mines as "a soft, porous, and carbonaceous material that is the intermediate stage between peat and subbituminous coal." Lignite is also defined as the lowest rank coal having a calorific value less than 8,300 Btu/lb (moist, mineral-matter-free basis). Further, it may be subdivided into "lignite A," having heating values from 6,300 to 8,300 Btu and "lignite B," having heating values less than 6,300 Btu (Sheridan, 1965, p. 511–512).

LOUISIANA RECOVERY

Lignite was recognized in Louisiana as early as 1812. Since that time, the Louisiana Geological Survey has published two bulletins on the subject: one by Glenk (1921) and the other by Meagher and Aycock (1942). The former was primarily a laboratory study, and the latter was a study of the lignite outcrop distribution pattern of northwest Louisiana. The State's high rank in the production of oil and gas for the past 30 years or so has kept the subject of lignite completely out of the picture as far as a source of energy is concerned.

The nationwide "energy crisis" brought about a renewed interest in other forms of energy, including lignite, and funds became available for this type of research.

All of Louisiana's significant known near-surface deposits occur in the northwest part of the State (fig. 1) in the area of the Sabine uplift. This uplift, the most prominent subsurface structural feature of the Gulf embayment region, centers approximately in the area of De Soto Parish and extends in all directions in northwest Louisi-

Figure 1. Location map: lignite survey.

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[1] Louisiana Geological Survey; Baton Rouge, Louisiana 70803.

ana and approximately 50 miles into Texas (fig. 2). This feature is delineated by a large inlier of Wilcox sediments encircled by lower Claiborne deposits.

Lignite occurs chiefly in the Gulf Coast province in the beds of the Wilcox Group (Eocene) and to a lesser extent in the overlying beds of the Claiborne and Jackson Groups of Texas, Arkansas, Louisiana, Mississippi, and Alabama. For purposes of this report, Wilcox is defined as all of the sedimentary beds overlying the Porters Creek clay (Midway) and underlying the Cane River Formation (Claiborne) (fig. 3).

The main area selected for study is in De Soto Parish and is situated on the southwest flank of a rather prominent local structure, the Red River-Bull Bayou domal anticline (fig. 2). As a result of probable thinning due to structural movement contemporaneous with deposition and subsequent erosion, only the two lowermost Wilcox formations are present in the immediate area: Dolet Hills and Naborton. The primary lignite bed is the Chemard Lake lentil which occurs at the top of the Naborton Formation. The Wilcox Group in De Soto Parish ranges from 150 to 500 ft in thickness within the area surveyed.

The secondary area selected for study is located in Sabine Parish on the south plunging part of the Sabine uplift. The Wilcox exposures in this area are structurally 1,500 to 2,000 ft lower than those in southeast De Soto Parish, and the surface and near-surface formations (Pendleton and Hall Summit) are stratigraphically higher in the section. The Wilcox in Sabine Parish ranges in thickness from 1,200 to 2,500 ft.

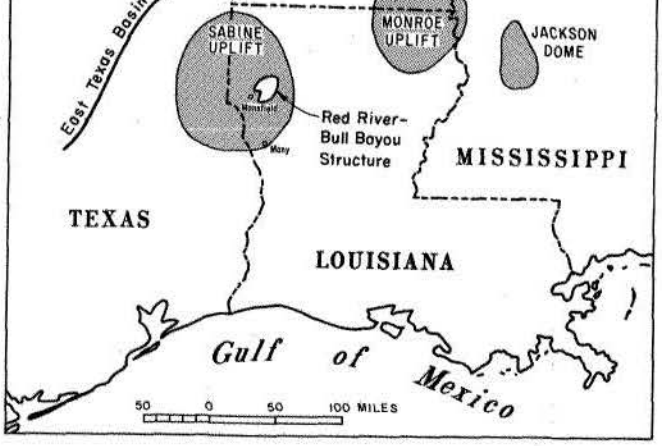

Figure 2. Location map: Sabine uplift and other structures.

ERA	SYSTEM	SERIES	GROUP	FORMATION
CENOZOIC	QUATERNARY	HOLOCENE		Recent Alluvium
		PLEISTOCENE	TERRACE DEPOSITS	Undifferentiated
	TERTIARY	PLIOCENE		Undifferentiated
		MIOCENE		Undifferentiated
		OLIGOCENE		Undifferentiated
		EOCENE	JACKSON	Undifferentiated
			CLAIBORNE	Cockfield
				Cook Mountain
				Sparta
				Cane River
			WILCOX	Carrizo
				Sabinetown
				Pendleton
				Marthaville
				Hall Summit
				Lime Hill
				Converse
				Cow Bayou
				Dolet Hills
				Chemard Lake Lentil
				Naborton
		PALEOCENE	MIDWAY	Porters Creek
				Kincaid
MESOZOIC ERA - CRETACEOUS SYSTEM				

Modified from Andersen, 1960

Figure 3. Stratigraphic chart for study area.

Several lignite beds were located in both surveyed areas. The average overburden is approximately 75 ft.

The most important result of the survey in De Soto Parish was to find that the Chemard Lake lignite occurs with consistent thickness and continuity over a rather large area (fig. 4). Some discontinuity is evident, particularly in T11N–R11W. These interruptions in continuity are shown in the figure as "F/S," which denotes either the presence of faults or variations in the stratigraphic position of the lignite bed.

The extent and character of the Chemard Lake remains undefined in several directions—west, northwest, south, and southeast. Obviously, potential areas for additional reserves exist in these directions. However, to the south and west the lignites, if present, will be found at a greater depth because of the dip of the formations in these directions (except where controlled by local structure).

The isopach map (fig. 5) further illustrates the continuity of the Chemard Lake lignite. The thickness ranges from less than 1 ft to as much as 8 ft. The thickness of the lignite seems to

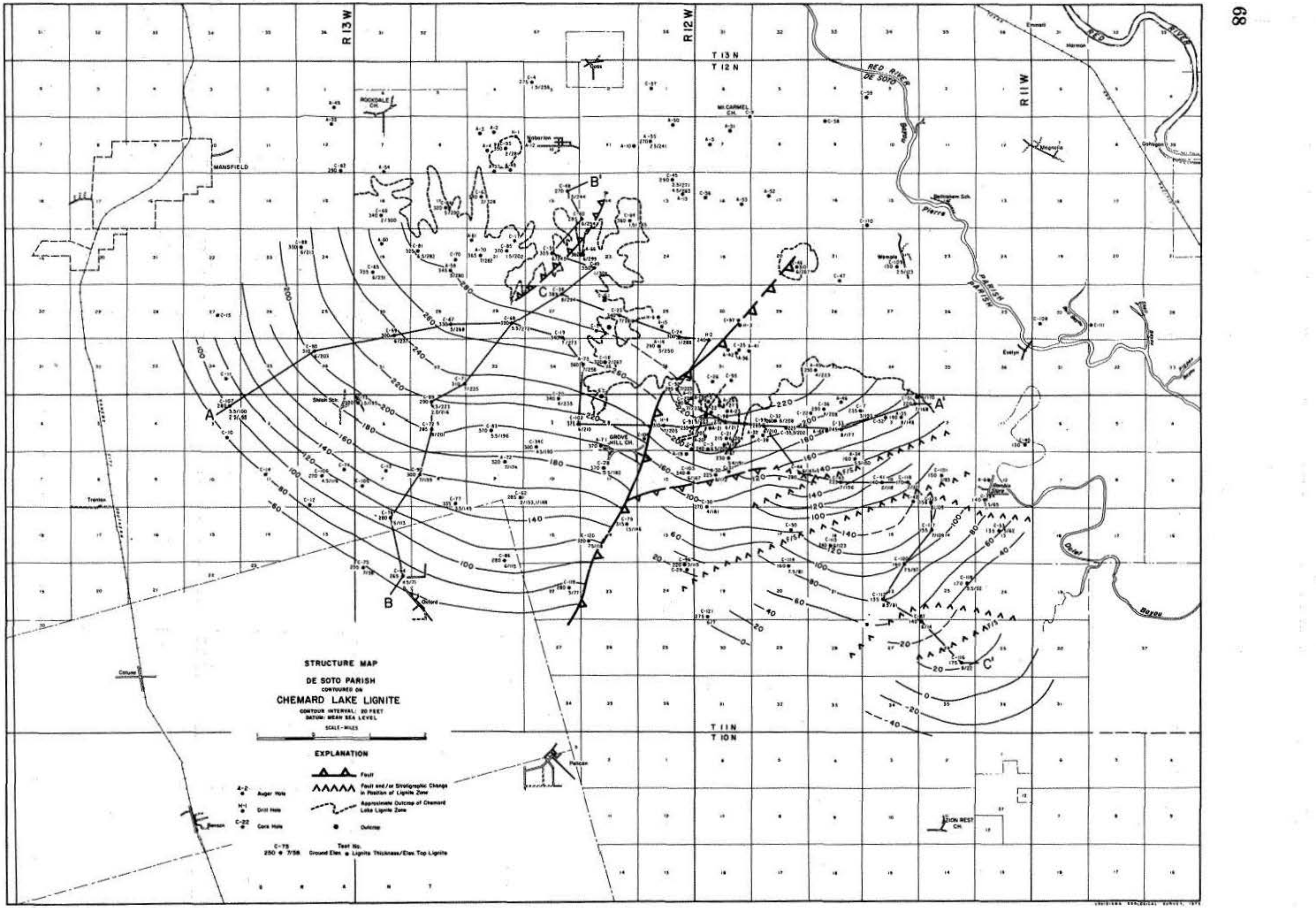

Figure 4. Structure map: De Soto Parish contoured on Chemard Lake Lignite.

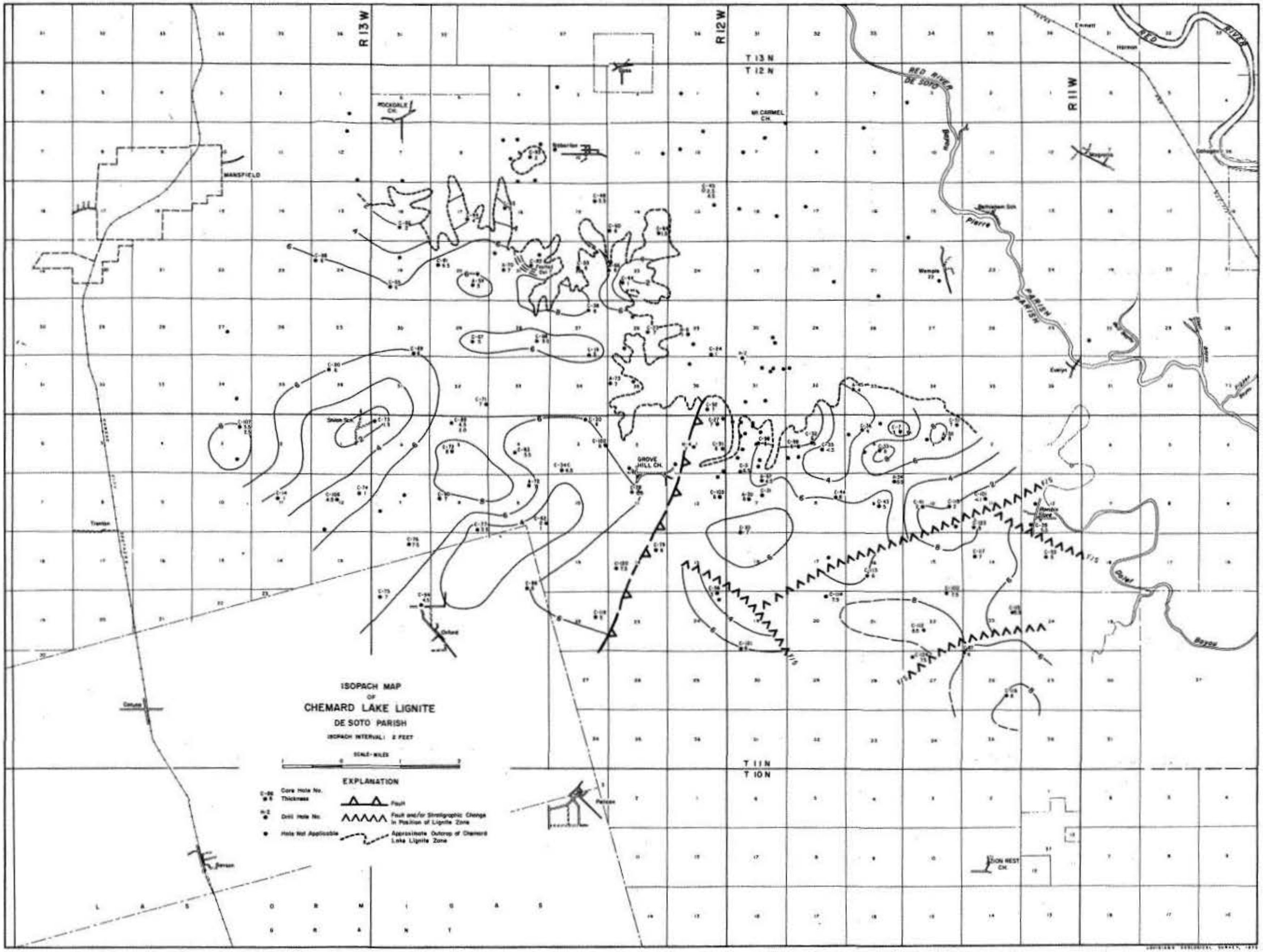

Figure 5. Isopach map of Chemard Lake lignite, De Soto Parish.

hold fairly consistent at 6 ft with only a few variations.[2]

Figures 6, 7, and 8 are cross sections showing the attitude of the Chemard Lake lignite at the top of the Naborton and its relationship to the overlying Dolet Hills Formation. The Naborton consists of dark-gray clay and gray silty clay with occasional thin silty sands. None of the exploratory holes penetrated the entire Naborton Formation. The Dolet Hills consists of sand with some clay. In many, if not most, locations this thick sand overlies the lignite with minimal separation by clay or other less permeable beds. This sand has good continuity, but irregular thickness. Where found, it is a primary source of ground water in the area.

Figures 9 and 10 show some examples of the relationship of the spontaneous potential (SP) and resistivity curve, density curve, and lithologic log to the lignite and related formations. The occurrence of lignite consistently shows little change in SP, a slight increase in resistivity, and a dramatic decrease in density.

In the Sabine Parish survey, several beds of lignite in the Pendleton and Hall Summit Formations were encountered at depths ranging from 70 to 300 ft[2] (fig. 11).

One bed, located near Negreet, Louisiana, was sufficiently extensive to be mapped and structurally interpreted. The thickness of the deposit ranges from 1 to 10 ft; however, the topography (relief) and a rather steep dip of approximately 100 ft per mile limit the extent to which it could be economically exploited. The deposit was traced over an area of approximately 15 square miles and has an average thickness of about 3 ft.

ENVIRONMENTS OF DEPOSITION

Fisher and McGowen (1967) have described the Wilcox Group of Texas employing the concept of depositional systems or complexes rather than formal stratigraphic units. Three of the seven depositional systems which they describe are shown on figure 12. Of these, only the Pendleton bay-lagoon system appears to be related and pertinent to the two areas covered by this report.

According to Kaiser (1974) lagoonal lignite has a high sulfur content suggesting a salt-marsh origin and a high ash content indicating frequent introduction of clastic material. In comparison, the Chemard Lake lignite has woody structure, high ash content, moderate Btu values, and low sulfur content. The low sulfur content suggests deposition in a fresh-water environment.

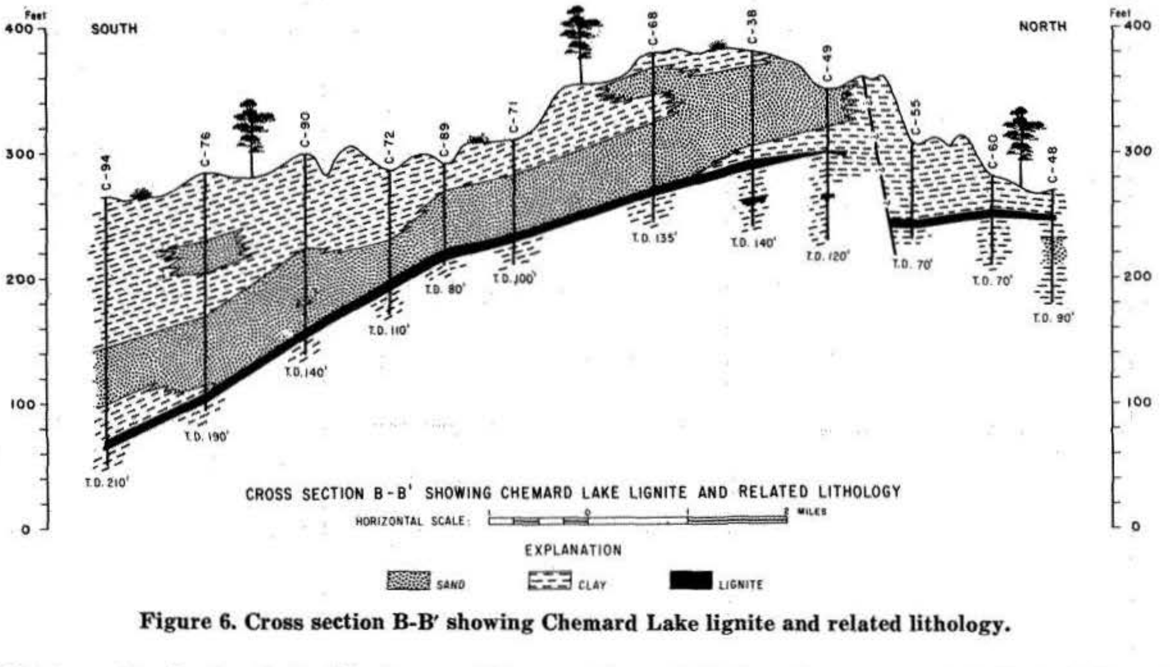

Figure 6. Cross section B-B′ showing Chemard Lake lignite and related lithology.

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[2] Tabulated raw data (location, depth to lignite, seam thickness, and log availabilty) on the occurrence of lignite in DeSoto and Sabine Parishes are available from the Louisiana Geological Survey.

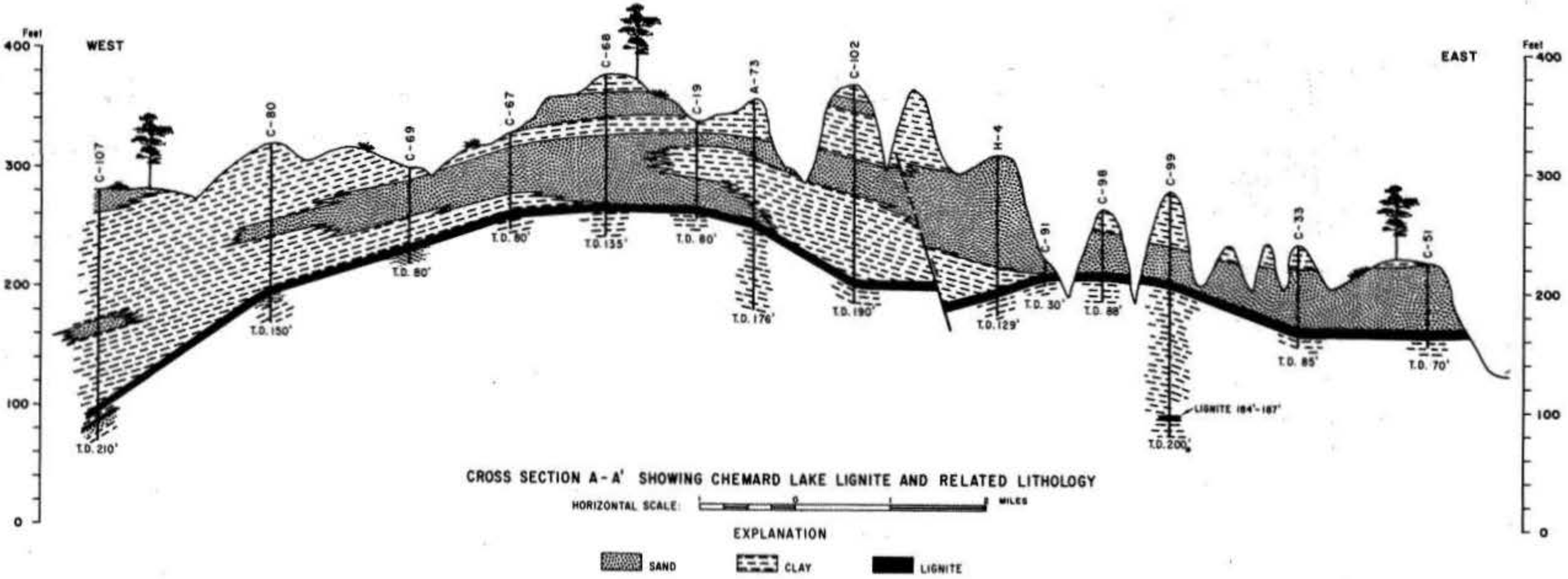

Figure 7. Cross section A-A′ showing Chemard Lake lignite and related lithology.

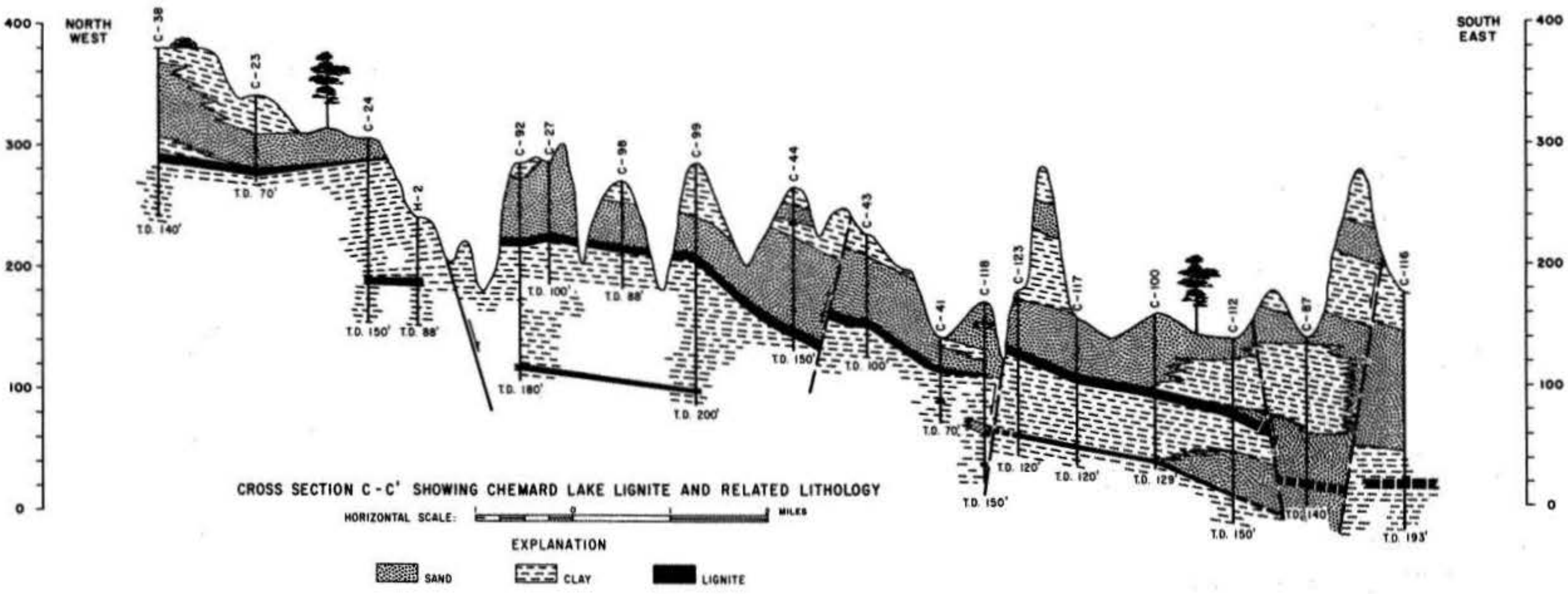

Figure 8. Cross section C-C′ showing Chemard Lake lignite and related lithology.

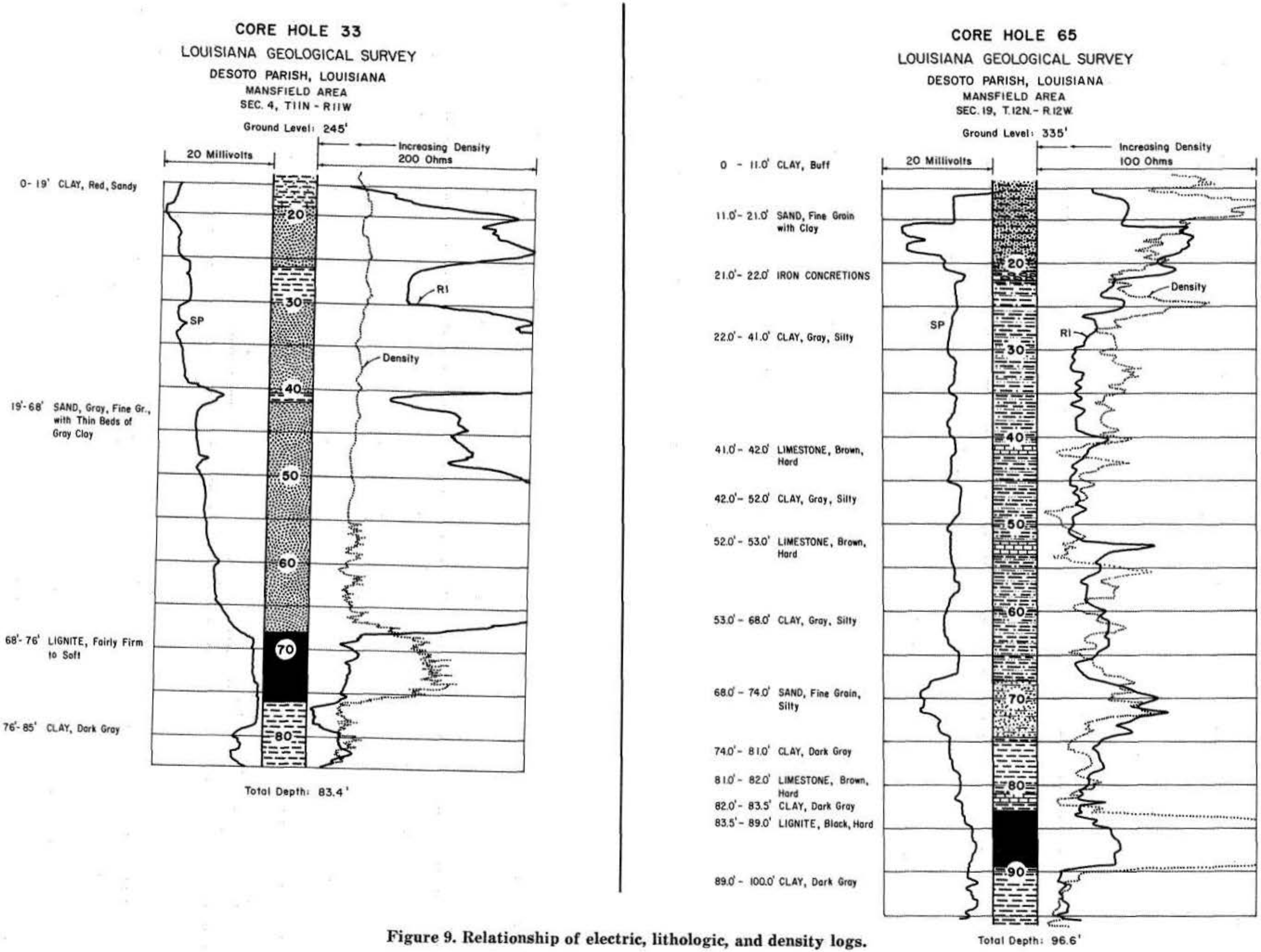

Figure 9. Relationship of electric, lithologic, and density logs.

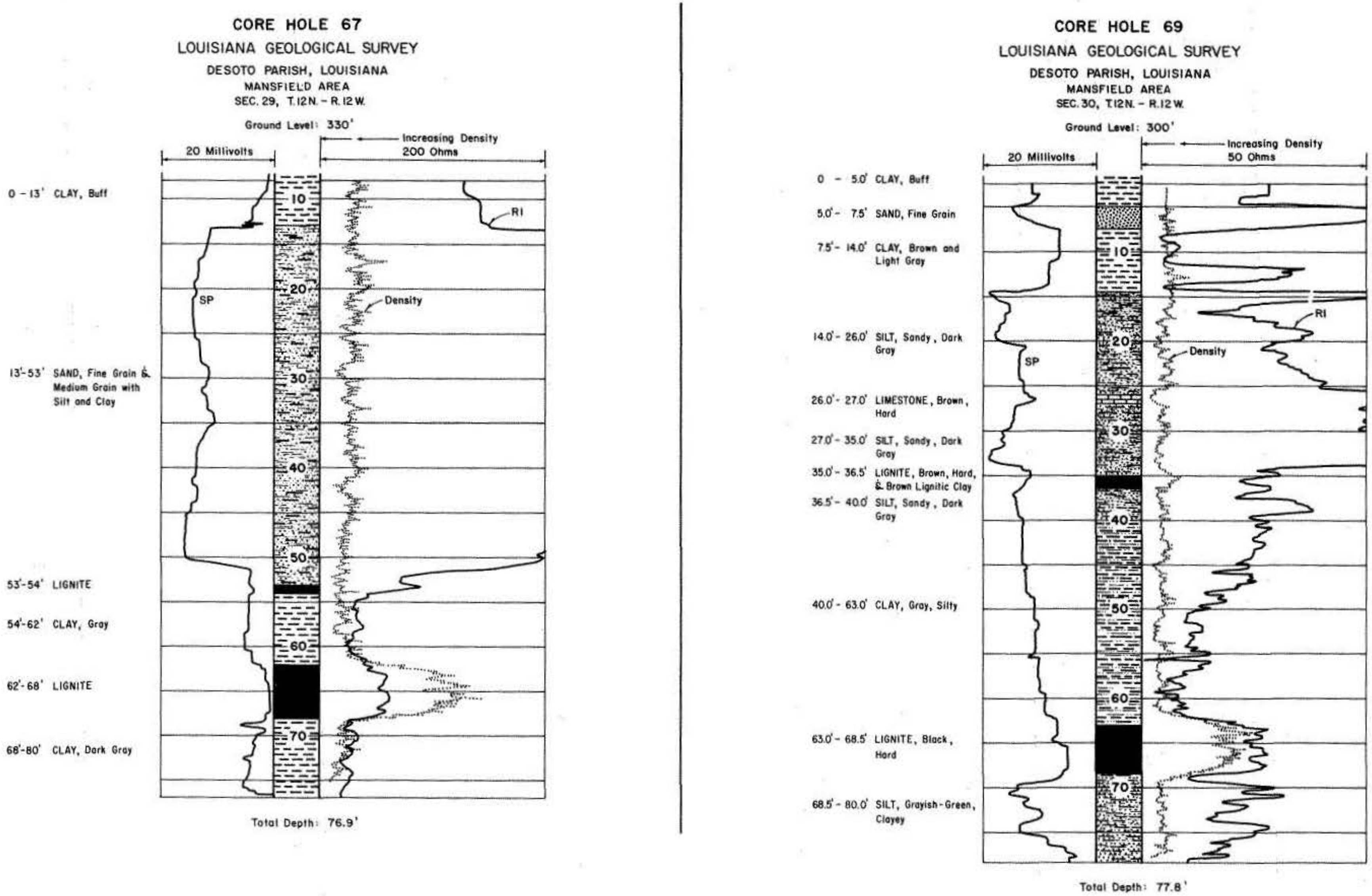

Figure 10. Relationship of electric, lithologic, and density logs.

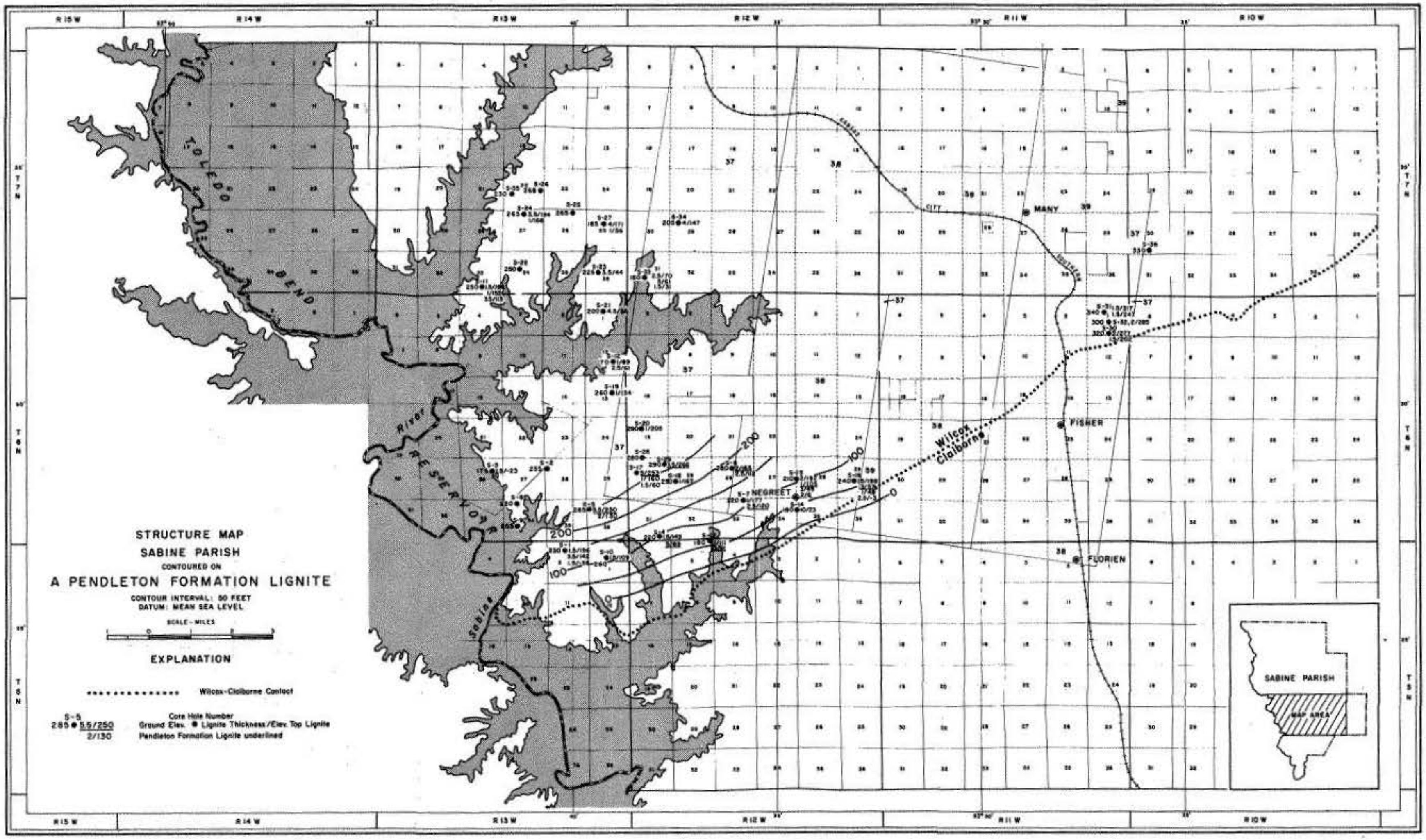

Figure 11. Structure map: Sabine Parish contoured on a Pendleton Formation lignite.

GRADE OF LIGNITE

The analyses of the lignite from De Soto and Sabine Parishes (table 1) were made by the U. S. Bureau of Mines in Pittsburgh, Pennsylvania. The results indicate that the near-surface lignites of northwest Louisiana appear to be near the midrange of the "lignite A" category, that is with a calorific value between 6,300 and 8,300 Btu/lb. The actual average calorific value of the core samples is 7,157 Btu/lb. The sulfur content is low, averaging only 0.63 percent (as-received basis). Ash content averages 16.1 percent and moisture content 30 percent, both on an as-received basis (table 1).

RESERVES

The structure map drawn on the primary lignite bed (Chemard Lake) in De Soto Parish indicates approximately 52,000 acres with adequate control to calculate the reserves with some degree of accuracy. Assuming an average thickness of 6 ft and a specific gravity of 1.29, the reserves are estimated to be about 546 million tons. This estimate is a rather conservative figure since it does not include several other lignite beds in the area and is confined to the area actually delineated by the mapping program.

The energy contained in this lignite deposit is equivalent to approximately 1.3 billion barrels of oil or 8.2 trillion ft^3 of gas.

The 15-square-mile area mapped in Sabine Parish indicates an average thickness of 3 ft of lignite. The reserves are calculated to be approximately 50 million tons of lignite in the area mapped.

Modified from Fisher and McGowan, 1967

Figure 12. Location map showing three of the Wilcox depositional systems of Texas.

FUTURE PLANS

A proposal to expand the investigation of lignites in Louisiana has been submitted to the Department of Conservation. These plans call for an in-house study of the electric logs, driller's logs, water-well information, and any other data available in an attempt to trace the lignite deposits across all of northern Louisiana.

CONCLUSIONS

The data obtained by this exploratory program suggest the following conclusions:

1. Lignite occurs in southeastern De Soto Parish as a near-surface deposit of the lower portion of the Wilcox Group.
2. The main lignite deposit (Chemard Lake) is 5 to 7 ft thick and occupies most of an approximate 80-square-mile area.
3. The average calorific value of the lignite is 7,157 Btu/lb on an as-received basis, which places it in the "lignite A" category. The sulfur content (as received) averages 0.63 percent, and ash content, 16.1 percent.
4. Potential resources are estimated at 546 million tons having an equivalent calorific value of 1.3 billion barrels of oil or 8.2 trillion ft^3 of gas.
5. Water, especially in sands directly overlying the lignite, may present unique mining problems to a producer as well as environmental problems to the local inhabitants.
6. The lignite, as mapped in Sabine Parish, occurs stratigraphically higher in the Wilcox group and is not as extensive as that in De Soto Parish.
7. The reserves in Sabine Parish are estimated to be approximately 50 million tons in the area mapped during this program; however, this area needs more investigation.

Table 1. Proximate and ultimate analyses.

DE SOTO PARISH

Hole Ident. C.H.	Location	PROXIMATE ANALYSIS									ULTIMATE ANALYSIS																		Specific Gravity
		Moist.	Volatile Matter			Fixed Carbon			Ash		Hydrogen			Carbon			Nitrogen			Oxygen			Sulphur			BTU			
			*	**	***	*	**	***	*	**	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***	
2-1	SE SE NE S1-11N-12W	15.9	34.2	40.6	45.5	40.9	48.6	54.5	9.0	10.8	5.5	4.5	5.0	56.0	66.6	74.6	1.2	1.4	1.6	26.4	14.4	16.2	1.9	2.3	2.6	9,730	11,560	12,960	1.482
3-1	SE/c SW SW S6-11N-11W	26.5	26.4	36.0	48.4	28.2	38.3	51.6	18.9	25.7	5.9	4.0	5.4	39.0	53.0	71.4	0.8	1.1	1.5	34.5	15.0	20.1	0.9	1.2	1.6	6,650	9,050	12,180	
8-1	S12-12N-12W	34.1	27.7	42.0	49.1	27.8	42.2	50.1	10.4	15.8	6.8	4.6	5.5	40.7	61.8	73.4	0.9	1.4	1.7	40.7	15.6	18.4	0.5	0.8	1.0	7,060	10,710	12,720	
10-1	S3-11N-13W	19.2	16.1	19.9	--	10.0	12.4	--	54.7	67.7	3.7	2.0	--	17.8	22.0	--	0.4	0.5	--	23.1	7.5	--	0.3	0.3	--	3,020	3,740	--	
11-1	S34-12N-13W	36.6	26.3	41.4	50.6	25.6	40.4	49.4	11.5	18.2	6.8	4.3	5.3	37.4	58.9	72.0	0.8	1.3	1.6	42.4	15.5	18.9	1.1	1.8	2.2	6,420	10,120	12,370	
19-1	SW/c SE S27-12N-12W	22.3	33.3	42.8	48.9	34.7	44.7	51.1	9.7	12.5	6.0	4.5	5.2	51.0	65.6	74.9	1.1	1.4	1.6	31.1	14.6	16.7	1.1	1.4	1.6	8,730	11,230	12,830	
(cuttings) 19-2	SW/c SE S27-12N-12W	35.5	20.1	31.2	56.0	15.8	24.4	44.0	28.6	44.4	6.0	3.1	5.6	25.2	39.0	70.1	0.6	0.9	1.6	39.1	11.8	21.3	0.5	0.8	1.4	4,300	6.670	11,990	
20-1	N/2 NW NE S3-11N-12W	36.2	26.8	42.0	45.4	32.1	50.4	54.6	4.9	7.6	6.9	4.5	4.9	44.2	69.2	74.9	1.0	1.5	1.6	42.5	16.3	17.7	0.5	0.9	0.9	7,480	11,720	12,690	
21-1	SW SE S6-11N-11W	38.5	27.2	44.2	47.4	30.1	49.0	52.6	4.2	6.8	7.2	4.8	5.1	42.6	69.3	74.3	1.0	1.6	1.7	44.4	16.5	17.8	0.6	1.0	1.1	7.330	11,920	12,790	
(cuttings) 24-1	SE/c SW SE S25-12N-12W	39.3	16.8	27.6	54.9	13.7	22.7	45.1	30.2	49.7	6.2	3.0	6.0	22.1	36.4	72.4	0.5	0.9	1.8	40.7	9.5	18.8	0.3	0.5	1.0	3,750	6,180	12,280	
25-1	c/NE S31-12N-11W	16.4	38.9	46.5	49.7	39.3	37.1	50.3	5.4	6.4	6.2	5.2	5.6	58.1	69.4	74.2	1.3	1.6	1.7	28.2	16.5	17.5	0.8	0.9	1.0	10,120	12,090	12,390	
(cuttings) 25-2	c/NE S31-12N-11W	9.4	33.9	37.5	49.0	35.5	39.1	51.0	21.2	23.4	4.8	4.2	5.4	50.3	55.5	72.5	1.1	1.3	1.6	21.9	14.8	19.5	0.7	0.8	1.0	8,660	9,560	12,490	
25-3	c/NE S31-12N-11W	11.2	25.1	28.3	46.8	28.6	32.2	53.2	35.1	39.5	4.1	3.2	5.3	38.8	43.7	72.3	0.7	0.8	1.3	20.6	12.0	19.8	0.7	0.8	1.3	6,550	7,380	12,220	
(cuttings) 27-1	NE NE S1-11N-12W	45.5	23.2	42.6	49.9	23.3	42.7	50.1	8.0	14.7	7.7	4.8	5.6	34.4	63.1	74.0	0.7	1.4	1.6	48.8	15.2	17.8	0.4	0.8	1.0	5,970	10,960	12,860	
28-1	c/SW S5-11N-11W	12.7	34.3	39.3	44.0	43.6	50.0	56.0	9.4	10.7	5.2	4.3	4.8	58.5	67.0	75.1	1.3	1.5	1.6	24.6	15.3	17.2	1.0	1.2	1.3	10,000	11,450	12,820	
30-1	NE/c NW NW S18-11N-11W	28.7	27.1	38.0	52.6	24.4	34.3	47.4	19.8	27.7	6.0	4.0	5.5	36.1	50.7	70.1	0.8	1.1	1.6	36.8	15.8	21.8	0.5	0.7	1.0	6,390	8,960	12,400	
32-1	NE NW SW S5-11N-11W	45.4	19.8	36.2	45.6	23.5	43.1	54.4	11.3	20.7	7.3	4.0	5.1	31.8	58.3	73.5	0.7	1.3	1.6	48.5	15.0	18.9	0.4	0.7	0.9	5,450	9,970	12,580	
33-1	NW SE S6-11N-11W	33.5	24.2	36.4	48.7	25.5	38.4	51.3	16.8	25.2	6.3	3.9	5.2	35.5	53.3	71.3	0.8	1.2	1.5	40.2	15.8	21.2	0.4	0.6	0.8	6,090	9,160	12,250	
(cuttings) 33-2	NW SE S6-11N-11W	47.0	19.4	36.7	47.8	21.2	40.0	52.2	12.4	23.3	7.3	3.9	5.1	29.4	56.4	73.6	0.7	1.3	1.6	49.4	14.4	18.9	0.3	0.7	0.8	5,090	9,610	12,540	
46-1	NE/c SE SE S20-12N-11W	33.3	30.0	45.0	49.1	31.2	46.7	50.9	5.5	8.3	6.9	4.8	5.2	44.5	66.8	72.8	1.0	1.5	1.6	41.3	7.4	19.1	0.8	1.2	1.3	7,670	11,500	12,540	
49-1	SE/c NW SW S23-12N-12W	28.8	29.1	40.8	53.9	24.8	34.9	46.1	17.3	24.3	6.2	4.3	5.6	38.1	53.5	70.7	1.0	1.4	1.8	36.7	15.5	20.6	0.7	1.0	1.3	6,610	9,280	12,250	
51-1	S3-11N-11W	35.9	29.3	45.8	48.7	31.0	48.2	51.3	3.8	6.0	7.2	4.9	5.2	44.8	70.0	74.4	1.0	1.6	1.7	42.7	16.8	17.9	0.5	0.7	0.8	7,720	12,060	12,830	1.368

* As Received ** Moisture Free *** Moisture and Ash Free

Table 1. Proximate and ultimate analyses — (*continued*).

Hole Ident. C.H.	Location	Moist.	PROXIMATE ANALYSIS Volatile Matter			Fixed Carbon			Ash		ULTIMATE ANALYSIS Hydrogen			Carbon			Nitrogen			Oxygen			Sulphur			BTU			Specific Gravity
			*	**	***	*	**	***	*	**	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***	
53-1	SE SE NW S13-11N-11W	31.7	31.7	46.4	50.5	31.1	45.5	49.5	5.5	8.1	7.0	5.0	5.4	45.8	67.0	72.9	1.1	1.6	1.8	40.2	17.7	19.2	0.4	0.6	0.7	7,880	11,530	12,550	
55-1	c/Sec. S22-12N-12W	33.4	27.0	40.6	49.7	27.5	41.2	50.3	12.1	18.2	6.6	4.4	5.3	39.9	59.9	73.3	1.0	1.5	1.8	39.9	15.3	18.7	0.5	0.7	0.9	6,880	10,330	12,640	1.451
60-1	NW/c SW SW S14-12N-12W	32.4	21.1	31.2	51.8	19.6	29.0	48.2	26.9	39.8	5.9	3.3	5.5	24.1	43.1	71.5	0.7	1.0	1.7	36.8	11.9	19.9	0.6	0.9	1.4	5,010	7,410	12,300	
64-1	SE SE S14-12N-12W	23.5	21.4	28.0	55.9	16.8	22.0	44.1	38.3	50.0	4.8	2.9	5.8	27.0	35.2	70.5	0.7	0.9	1.7	28.8	10.5	21.0	0.4	0.5	1.0	4,660	6,090	12,170	1.373
65-1	NW/c SE SW S19-12N-12W	30.3	29.6	42.5	47.6	32.5	46.6	52.4	7.6	10.9	6.6	4.6	5.2	46.2	66.2	74.3	1.1	1.5	1.7	37.9	15.9	17.8	0.6	0.9	1.0	7,920	11,360	12,750	1.457
67-1	NW/c SE SE S29-12N-12W	31.6	29.7	43.4	48.3	31.7	46.4	51.7	7.0	10.2	6.8	4.8	5.3	45.8	66.9	74.5	1.0	1.5	1.7	38.7	15.6	17.4	0.7	1.0	1.1	7,840	11,460	12,760	1.465
68-1	NE SE SE S28-12N-12W	31.0	29.2	42.4	46.4	33.9	49.0	53.6	5.9	8.6	6.6	4.6	5.1	46.5	67.4	73.7	1.0	1.5	1.6	39.2	16.8	18.4	0.8	1.1	1.2	7,910	11,460	12,540	1.371
69-1	S30-12N-12W	33.9	30.2	45.8	50.5	29.7	44.7	49.5	6.2	9.5	7.0	4.8	5.3	44.6	67.5	74.5	1.0	1.5	1.7	40.7	15.9	17.6	0.5	0.8	0.9	7,640	11,560	12,770	1.357
71-1	NW/c SW SW S33-12N-12W	29.9	28.6	40.8	45.8	33.8	48.2	54.2	7.7	11.0	6.3	4.3	4.8	46.4	66.2	74.4	1.0	1.4	1.6	37.8	15.9	17.9	0.8	1.2	1.3	7,910	11,280	12,670	1.467
72-1	NE SW S5-11N-11W	31.3	27.4	39.8	44.2	34.6	50.4	55.8	6.7	9.8	6.5	4.4	4.8	46.0	67.0	74.2	1.0	1.5	1.7	39.3	16.6	18.4	0.5	0.7	0.8	7,790	11,350	12,580	1.397
76-1	NW NE NE S18-11N-12W	31.1	29.2	42.4	47.2	32.7	47.5	52.8	7.0	10.1	6.6	4.6	5.1	46.0	66.8	74.4	1.0	1.5	1.7	38.0	15.0	16.6	1.4	2.0	2.2	7,930	11,510	12,810	1.545
80-1	SE/c NE NW S36-12N-13W	29.7	31.0	44.1	51.7	29.0	41.2	48.3	10.3	14.7	6.4	4.4	5.2	44.4	63.2	74.1	1.0	1.5	1.7	37.3	15.3	18.0	0.6	0.9	1.0	7,730	11,000	12,890	
(cuttings) 109-1	NW SE	43.6	22.6	40.0	52.1	20.7	36.7	47.9	13.1	23.3	7.2	4.2	5.5	31.3	44.4	72.3	0.7	1.2	1.6	47.2	15.0	19.5	0.5	0.8	1.1	5,420	9,600	12,520	
(cuttings) 110-1	SW SW SW S15-12N-11W	43.0	16.4	28.7	56.4	12.6	22.2	43.6	28.0	49.1	6.4	2.9	5.7	20.3	35.6	70.0	0.4	0.8	1.5	44.6	11.1	21.8	0.3	0.5	1.0	3,440	6,040	11,850	
(cuttings) 111-1	NW/c SW SW S29-12N-10W	6.8	24.3	26.1	--	13.3	14.2	--	55.6	59.7	3.0	2.4	--	26.4	28.3	--	0.6	0.7	--	13.9	8.4	--	0.5	0.5	--	4,400	4,720	--	
(cuttings) 113-1		48.3	20.7	40.0	51.3	19.6	38.0	48.7	11.4	22.0	7.5	4.1	5.3	29.5	57.1	73.2	0.7	1.3	1.6	50.5	14.8	19.0	0.4	0.7	0.9	5,040	9,750	12,500	
(cuttings) 114-1	NE NE S20-11N-11W	44.0	19.3	34.5	49.5	19.7	35.2	50.5	17.0	30.3	6.8	3.5	5.0	28.4	50.7	72.7	0.6	1.1	1.6	46.8	13.7	19.8	0.4	0.7	0.9	4,820	8,620	12,370	
115-1	SE NE S23-11N-11W	34.2	22.0	33.4	57.9	16.0	24.3	42.1	27.8	42.3	5.9	3.2	5.5	27.3	41.5	72.0	0.6	0.9	1.6	38.1	11.6	20.0	0.3	0.5	0.9	4,630	7,050	12,210	
														SABINE PARISH															
S- 1	S2-5N-13W	39.8	13.0	21.6	--	9.6	16.0	--	37.6	62.4	5.7	2.1	--	16.1	26.8	--	0.3	0.6	--	39.2	6.3	--	1.1	1.8	--	2,730	4,540	--	
S- 5	S36-6N-13W	41.5	26.4	45.0	49.8	26.5	45.4	50.2	5.6	9.6	7.2	4.4	4.9	39.9	68.2	75.5	0.8	1.4	1.6	45.0	13.9	15.2	1.5	2.5	2.8	6,790	11,590	12,820	
(cuttings) S-11	S33-7N-13W	45.1	17.4	31.6	53.7	14.9	27.3	46.3	22.6	41.1	6.7	3.0	5.1	23.2	42.2	71.7	0.5	0.8	1.4	45.8	10.7	18.1	1.2	2.2	3.7	3,940	7,170	12,180	

* As Received

** Moisture Free

*** Moisture and Ash Free

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GEOLOGY OF THE SAN MIGUEL LIGNITE DEPOSIT (ATASCOSA AND McMULLEN COUNTIES, TEXAS)

J. E. McNulty, Jr.[1]

ABSTRACT

The San Miguel lignite deposit is named for outcrop exposures in San Miguel Creek in northern McMullen County. Authors have considered this lignite to be in the upper Yegua Formation or in the lower part of the Jackson group of the upper Eocene. The Yegua-Jackson contact has not been established in this area.

Extensive drilling in 1970 and 1973 defined the quantity and quality of the lignite and determined the feasibility of economic recovery by surface-mining methods.

The San Miguel lignite is a complex bed, that is, one composed of benches of lignite separated by partings of clay and carbonaceous shale. This deposit is considered part of the Jackson South Texas lagoonal coastal-plain system. The lagoonal depositional environment is reflected in the quality of the lignite, which affected the design parameters of the proposed fuel utilization.

Proven reserves of this deposit are dedicated to the proposed San Miguel Plant of Brazos Electric Power Cooperative and South Texas Electric Cooperative.

INTRODUCTION

The San Miguel lignite deposit is located in South Texas, in northern McMullen and southeastern Atascosa Counties, approximately 50 miles south of San Antonio. The climate of the region is subtropical with about 25 inches of rainfall annually, and the predominant land use is grazing. The largest nearby town, Christine, Texas, has a population of approximately 300.

The near-surface lignite deposits, compiled from Kaiser (1974), and the location of the San Miguel deposit are shown in figure 1. The deposit is named for outcrops along San Miguel Creek, near the junction of the creek and Highway 16 (formerly Route 173), between Tilden and Jourdanton.

These outcrops were measured and described by Deussen (1924) and also by Maxwell (1962). Maxwell reports that core-drilling programs were conducted in the area in 1927 and again in 1955. No doubt others have investigated intermittently the commercial potential of lignite from this area.

In 1971, a program of 50 core holes was conducted for the Brazos Electric Power Cooperative and the South Texas Electric Cooperative. The results of that program confirmed a reserve potential of sufficient magnitude to warrant a further, more extensive investigation.

In the summer of 1973, the cooperatives authorized another drilling program to determine commercial feasibility. This program consisted of 240 closely spaced rotary holes, 40 lignite core holes, and 5 continuous cores of overburden. Subsequent studies based on these results indicated that the San Miguel lignite could be economically mined and burned for the production of electric power.

Maxwell (1962) considered this lignite to be in the upper part of the Yegua Formation. Kaiser (1974) states that it also could be assigned to the lower Jackson because the boundary (the marine Caddell Formation) is absent or not easily recognized in this area. Hence, the name Yegua-Jackson is suggested.

The location of the San Miguel deposit is shown in figure 2 in relation to a sand isolith map from figure 1(b) of Fisher and others (1970). These Jackson sands make up the South Texas strandplain/barrier-bar system. These authors have designated the area updip and landward as the South Texas lagoonal/coastal-plain system.

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[1] Paul Weir Company; Chicago, Illinois 60606.

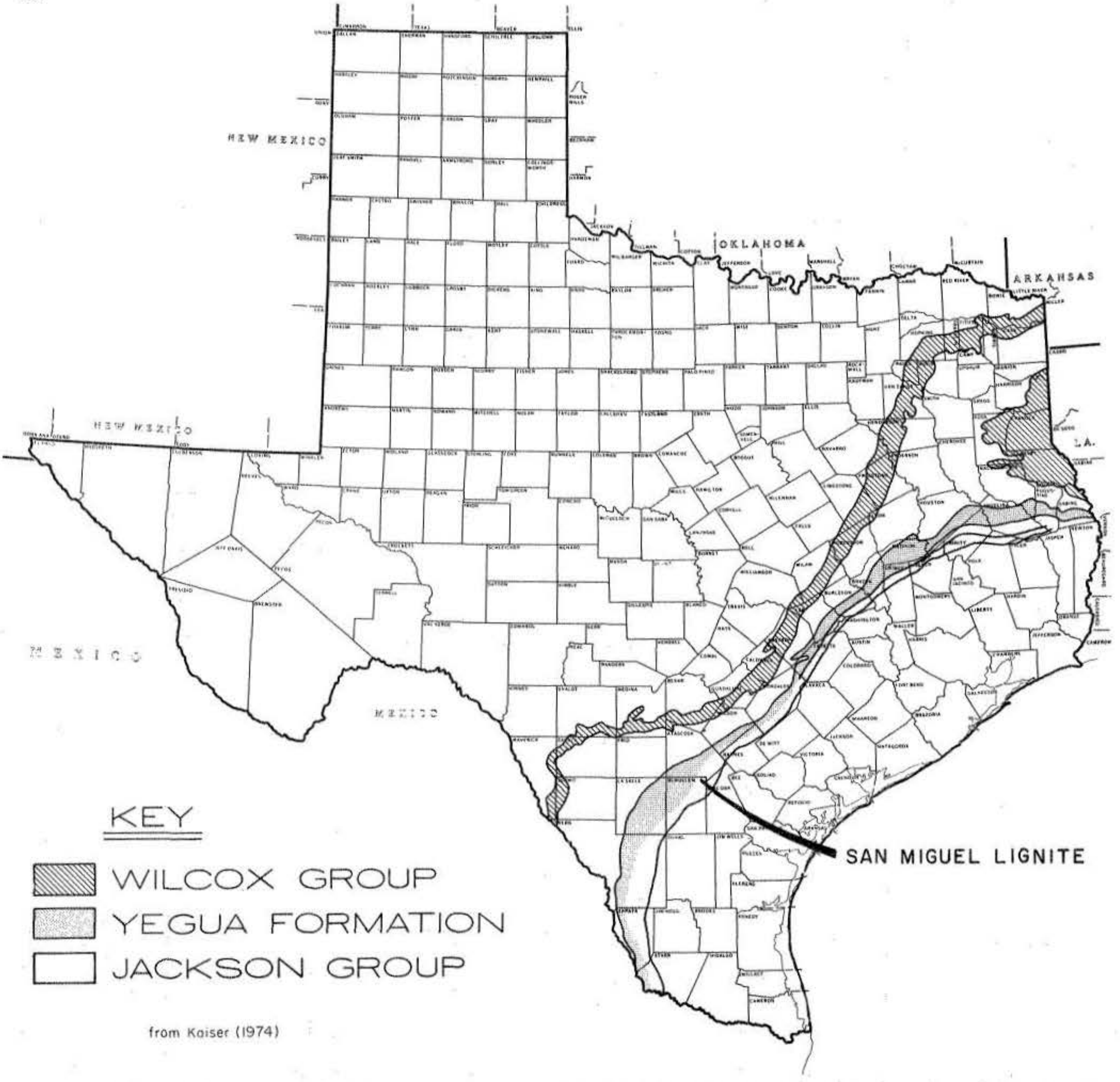

Figure 1. Near-surface lignite deposits in Texas and the San Miguel lignite deposit (from Kaiser, 1974).

The northeast-trending axes of the Yegua-Jackson barrier-bar/strandplain system from figure 13 of Kaiser (1974) are shown on figure 3. The San Miguel area is shown to the northwest (landward).

The barrier-bar/strandplain system provided the physiographic control for the depositional environment of the San Miguel lignite, an environment having the availability of contamination by terrigenous sediments and seawater access from storm tides.

The area of the San Miguel lignite that has been defined by detailed drilling is shown on figure 4. The shaded area is about 25 miles long and averages 3 miles wide. It is bounded on the northwest by the subcrop of the bed, which occurs at a depth of cover of from 15 to 25 ft.

In the north, the lignite bed is not well developed beyond the Atascosa River. The southern boundary of the shaded area is drawn just beyond the southwestern extent of the detailed drilling.

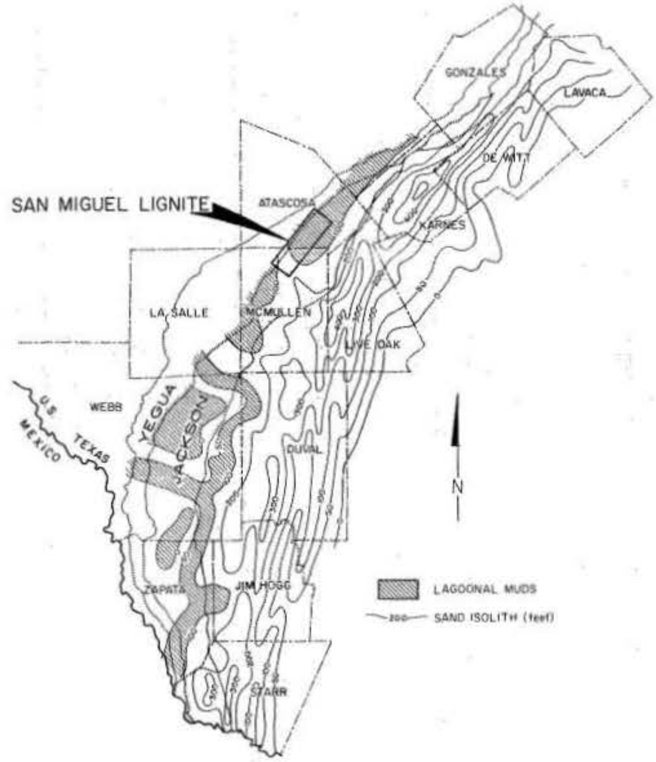

Figure 2. Location of San Miguel deposit in relation to sand isolith map from Fisher and others (1970).

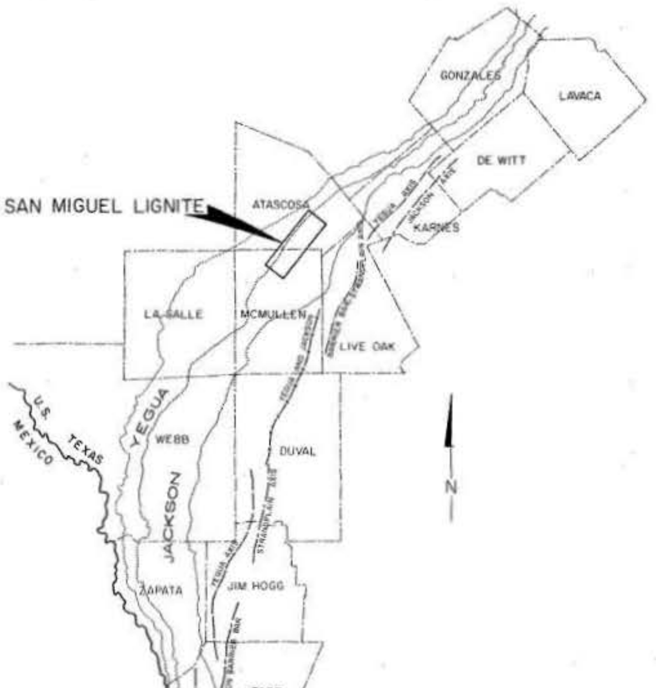

Figure 3. Northeast-trending axes of the Yegua-Jackson barrier-bar/strandplain system (from Kaiser, 1974).

The southeast or downdip limit is at approximately 150 to 200 ft of cover. The deeper part of the deposit has not been explored.

The overburden of the San Miguel bed is dominated by clays and shales. The occurrences of coarser clastics are thin and discontinuous. Typically, the surface unit consists of a soil zone, generally a foot or less in thickness, underlain by reddish-brown, silty to sandy clay or gravel.

At a depth of about 20 ft from surface, the strata become firmer and consist of shales that are mostly gray to brownish gray, generally silty, with occasional thin (less than 1 ft) lenses of silt or fine sand and occasional brown carbonaceous streaks.

Hard, gray silty shales occur toward the bottom of the section. The lignite bed is normally overlain by 3 to 5 ft of dark-brown carbonaceous shale.

The bed strikes about N. 40° E., with a gulfward dip that ranges up to 1½° but averages less than 1°. Including the internal partings, the bed ranges in thickness from about 6 ft to in excess of 14 ft.

The lignite bed is underlain by gray shale, which grades downward into green shales and

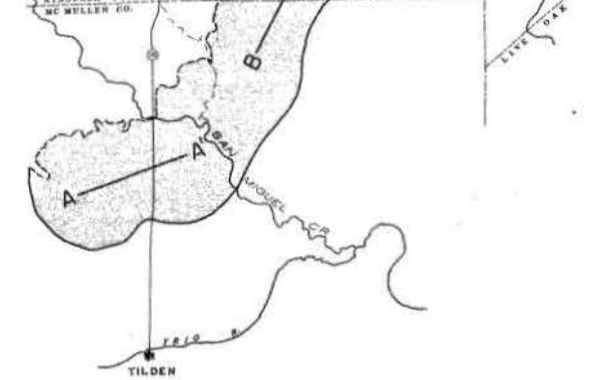

Figure 4. Area of San Miguel lignite defined by detailed drilling.

silts. A lower lignite bed occurs from 10 to 20 ft below the base of the main bed in the area south of San Miguel Creek. In general, the lower bed averages 3 to 4 ft in thickness.

In the megascopic cores, the lignite ranges in color from reddish brown to brownish black. It is nonbanded and is generally void of hard or woody material. The luster ranges from dull to waxy. It is relatively soft, with a Hardgrove grindability index of 89 (at 28.7-percent moisture level), and somewhat sectile.[2] The lignite is not well cleated. The average of analyses for pyritic sulfur content is 0.72 percent, but free pyrite crystals are rarely discernable megascopically.

Partings within the main lignite bed range in thickness from knife edge to greater than 2 ft. They range from light-tan clays to dark-brown carbonaceous shales. Minor partings tend to be lenticular and discontinuous. With the aid of the geophysical logs of the detailed drilling, major partings (0.5 ft and more thick) can be traced over a considerably large area; sometimes the entire length of the deposit can be traced.

A strike section of the lignite bed, showing the relative geometry of the lignite seam and partings in the south area, is shown on figure 5. The section at "A" represents the southwestern extent of data. The lower bed is present in this area. Toward the northeast, the thickness of lignite increases relative to the thickness of partings.

Figure 6 is representative of the central section of the deposit. The best development (economically) of the lignite occurs in this section.

A section through the northern part of the deposit is shown on figure 7. The increase in parting thickness and corresponding decrease in total lignite (approximately the middle of the section) occur quite close to the Atascosa River.

One of the most important factors affecting the economic recovery of lignite from the San Miguel deposit is the presence of partings within the bed. Indeed, one of the main targets of the 1973 drilling program was to define, by closely spaced holes, the thickness and distribution of partings.

Because of the low calorific value of this lignite, the overall heat content of the mined product must be maximized by selective loading. Mechanical separation by this method, however, has limitations. There are benches of lignite within the main bed series so thin that they cannot be economically loaded without excessive dilution from the subjacent and superjacent partings. Conversely, there are partings that are too thin to be separated.

A greater percentage of mining losses will be experienced as a result of selective loading practices. Normally, the expected recovery in a bed of this thickness would be approximately 85 to 90 percent. The recovery factor to be expected in the

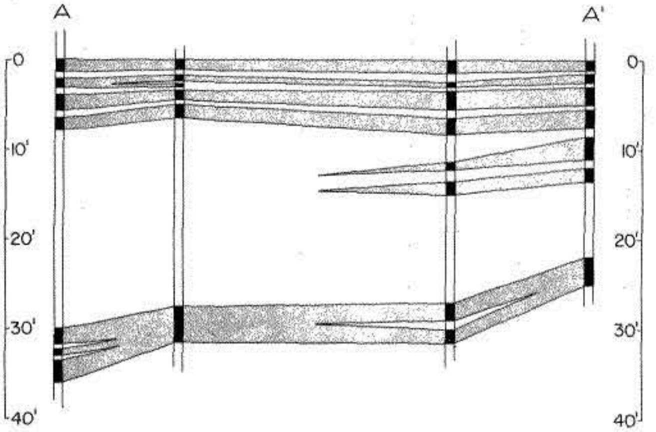

Figure 5. Strike section A-A′ of San Miguel lignite bed showing relative geometry and partings in the south areas.

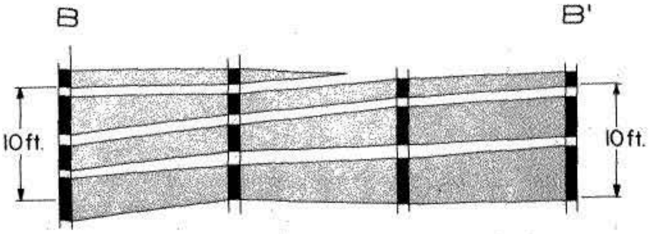

Figure 6. Central section of San Miguel lignite, B-B′.

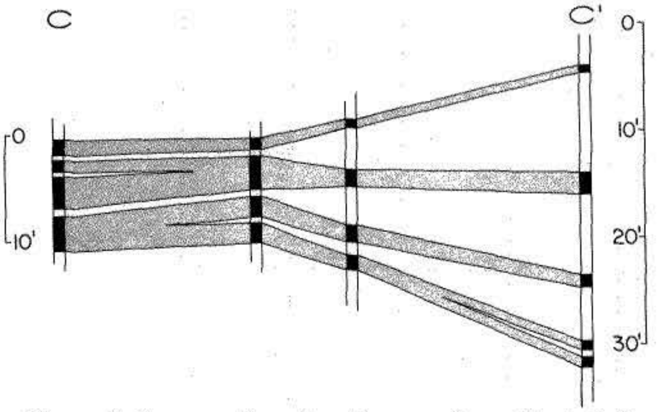

Figure 7. Seam section of northern portion of bed, C-C′.

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[2] Capable of being severed smoothly by a knife.

proposed mining operations will average somewhere between 65 and 70 percent. A higher recovery is certainly possible, but only at the expense of the calorific content of the mined product.

The presence of numerous partings in the lignite bed is not the only deposition-related effect of economic consequence. Figure 8 compares items of quality whose values reflect the depositional environment.

In the upper left-hand corner of figure 8 is a table by McGowen (1968) comparing characteristics for fluvial, deltaic, and lagoonal lignites. Added to the chart are average values for the San Miguel lignite, reflecting the as-mined quality.

In addition to the characteristics shown by McGowen, are values for chlorine (ultimate) and sodium oxide (dry coal basis). The difference in values between the lagoonal (San Miguel) and the delta-plain (Wilcox) deposits is attributed to the availability of seawater in the lagoonal environment. The economic effect of seawater is that some sodium compounds present combustion problems that result in relatively higher capital and operating costs.

	FLUVIAL	DELTA	LAGOON	SAN MIGUEL
SHAPE	ELONGATE	TABULAR	DISCONTINUOUS	--
SULFUR	LOW-MEDIUM	MEDIUM	HIGH	---- 1.47 %
BTU	LOW-MEDIUM	HIGH	LOW	---- 5,200 Btu/lb
SPECIFIC GRAVITY	LOW	HIGH	LOW	--
ASH	MEDIUM	MEDIUM	HIGH	---27.7 %
VOLATILE	HIGH	MEDIUM	LOW-MEDIUM	---23.2 %
FIXED CARBON	MEDIUM	HIGH	LOW	---18.4 %

from McGowen, 1968

CHLORINE ------------ 0.15 %
Na_2O (dry coal basis)---- 1.45 %
ASH (lb/10^6 Btu)------53.3
SO_2 (lb/10^6 Btu)------ 5.65

Figure 8. Comparison for fluvial, deltaic, and lagoonal lignites (from McGowen, 1968) with average value added for the San Miguel lignite including those for chlorine, sodium oxide, ash, and sulfur dioxide.

The amounts of ash and sulfur dioxide that are expected to be produced on a per-million-Btu basis are also shown in figure 8. Again, the depositional environment of the San Miguel lignite will be reflected in the capital and operating costs of its utilization.

However, despite the mining and quality problems associated with this fuel, the San Miguel lignite represents an economic source of energy for Texas. The first 400-megawatt unit of the San Miguel Plant (figure 4) of Brazos Electric Power Cooperative and South Texas Electric Cooperative is expected to be in operation in late 1979. The fuel source will be the San Miguel lignite, which will be produced from a surface mine having a capacity of 2.9 million tons annually.

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TECHNOLOGY AND ECONOMICS OF MINING TEXAS LIGNITE[1]

R. W. Brummett[2] and J. D. O'Donovan[2]

This paper covers the technology and economics of strip mining lignite in the Texas Gulf coastal area. The subject matter has been limited to current stripping methods applied to the present and future mining conditions in this region.

Although relatively large-scale strip mining began in 1971, the mines developed today are located in the thicker and essentially single-seam deposits under shallow to intermediate overburden depths. The reserve areas currently being explored commonly contain thin multiple seams that are lenticular and deep. As such, their mining will pose different problems and certainly result in higher costs than those of the current operations.

As of January 1, 1974, the identified coal resources in Texas totalled an estimated 6 billion 340 million tons or approximately 1 percent of the total in the United States. These resources comprise 10 billion 293 million tons of lignite from 0 to 200 ft in depth and 6 billion 48 million of bituminous coal from 0 to 3,000 ft in depth.[3] The lignite resources are located in the Gulf Coastal Plain, whereas bituminous coals are found in north-central Texas, the Rio Grande embayment, and Trans-Pecos Texas. Underground bituminous and lignite coal mining in Texas began in the 1880's and continued for 60 years into the 1940's. The production peaked at over 1.2 million tons annually in 1918, then decreased rapidly as natural gas supplies became abundant. At present the State's entire production is surface-mined lignite from four operations. The ICI United States, Inc. mine near Darco in Harrison County has produced lignite for activated carbon plants since 1931. Texas Utilities Generating Company, through subsidiary companies, mines lignite for steam-electric power generation at the Rockdale, Fairfield, and new Monticello operations. Statewide surface-mined lignite production totalled 7,238,000 tons in 1974 (up from 6,944,000 tons in the previous year). Planned and/or announced new plants such as those of Martin Lake in Rusk County and Athens in Henderson County will increase the coal requirements to the range of 50 million tons by 1985. We've based it on a calculation of the projected plants as listed in the powerplant factors book.

With excellent foresight, Texas Utilities began its lignite leasing and exploration activities in the 1940's. As a result, they were able to develop solid mineable block ownerships as attested by the present mining operations and future projections. In late 1972 following the energy crisis, Texas suddenly became an active area for coal exploration. Numerous companies, lease brokers, and speculators created a lease play and an exploration boom that is just now beginning to subside. It not only covered Texas, but spilled over into the adjacent States of Louisiana, Mississippi, and Alabama. The result of this feverish activity is that most companies generally lack the solid lease blocks necessary for the orderly and efficient development of surface mines. A certain amount of lease trades, outright sales, or joint ventures will result as the companies begin assessing the minability of their holdings. The willingness of companies to enter into these agreements could be the critical factor governing the mining feasibility in many reserve areas.

The Texas Gulf Coastal Plain lignite seams are widely distributed in several Eocene series rock units of lower Tertiary age. The formations containing the main lignite occurrences are from oldest to youngest: the Calvert Bluff of the Wilcox Group, the Yegua of the Claiborne Group, and the Manning of the Jackson Group. Structurally the

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[1] Transcript of oral presentation delivered by Mr. Brummett on June 2, 1976.

[2] John T. Boyd Company; Denver, Colorado 80203.

[3] Data from Averitt, P., 1975, Coal resources of the United States January 1, 1974: USGS Bull. 1412, 131p.

Eocene series rocks trend northeast from the Rio Grande to the eastern border of Texas and dip gently to the southeast. All of the mines are located north of the Colorado River in the Wilcox Group. Within relatively localized areas, the lignite seams can exhibit wide thickness variations over short lateral extent, especially in the thinner seam zones where a 5-ft-thick seam may extend only 2,000 or 3,000 ft along the strike, then thin to 2 ft over the same distance, and again become thicker. Also in these areas a number of seams can occur separated by variable parting thickness, but all within the strippable depth range. Studies of the lignite quality show there is a correlation between the grade and geologic occurrence that is transferred to lateral changes along the strike of certain lignite-bearing formations, and between the formations themselves. Lignite ranging from 6,500 to 7,500 Btu/lb is found in areas north of the Colorado River and between 4,500 and 6,500 Btu south of the river. This higher grade and the presence of more persistent seams has centered the main mining and exploration activities north of the Colorado River.

In discussing the technical aspects of lignite stripping and mining in Texas, we will cover the important features of the methods presently used and relate these to the probable mining conditions in future mine developments. There will be important differences in that future mine developments will involve generally thinner and more lenticular seams with attendant higher stripping ratios and more complex mining situations.

Lignite mining methods employed today closely follow those used in the midwestern coal fields that employ area-stripping techniques. The stripping sequence starts from a box cut, usually along the lignite crop line beginning generally at the 20 ft cover-depth line. Although local variations can occur, the lignite from the outcrop of the 20 ft cover line is usually highly oxidized and poor in quality. From this box cut, successive strips are often downdip and into deeper cover. Initially the pits are maintained as wide as possible, ranging from 160 to 180 ft in low cover, then narrow to 120 ft at depth. This width is a function of the overburden depth in the range of the stripping unit employed. The pit width in the range of 120 ft is considered minimal (width to be a function of being able to get the equipment in and out of the pit to mine the lignite). The overburden material is predominantly a loosely consolidated sand to sandy clay that a dragline can dig without requiring power drilling and blasting. As such, it readily packs into a dragline bucket, and very high average bucket fillability factors are a general rule, making mining Texas lignites economically advantageous. Sometimes conditions exist in which the overburden material will pack in the bucket and then actually overhang the bucket lift. A disadvantage is that the material becomes sticky under certain conditions causing intermittent problems dumping the bucket clean on each pass.

To date, walking draglines have been the most successfully applied machines for overburden removal, and no change in this trend is foreseen. They are available in a wide variety of bucket sizes and boom lengths to give them greater range. The great flexibility in handling variable overburden depths in placement of spoil can be utilized to the best advantage in the relatively flat land and soft digging conditions of the mining area. Dragline productivity rates are generally good in the Texas lignite area, ranging between 250,000 to 300,000 bank yd^3/yr per yard-bucket capacity. These rates indicate that a 60 yd^3 dragline would strip from 15 to 18 million bank yd^3/yr on a sustained basis. The lignite loading and hauling operation is predominantly by shovel and trucks with the lignite delivered directly to a hopper at the generating station. It is not unusual for the lignite bed being mined to have a thin in-seam parting that is separated during mining. To mine this, the shovel loads the lignite to the parting material, then the parting is dozed, usually against the spoil, and the remaining lignite is loaded on a second pass. At the Big Brown mine they say they can remove a parting down to around 3 inches. Below that, the parting materials are included in the mined lignite. Because of the thin seam loading, the shovels used are generally clipped with 8 to 16 yd^3 buckets, and they are supplemented with 10 yd^3 front-end loaders for loading, cleanup, and parting removal as needed. The shovels and/or the front-end loaders load the lignite into 100- to 120-ton highway haulage trucks for delivery to the hopper. At the Big Brown mine, the hoppers are at the generating station, which requires a long 5- to 10-mile haul. (Some maintenance problems have developed along this main hauling road.) The trucks leave the lignite loading area via ramps maintained through the spoil area. Texas reclamation standards require filling the ramps as the mining progresses, leaving a 6- to 7-percent grade in the pit. Scrapers are used then for advancing the ramps every three to four mining cuts. Actually this system aids the loading and hauling because it reduces surface drainage into the pits during rainstorms. Because of the high annual rainfall and the nature of the overburden material, reclamation in Texas has been effective and reasonable in cost. No top soiling is required because the overturned material supports pasture growth equally as well as the former top soil. After grading to approximately the same contour as that prior to mining, the spoils are seeded generally with crimson clover in the cool weather or coastal Bermudagrass in the summer.

In the future, longer range draglines will probably be used. The draglines now have booms extending out to 360 ft. This length gives them the ability to dig and place deeper spoil in one pass. Generally, in mining the thinner and more lenticular seams, mining conditions will become more complex. That is, stripping a single seam is relatively simple. When there are two or three seams, it becomes more and more complex to mine. Draglines will probably be used in tandem operations, and more than one machine will possibly be assigned to a pit, one machine on top removing the overburden down to the first seam and another machine removing the parting material. The geometry of the seams that are present has a great influence on the mining conditions. Perhaps there are two seams that are rather far apart, or perhaps there are two seams that are relatively close together. Scheduling the machines becomes a problem, and the size assigned becomes critical because a more powerful, larger machine might easily become separated from the tandem position.

The lenticular seams will be a problem in mining and maintaining pit lengths. Generally, a stripping operation can sustain pit lengths down to one-half mile, but this is not recommended. A mile or more is considered an optimum distance. Reserve requirements can be a factor in future mining; that is, if you have a 1,100-megawatt (MW) plant, it takes approximately 5 million tons per year for 30 years. Reserves would be 150 million tons or more. In general, some of the smaller deposits may not contain the reserves necessary to sustain a plant.

Mining will be from several deposits with the material transferred by rail to the generating station over short to intermediate distances. Another factor in mining from several seams or from several localized areas, is that the lignite can be blended for higher Btu and lower sulfur content.

It is very difficult to predict single costs for mining the lignite because it varies as to the ratios and the complexity of the system. However, the lignites generally will have to be competitive with the imported coal. As we see it, the coal imported to the area will come mainly from Montana and Wyoming and to a lesser extent from New Mexico. Texas Utilities just signed an agreement with Santa Fe Railroad for mining in New Mexico. However, the studies done by the authors indicate that the FOB mine price from the Montana-Wyoming-Colorado area averages around $7.00 to $7.50 a ton plus the railroad cost for transporting material from that area into Texas. Transportation prices can vary considerably, and it is difficult to formulate concrete answers on what the price is. Generally, it will be from $13.00 to $17.00 a ton or more than twice the FOB mine price of the coal. Total these, $15.00 for transportation and $7.00 per ton, and the cost is $22.00 per ton of coal. On a Btu basis, it is over a $1.20 to $1.50 per million Btu. The Texas lignites, will have the advantage in that the transportation costs will be much lower, and they can compete with the imported coal. Another factor is not so apparent in dollars and cents. That is, the mines are not subject to the vagaries of some of the western state governments. The Governor of Colorado, for instance, is trying to promote a severance tax on molybdenum and coal. The reason why these were singled out is not clear.

At this time, the future of Texas lignite appears to be bright. We have confidence in the development of lignites. This is attested by the fact that the John T. Boyd Company recently opened an office in Houston.

STATE OF TECHNOLOGY OF DEEP MULTISEAM MINING IN EUROPEAN OPEN-CAST MINES[1]

K. H. Peretti[2]

My paper has three parts. First, I will talk to you about some aspects of choosing bucket-wheel excavators for selective mining; secondly, I will give you an example of one project which we carried out in Greece; and, thirdly, I would like to talk about the new developments in our Rheinbraun mines in West Germany.

The necessity to win coal in multiseam open-pit mines arose in the mines of the Rheinische Braunkohle area about 30 years ago. At that time, in the deposit in the south of the area, where coal seams are about 260 to 320 ft thick, mining by bucket-chain excavators came to an end. This mine is still in production because it is a very clean coal which we use for briquetting. Since the seam splits up towards the north and west, only multiseam selective operation is possible in that area. However, the geological conditions are much better in the Rheinische district than, for instance, here in Texas or in other parts of Europe, because in this part of the Rhineland, the seams have thicknesses between 6.5 ft and 115 ft. The technology, however, which was largely developed in the surface mines in Germany, is the same as that used with seams of lesser thickness. The Rheinbraun open-pit mines using multiseam operations are the Frimmersdorf mine in the north and the Zukunft mine in the west. Upon the opening of the Rheinbraun open-pit mines as multiseam operations, bucket-wheel excavators with relatively small bucket-wheel diameters and low capacities were used. But today, only bucket-wheel excavators with a daily output between 78,000 yd^3 per day and 130,000 yd^3 are used in selective mining. Three slides from our Zukunft mine in the west show selective mining. On the first level, there is a smaller bucket-wheel operating, but on the second bench, there is a bucket-wheel operating with 130,000 yd^3 per day. At the next bench one can see the intermediate layers and then another coal seam in the bottom. This mine has an annual output of about 22 million tons of coal and an overburden removal of 85 million yd^3. In similar open-cast mines in the east, southeast, and southwest of Europe, lignite seams are successfully mined in selective operations. There the geological and mining conditions are by far worse and more difficult. The following pictures show open-pit mines in Rumania and Yugoslavia where bucket-wheel excavators of a lower capacity are used in selective-mining operation. At the Dobro Selo mine in Yugoslavia, excavators from Eastern Germany are used. The conditions in this area are difficult.

Now we are back in our Zukunft mine. That is a bucket-wheel excavator of high capacity to select intermediate layers of about 1 to 2 m. Both the simultaneous mining of similar seams in the Rheinbraun open-cast Zukunft and Frimmersdorf mines and also the inclined seams in the open-cast Fortuna Garsdorf mine are reasons for the selective operation and thus the use of bucket-wheel excavators. The bucket-chain excavator which was briefly mentioned and which is still used in some of the Rheinbraun mines efficiently and economically, both for overburden and for continuous coal seams is not suited for selective operation.

Three factors are decisive for selective operation. The lifting mechanism of the bucket-wheel boom which permits lifting and lowering of the bucket wheel during the excavation and during the swivel or slewing operations. In this way the bucket wheel can be adjusted to the inclination of the layers during the excavation operation. Secondly, the arrangement of the operator's stand is coordinated with the cutting height. Therefore, it is possible for the operator to watch and control

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[1] Paper edited from a transcript of oral presentation.

[2] Rheinbraun-Consulting GmbH; Koln, West Germany.

the excavating operation through the different layers. This is not possible with the bucket-chain excavator or with a dragline. Then thirdly, the telescoping bridge which separates the excavator part from the loading part can be extended and retracted so that it is possible for the bucket-wheel excavator to cut above and below the conveyor-belt level. In this way, the excavation can be lifted and lowered and adjusted to certain seam conditions and work in selective operations. In our Rheinbraun mines we do not only use selective operation in coal seams with intermediate layers, but also in the respective overburden layers. Apart from the topsoil layer used for reclamation, gravel and sand layers are removed separate from the clay layers; gravel and sand is conveyed by belts to the lower sector and deposited for a drainage layer in the lowest part of the dump to provide for overall stability of the dump.

Next, let me speak about the interdependence between the actual excavating output and height of slices when using bucket-wheel excavators in the selective operation. The slide shows this interdependence with three bucket-wheel excavators of different capacities. To the right side, the height of the slices will be shown, and to the top the actual excavating output in cubic meter bank per hour will be shown. We have investigated three bucket-wheel excavators of different sizes and different bucket-wheel diameters. The excavator type B under consideration which has an actual output of 1,800 m^3 bank or 2,340 yd^3/hr and a bucket-wheel diameter of 11.5 m (about 38 ft). The guaranteed capacity is reached with a slice height of 15 ft if a maximum swivel or slewing speed is 98 ft per minute (30 m per minute). If, however, the swivel speed is limited to 66 ft or 20 m per minute, the actual capacity will be obtained with a slice height of 17 ft. So when choosing bucket-wheel excavators for selective operation, detailed planning considerations are necessary to adapt the desired capacity of the equipment to the geological conditions. The examples show that in mining relatively thin seams, the larger the equipment capacity, the larger the reduction in output. However, by increasing the slewing speed, the capacity decrease can be reduced.

We have suggested that the equipment for an open-pit mine in Spain be excavators of the type B with a swivel or slewing speed of 40 m or 130 ft per minute. A higher cutting speed produced by a faster bucket-wheel speed does not lead to an increase in the output. In this connection, the bucket height has to be variant for a thinner seam, and the buckets have to be fitted with cutting edges and not with teeth, which have been successfully used for thick coal seams and clay layers in our mines.

With the help of the following examples let me explain to you the possibilities of mining in multiple-seam operations. In the area of the planned open-cast mine of Ptolemais southern field in Greece. The field surface displays a general slight inclination toward the south and southwest. Numerous faults split up the coal field into many narrow fault blocks. The seam-bearing series consists of a number of partial lignite seams (on the average 18) and intermediate layers both of which are different thicknesses. The total thickness of the series, coal and intermediate layers, varies between the extreme figures of 130 ft and 460 ft in the western part of the field. In the areas of the southern and western boundaries of the mining field, the thicknesses of the individual seams are probably reduced toward the boundaries, whereas the intermediate layers become thicker in the same direction. The overburden consists of alternating layers of sandy clay, clayey marl, marly sands as well as limy clays, and some marly limestone and sandstone. The mining plan is as follows: open the field at the north, then parallel operation on the eastern side of the field, followed by swivel operation at the south side, again parallel operation on the western side of the mine moving towards the north, and finally residual exploitation of the northwestern part of the field. The open-pit mine of Ptolemais southern field in Greece was planned by my company in compliance with the required power-station capacity for an output of 18 million tons per year. The overburden and the immediate mass-to-coal ratio of the mining field is 3.3 to 1. That means approximately that 60 million m^3 of overburden would have to be removed every year.

The following should be said about selection of the equipment. The deposit conditions in the southern field of Ptolemais are so diverse that during the first 10 years of operation, on the average, approximately 73 percent of the excavated mass will be overburden and only approximately 27 percent will be selective material, that is, intermediate layers and coal. In the following 10 years, the average ratio will be approximately 55 to 45, and for the last 10 years, there will be only approximately 16 percent of overburden on the average and 84 percent of selective material to be excavated. The excavation and separation height of the excavators should be as large as possible so that, in spite of the large mining depth of 590 ft, as few cuts as possible are made keeping the mine widths and outside dump as small as possible. Dimensioning of the excavators, however, is limited in the southern field by the fact that comprehensive selective excavation for about 48 percent of the mass is necessary with the average cutting height approximately 4.9 to 5.6 ft and with the calculated smallest figures of about 12 inches. It is well known that in selective-excavator operations, the output of the excavator is reduced by its increasing size or by an increase of the size of the bucket wheel and the buckets. For this reason, a suitable compromise had to be found between the excavator size and the tolerable output decrease in selective operation. Prior to the planning of the selection of the equipment it was decided that partial lignite seams of 20 inches or more should be separately excavated. Seams of a thickness of less than 20 inches should be excavated together with the intermediate mass. Intermediate layers of a thickness of 12 inches should be excavated together with the lignite. With the help of examples and optimization calculations of bucket-wheel excavators of different outputs as they are used in European lignite mining and German brown coal mining, the optimum unit sizes for the southern field were determined. The following excavator sizes were taken into consideration: types A, B, and C from 1,430 to 3,900 yd^3/hr. Then we investigated type D, 5,850 yd^3/hr. With the required annual production of 18 million tons of lignite and 60 million m^3 of overburden the following equipment would be required for the deposit conditions for the Ptolemais south field, 16 units of type A or 11 units of type B or 7 units of type C or 5 units of type D. For Ptolemais, seven identical bucket-wheel excavator units with guaranteed output of 3,900 yd^3 were suggested as the optimum. In the meantime, the equipment has been ordered from German companies. The aforementioned output will be achieved in normal operation; in selective operation, excavators will reach approximately 60 percent of the guaranteed output. Transportation of the total overburden to the outside dump and later to the inside dump and of the coal to the power station will be done by conveyor-belt systems with a belt width of 71 inches. In total, 37 miles of conveyor belts are needed on the different levels and as connecting belts for the dumps and to the power station. Reclamation of both the surface of the outside dump and the inside dump will be done by the respective uppermost stacker. The areas where the mining operation shall take place are mainly agricultural estates.

In the last part of this paper, I will speak about the latest development in the Rheinbraun mines. In the Köln basin, we had about 50 billion tons of lignite of which 35 billion could be mined in deep-surface-mining operations. With the five open-cast mines, Rheinbraun produced 110 million tons of coal; that is, more than 87 percent of all the brown coal produced in the Federal Republic of Germany. In order to mine this coal, 340 million yd^3 of overburden had to be removed in 1975. The largest of the five mines is the open-cast Fortuna Garsdorf. In 1975, 45 million short tons of brown coal and about 100 million yd^3 of overburden were excavated in this mine. This equals about 215 million short tons of material; the largest annual output in the world. Up to the present time, exploitation is by bucket-wheel excavators with a daily output of 130,000 yd^3 of unconsolidated sediments and the refilling by stackers of corresponding size (fig. 1). Traditionally we have to increase our production, and so we ordered new machines. These 260,000 yd^3 per day bucket-wheel excavators are expected to streamline operations substantially and increase the specific efficiency per man and shift to 130 short tons of brown coal. In 1950, we had in our area 23 mines with about 70 million tons per year, and we have now only 5 mines in 1975 which have an output of 110 million tons of coal. It was impractical to achieve that output with only slight adjustments to the basic dimensions of a 130,000 yd^3 machine when the wheel excavator was developed. To enable independent movement of the bucket-wheel excavator plant on the one hand and the loading part on the other, the basic concept is that the excavator portion is separated from the loading portion, and a connecting telescoping belt bridge is used. The upper excavation height is about 165 ft, and the maximum possible downward cut is about 60 ft. The excavation range can be widened by lifting or lowering the excavator level above or below the level of loading parts so that total excavation height of 320 ft can be reached. The machine measures 740 ft in length, a 69 ft diameter was selected for the bucket wheel which is equipped with 18 buckets holding 8.5 yd^3 each. When using 230 ft bucket-wheel boom, a block width of 300 ft can be obtained. The excavator weighs 13,000 tons; electric power consumption would total 14,000 kilowatts (kW); 2,500 kW is to drive the bucket wheel of the machine. The doubled capacity

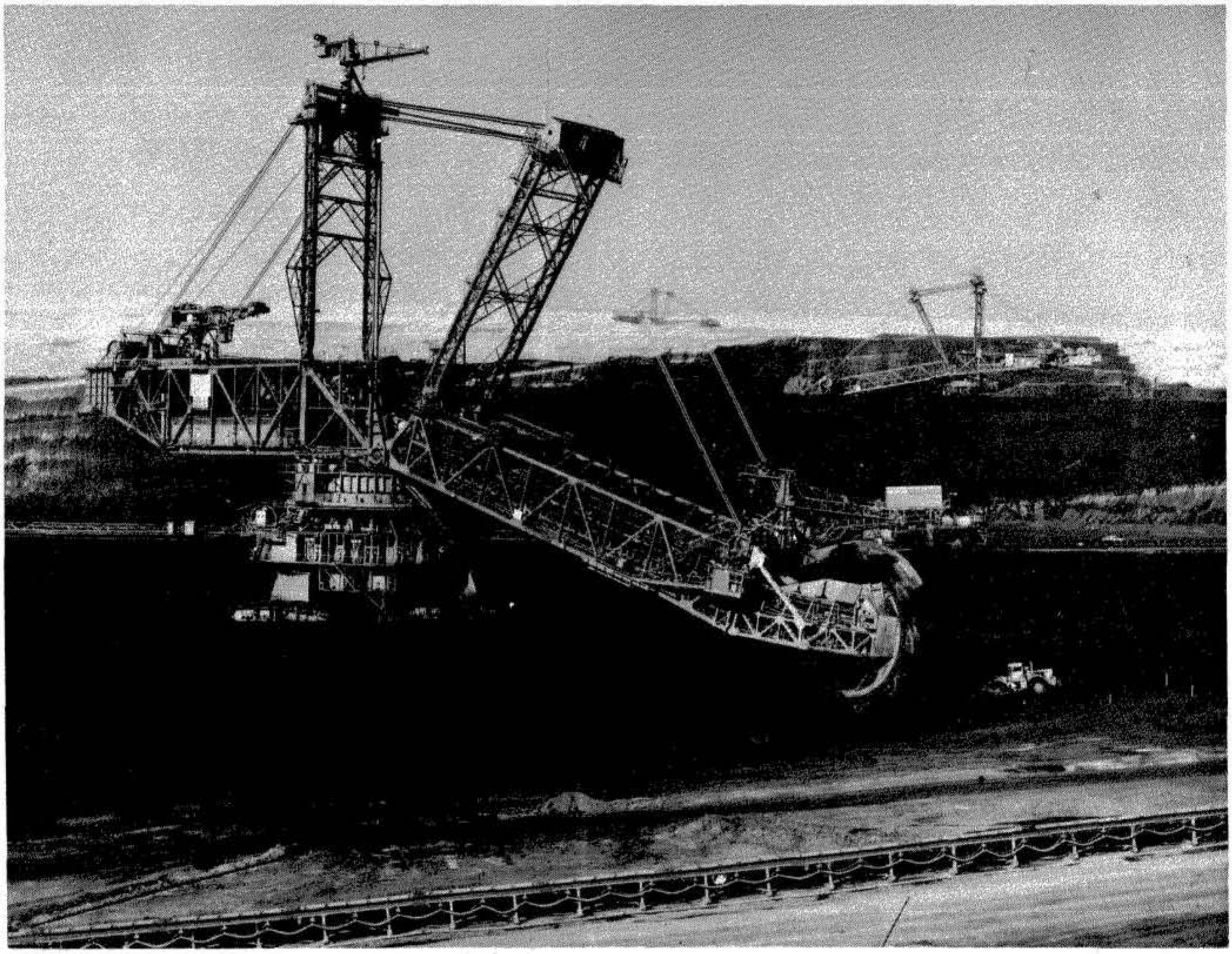

Figure 1. Rheinbraun 130,000 yd³ bucket-wheel excavator, machine about 190 ft high.

of the excavator must be matched by corresponding development at the stackers which dump the overburden; their capacity is increased by wider conveyor belts. The installed capacity of the stackers is 310,000 yd³ per day, slightly exceeds the excavator's capacity so that temporary load peaks of the bucket wheel can still be dumped by the stacker without necessitating shutdowns. The three-belt stacker with a receiving belt supported on a separate driving unit was chosen to keep the construction weight as low as possible. The new machine is able to stack up to a height of 130 ft. The depth in downward stacking is influenced by the fact that the discharge material must be built up on the bottom of the spoil banks to solidify the slopes. Assuming a 35° dumping slope, its resulting height will be about 200 ft. To widen this range the machine is designed to enable the stacker to be placed up to 65 ft below the level of the dump site belt. The stacker's unloading range thus totals 380 ft in height. Within our open-cast mines, trains are not frequently in use as conveyor belts because of their poor climbing capacity. All conveyor belts are operated and controlled by only one dispatching desk. Automatic devices control the unmanned driving and transfer stations and would stop the installation in case of emergencies. The operation of the new types of excavators and stackers requires modern conveyor-belt systems. Note the comparison between the smaller ones which we use now with 118-inch belt widths. The driving stations of this new conveyor belt are equipped with 1,500 kW machines. The belt runs at 20 ft/sec. Corresponding to the driving stations, the individual belt frames likewise will be substantially enlarged. Repair work of these belts, for instance, replacement of rollers, will not be feasible without mechanical help anymore. We use

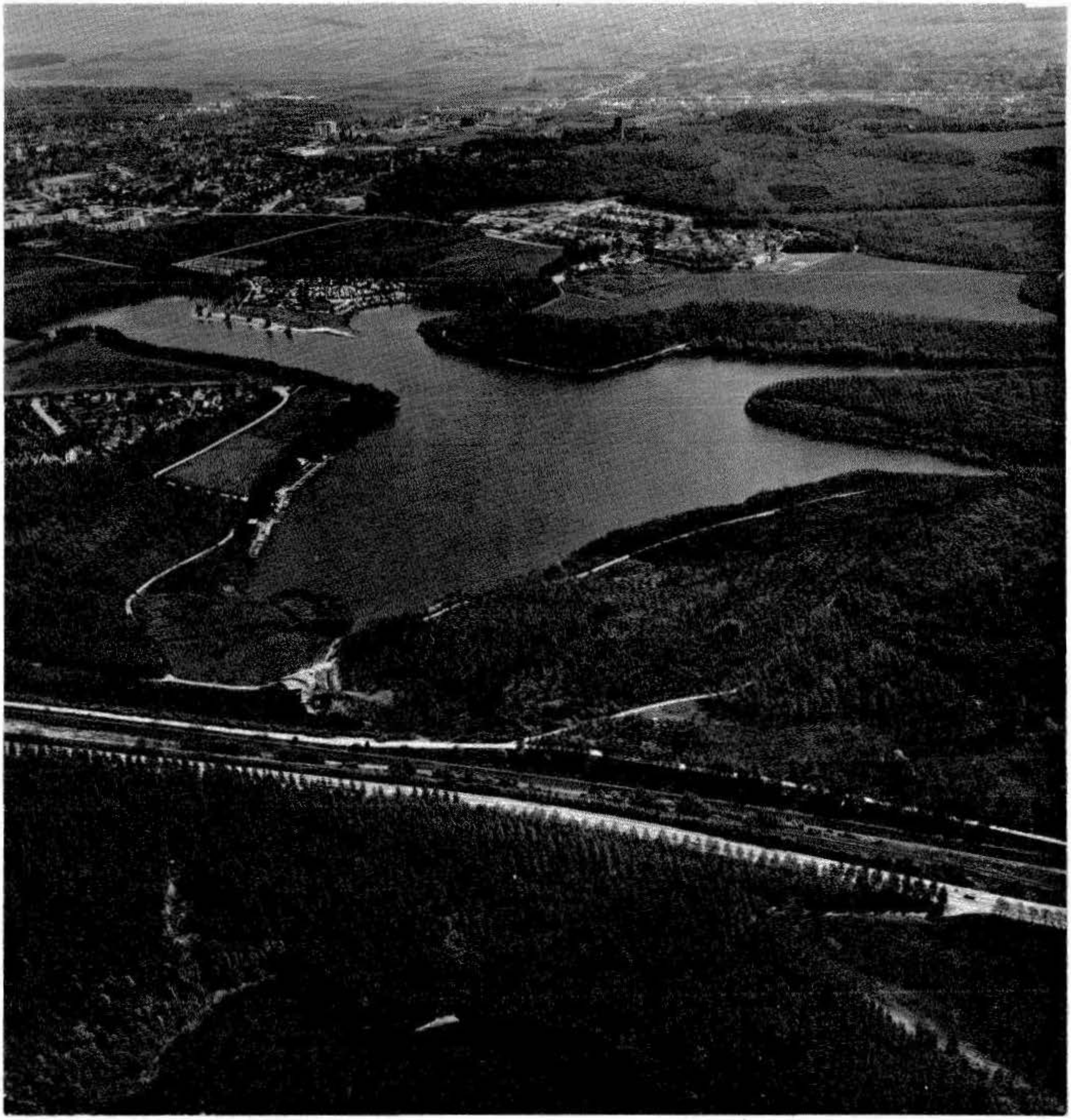

Figure 2. Open-cast area reclaimed by Rheinbraun in the vicinity of Köln.

caterpillar bulldozers or pipe layers in our Fortuna Garsdorf mine.

I would like to say a few words about the advantages of the bucket-wheel excavator conveyor-belt stacker system for reclamation purposes. At the time being, there are very good conditions in the Rheinbraun mines for reclaiming possibilities. For agricultural reclamation, we dispose of very thick loess layers removed by bucket-wheel excavators in selective operation. For forestry reclamation, this loess is mixed with alluvial gravel. If the layout of the mine is of the kind just described, thin layers of topsoil could be removed in selective operation and spread by the uppermost stacker in high-dumping operation on the sterile soils of the upper dump. In this method, we see the following advantages: (1) avoidance of a separate operation for reclamation; (2) avoidance of an expensive intermediate storage of the topsoil; (3) due to the stacker operation, prevention of harmful solidification of the soil on the reclamation site. Because of the dense population of the Rhineland (510 persons per square kilometer) and the intensive agriculture, it was clear from the beginning that the mined-out coal fields should be reclaimed so that farming could start again after refilling, or, in other cases, so that recreation areas of forest and lakes could be available for the people out of the towns and the city of Köln and its environs (fig. 2). It has been proved that the yields of the agricultural fields reclaimed by Rheinbraun were better or at least equal to those produced on the old land. Since the beginning, we have reclaimed, in our area, about 10,000 hectares (about 25,000 acres). But also on reclaimed surfaces for which there was no good soil available, good crops have been obtained. In the open-cast mines in Rumania mentioned earlier, plum trees were planted on clay soil upon our suggestion, and these trees will render a valuable contribution to the increase of the plum-liquor production of this district. That's no joke.

HYDRAULIC TRANSPORTATION OF LIGNITE

D. A. Shock[1]

ABSTRACT

The cost of transportation in producing and delivering a bulk product to its end use is one of the major items in the final cost. With the probability that the Gulf Coast lignite will be developed as a fuel in the near future, the various transport modes in coal mining are examined. The newer developments in the use of hydraulic transport are presented, and the possible application to lignite discussed.

INTRODUCTION

One of the most significant costs in producing a bulk material and delivering the product to the consumer is cost of transportation. Surprisingly enough, this cost often receives scant attention, particularly as a research topic. These transportation costs often are hidden within operations of the system of production and consequently are not identified as a researchable area.

As energy and capital goods costs increase, it is obvious that innovative total-system approaches to transportation must be researched, initiated, and developed. The objective of this paper is not only to briefly outline the present transportation modes in the mining of coal and lignite, but also to discuss more extensively the advances which have been made in hydraulic transportation. These developments will be discussed in relation to lignite.

TRANSPORTATION MODES

COMPARISON OF COSTS

As an illustration of the comparative transportation costs to mine value, the U. S. Department of Commerce completed a study based on 1969 costs of several bulk compounds. Figures 1, 2, and 3 present these comparative costs for iron ore, phosphate rock, and coal. In the study, transport of iron ore was shown to be 3.41 times mine value; transport of phosphate rock was 6.54 times mine value; and that of coal was 1.9 times mine value. The coal considered was eastern bituminous coal that had been through a preparation plant. If the costs of bringing the coal out of the mine to the preparation plant were considered, these transportation costs would increase considerably. The phosphate rock example, which is a strip-mine operation, is much more similar to the costs one would project for a strip-mined, hydraulically transported coal.

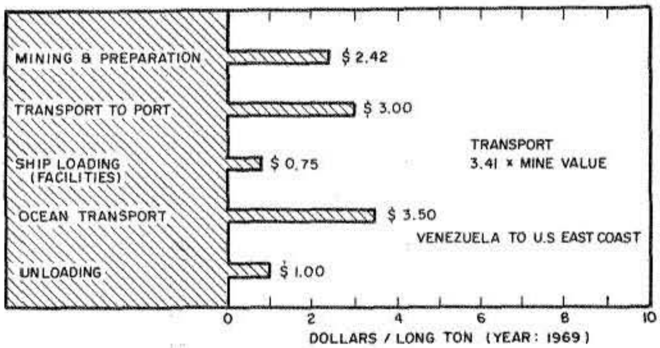

Figure 1. Estimated costs, iron ore.

Mine Transportation

Considering that lignite will be primarily strip mined, underground transport will not be discussed. In a general strip-mine operation the earth above the coal is removed by a large shovel or a drag line with a capacity of approximately 100 yd^3 and piled on one side of a long cut. The coal is subsequently removed by several different techniques, the most common being a smaller

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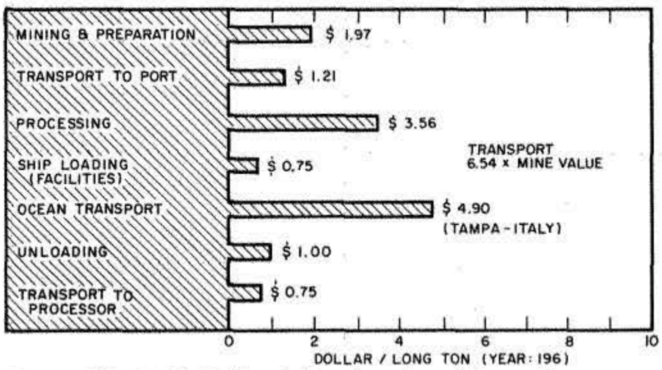

Figure 2. Estimated costs, phosphate rock.

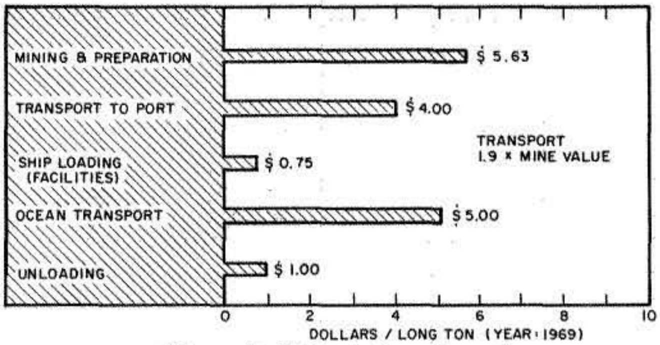

Figure 3. Estimated costs, coal.

power shovel, with approximately a 10 yd^3 capacity, which loads the coal into trucks. The trucks commonly are in the range of 100-ton capacity and operate between the advancing uncovered coal and a storage destination. The method of transport and interfaces at this point depend on the mine situation. Belts and rail transport are often used in long-distance shipping as the mine advances farther away from the use point. The problem of flexibility of transportation, distance to end use, and variability of mine terrain complicates the system so that a mine may use trucks, belts, and rail as well.

Truck transportation is the most expensive in cost per ton-mile, but it is the most flexible. Belts are commonly used, particularly if they can be kept loaded. Costs of 5 to 6 cents per ton-mile can be expected with optimum operation. They can be constructed to traverse rugged terrain where it would be difficult to operate rail and truck transport (fig. 4). Rail haulage is not usually used for relatively short haulage around a mine, however, as a mine is extended, large train loads become more efficient. The three main modes of transportation of strip-mined coal are truck, belt, and rail.

DISTRIBUTION TRANSPORTATION

A graphic presentation of the types of distribution and transportation is shown in figure 5. Because of the variability in sources and destinations, truck and rail shipments are preferred. For large bulk transport, these modes become less efficient so that barge, pipeline, and unit train transport modes which operate between a single source to a limited number of destinations become economically preferable. Table 1 illustrates these points, showing that barge transport is the least expensive, with slurry pipeline and unit trains being next.

IN-MINE TRANSPORT

The hydraulic transport of run-of-mine phosphate rock from the working face to processing plant is an old, established practice. Because the mining method is accomplished by high-pressure hydraulic streams breaking up the rock matrix, the subsequent transportation system is naturally established using high velocity to transport the variable solid concentration to the processing plant where the phosphate rock is separated and concentrated. Hydraulic mining and subsequent sluicing is used in several locations. A Canadian installation operated by Kaiser reported the details of their hydraulic coal-mining installation (Parker and Grimley, 1975).

For some time, Conoco has had under development a mine-face haulage system whereby the coal produced by a continuous miner is sized to 4 inches, fed into a slurrying hopper, and transported to a processing plant or to storage points (McCain and Umphrey, 1974; Dahl and McCain, 1974; and Shock, 1974). The system is illustrated by the schematic in figure 6, which shows the continuous miner feeding a simple mobile crusher which, in turn, feeds a slurry hopper where the solids are fluidized by continuous circulation of water. From the fluidizing hopper the coal slurry is pumped to the preparation plant. This system has worked underground for 2 years transporting several hundred thousand tons of coal. The flexible hose allows the transport system to follow any mine machine and is quite adaptable to any mining program. Using a 10-inch-long hose we have demonstrated that 10 tons per minute can be transported with no difficulty. Thus, it seems feasible that direct, continuous haulage can be accomplished in a surface mine if the comparative eco-

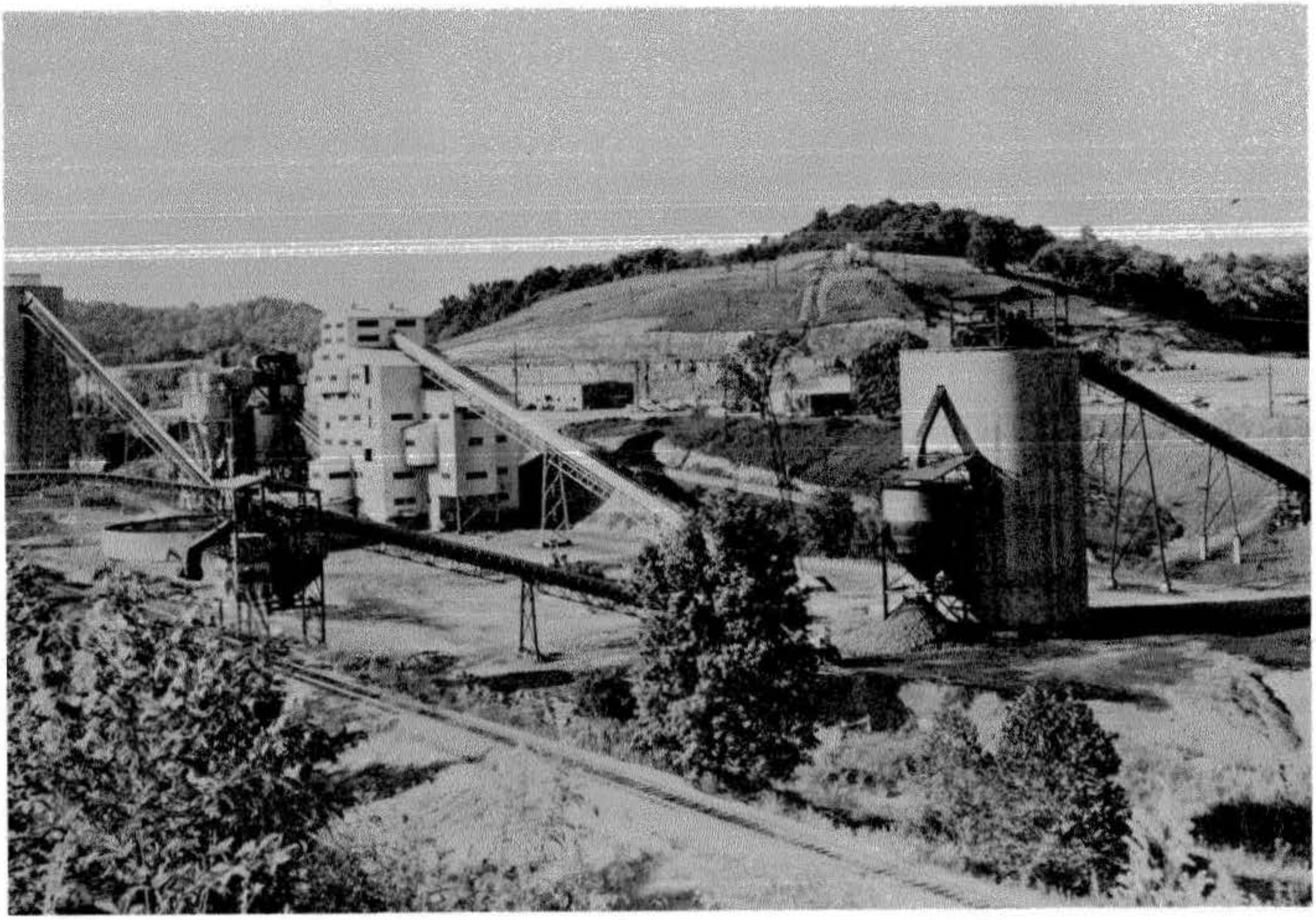

Figure 4. Belt haulage.

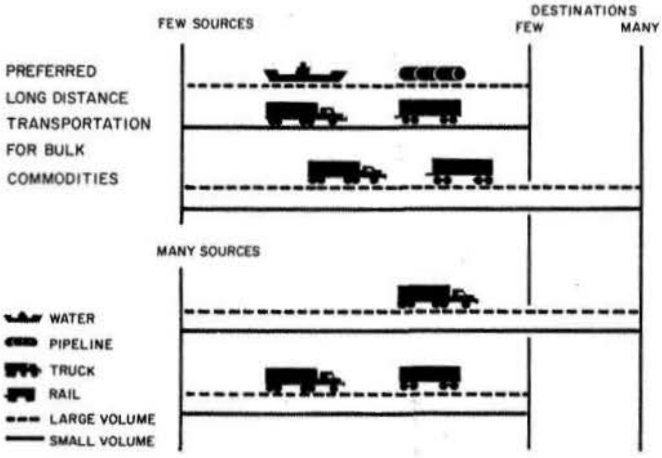

Figure 5. Sources, destinations, and transportation modes.

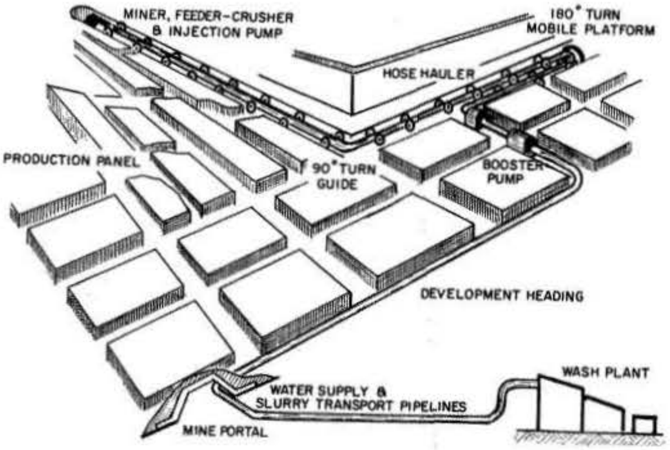

Figure 6. Mine-face haulage system.

nomics are favorable. The details of the components have been under proprietary development for some time and are presented in numerous patent disclosures (Tarter, 1974a and 1974b; McCain, 1974; Tarter and others, 1975; and McCain, 1976).

HYDRAULIC TRANSPORT PRINCIPLES

Although the use of hydraulics to move solids has been used for a number of years, its utilization as a general transport method has evolved slowly. The engineering practice has been established on a sufficiently sound basis that numerous solids pipeline systems are operating throughout the world for specialized situations. The first commercial hydraulic coal transportation line was installed by the Consolidation Coal Company and operated from Cadiz, Ohio, to an electric power plant near Cleveland, Ohio. The most recent coal slurry line in the United States is the fine-coal slurry line which runs between the Black Mesa coal mine in Arizona and the Mojave powerplant on the Colorado River (Ellis and Bochette, 1971). Much of the engineering technology evolved from designing dredging operations. The early work done at the Laboratoire Duphnoes d'Hydraulique in Grenoble, France, laid much of the groundwork for the present empirical design base (Durand and Condolios, 1952; Durand, 1953; Condolios and Chapus, 1963a and 1963b). A generalized relationship between the velocity of the liquid, the various observed flow regimes of solids, and the particle diameter was presented by Newitt and others (1955) and is shown in figure 7. This correlation was made with sand particles; however, it is generally accepted for solids which are not thixotropic. As illustrated in the figure, the large particles move slowly, if at all, when the velocity is relatively low. As the velocity increases and particle size decreases, the solid flow is first seen as a moving bed, then a heterogeneous suspension, and lastly as a homogeneous suspension. The design of a solid pipeline becomes one of adjusting the particle size and velocity. Figure 8 illustrates a typical set of curves determined on three solids concentrations. The objective is to determine the velocity at which solids are moving and not settling. When the data for head loss versus velocity are plotted on a log-log graph, the operating range of velocity that must be maintained is between the lowest critical velocity and a reasonable upper limit at which power will be wasted. Pilot runs on the specific solids to be handled in pipe of 4-inch and greater diameters are usually obtained before a new transport system is constructed. The data are used in optimizing power requirements, pump station location, pipe diameter, operating pressure, and so forth. Figure 9 illustrates the integral parts of a long-distance slurry transport system, taking the coal from the mine to a powerplant or shipping point. A significant advance using hydraulic methods for barge and tanker transport has been accomplished by the use of the Marconyaflo system (Faddick and others, 1976). Solids are pumped into the ship's bunkers, the excess water is drained off, and, at destination, the solids are slurried by jets and pumped to storage for use (fig. 10).

Table 1. Comparative transportation costs for minerals movement (2 to 6 million tons per year over 200–500 miles).

System	Range (cents/ton-mile)[a]	Cost Trend	Comments
Inland waterway	0.2-0.5	Level	Excludes loading and unloading charges
Rail			
Standard	0.8-1.4	Decrease	Includes car ownership
Unit train	0.5-0.9	Increase	Excludes loading and unloading charges
Truck	5.0-8.0	Increase	One-way and empty return
Slurry pipeline	0.3-0.7	Decrease	No slurry preparation charges

[a] Sum of operating costs and capital charges of 15 percent of investment per year.

LIGNITE CONSIDERATIONS

The principal advantage of Gulf Coast lignite is that the deposits circle the Gulf industrial area from the Mexican border at Laredo to Eagle Pass and extend through Louisiana, southern Arkansas, Mississippi, and into Alabama. Edgar and Richardson (1974) in an analysis of the use of Texas lignite as opposed to Wyoming coal, showed an estimated cost of 10.70 mills/kilowatt hour (kWh) (1980) for Texas as opposed to 20.38 mills/kWh (1980) for Wyoming coals at a mine-mouth generating plant. Kaiser (1974) estimated the potential near-surface resources at 10.4 billion short tons. Using the requirement of 250 million tons/1000 megawatt steam-electric plant (35-year life), this amount would operate 40 such plants. In short, this fuel resource would become a major alternate supply to hedge against the spiraling energy costs. Unfortunately lignite leaves much to be desired as a fuel. Lignite (a low-rank coal) is low in Btu value, high in water content, and generally high in ash. The sulfur content, fortunately, is generally low enough to make it a preferable fuel to eastern bituminous coal. It is less dense, more friable, more easily self-igniting, and more

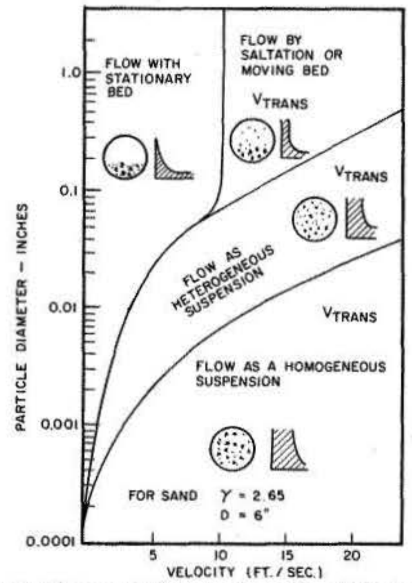

Figure 7. Observed flow regimes in a 6-inch pipe.

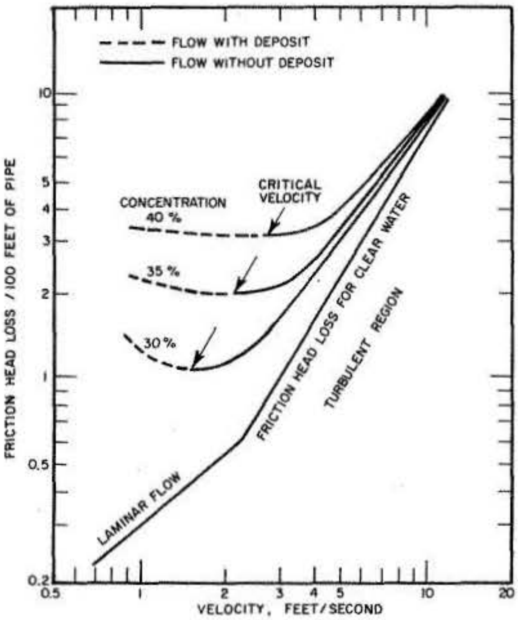

Figure 8. Critical velocities in pipe.

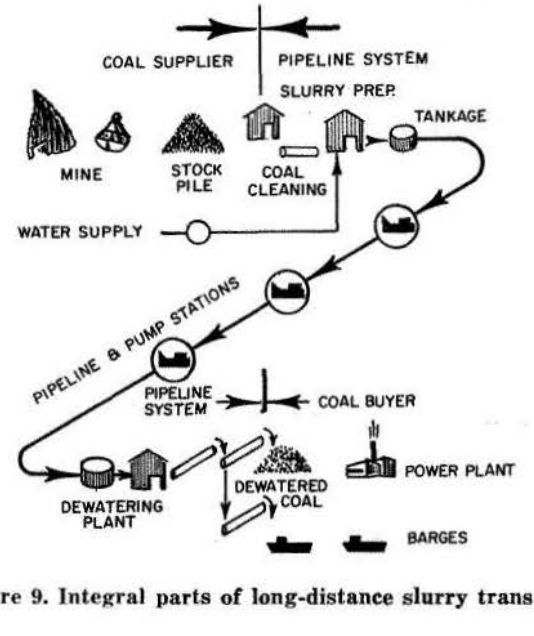

Figure 9. Integral parts of long-distance slurry transport.

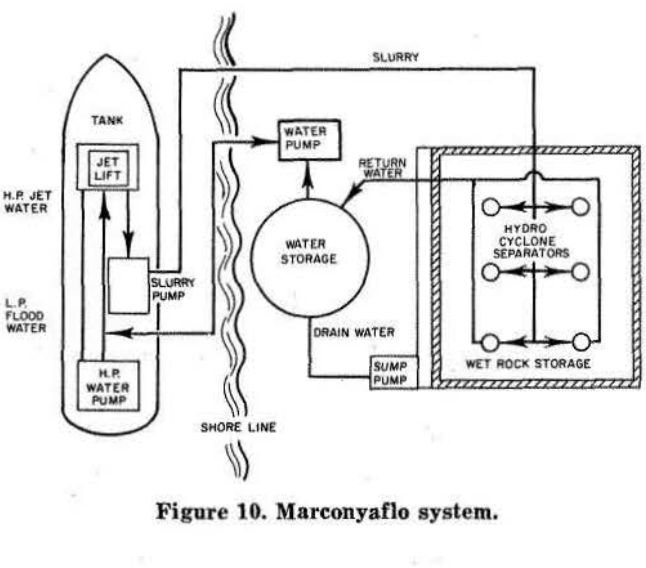

Figure 10. Marconyaflo system.

susceptible to dusting when dry than higher rank coals. Thus, the physical handling of lignite is different from the other coals.

It is significant that the potential of lignite was recognized by The University of Texas at Austin many years ago, and the power generation station at the university was fueled by lignite. The Bureau of Industrial Chemistry, under the direction of E. P. Schoch, conducted considerable research on its utilization (Schoch, 1939). The U. S. Bureau of Mines has maintained an active program in lignite research at its Grand Forks Energy Research Laboratory in Grand Forks, North Dakota. Three major symposia have been held in recent years accumulating a considerable library of lignite technology (U. S. Bureau of Mines, 1967, 1971, and 1973).

The properties of lignite present problems regarding transportation. The excess water (20 to 40 percent), if left in the coal, causes excess transportation cost. The dusting characteristics cause loss by blowing out of storage piles and open coal cars. The self-igniting characteristics require a careful preparation of storage piles to eliminate self-combustion. Although these characteristics present problems, they also provide opportunities for creative solutions and challenging research objectives.

As an answer to some of the transportation problems of lignite, the U. S. Bureau of Mines has conducted research projects where lignite was transported in a water slurry. Lammers and others (1958) concluded that the attrition rate of Texas lignite in water was so great that separation at the use point would be expensive. They further concluded that hydraulic transport of lignite was impractical. With the increasing knowledge of the hydraulic transportation mechanisms and with the possibility of special treatment of the lignite and the fluid, this conclusion should be reexamined. Every and Hughes (U. S. Patent 3,359,040) point out that by water-wetting petroleum coke or coal, hydraulic transportation in a light oil fraction is feasible. The solids are easily separated from the liquid, and properties of both liquid and solids are not altered. Because most lignites are water-wet, the transportation in a hydrocarbon carrier has potential for the future.

CONCLUSIONS

The utilization of Gulf Coast lignite as a source of fuel is a necessity to the future of states in the Gulf area. Development of the transportation modes which take into account the use system as a whole is important to keeping the energy cost low. It is felt that hydraulic transport can play an important role in bringing this needed resource to market.

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RESEARCH AND DEVELOPMENT RELATING TO LIGNITE USE IN POWER PRODUCTION

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ABSTRACT

The present emphasis on coal utilization in the United States together with the requirements for reduction of sulfur dioxide emissions have dramatically increased utilization of lignite and subbituminous coals to over 80 million tons annually, mostly for electrical power generation. Boiler and fuel specifications are summarized for three new facilities from 400 to 550 megawatts designed to use high-fouling lignites from Texas and North Dakota. Ash fouling of fireside boiler tubes is the most serious operating problem. Designs are conservative with low furnace heat-release rates, relatively wide tube spacing, and soot blowers. Research in ash fouling is described, and the role of sodium as an indicator of fouling is discussed. Particulate emissions from boilers fired with low-rank coals are being controlled using electrostatic precipitators and wet scrubbers. Design data are presented, and research activities are reviewed. High moisture and high sodium contents result in satisfactory performance for electrostatic precipitators operating on North Dakota lignite. Although lignites are considered low in sulfur, most lignite-fired boilers will require some sulfur dioxide removal to meet emission standards. Research work on use of the natural alkali in lignite fly ash in wet scrubbers is discussed. Included are data on operating and planned ash-alkali scrubbers. Emission standards are reviewed.

INTRODUCTION

The Grand Forks Energy Research Center (GFERC) is the only research center within the Energy Research and Development Administration (ERDA) working exclusively on lignite and subbituminous coals. The mission of the Center is to contribute to the development of technical options for utilizing these coals in an environmentally sound manner. Current research projects at the Center cover selected program areas in gasification, liquefaction, and combustion. The objective of this paper is to review research on combustion in relation to the state of technology in the lignite industry.

Research on lignite at Grand Forks under the U. S. Bureau of Mines and the University of North Dakota dates back to the period between 1910 and 1920 when studies were initiated on briquetting, carbonization, drying, and combustion. In 1944, the Bureau of Mines established a pilot plant on the campus of the University of North Dakota to test the gasification of lignite in an externally heated retort. In 1951, the present laboratory was built by the Bureau of Mines to provide facilities for 75 to 100 people to work exclusively on the study of lignite. Projects since then have included development of basic information on chemical and physical properties, petrography, pulverization, storage, carbonization, drying, gasification, combustion, and, most recently, liquefaction. Continuing since 1961, biennial lignite symposia have been held in North Dakota under joint sponsorship of the U. S. Bureau of Mines and the University of North Dakota to encourage technology transfer. In 1965, responsibility for research on all western coals was assumed with the phaseout of the U. S. Bureau of Mines Coal Laboratory at Denver, Colorado. In February 1975, the laboratory was transferred to the newly created ERDA. Work since has continued, with increased emphasis and funding on low-rank western coals and on lignite from throughout the United States, including the Gulf province. Close ties have always been maintained between ERDA and the University of North Dakota including graduate fellowships, part-time employment of students and faculty, and the exchange of information and facilities.

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Recent higher prices and reduced supplies of natural gas and petroleum have markedly increased the use of low-rank coals in the United States. Production in the decade from 1964 to 1974 was almost constant at about 9 percent or 50 million tons per year (Westerstrom, 1975). However, from 1973 to 1975, production of these coals has increased to 77 million tons, an increase of 48 percent (Merritt, 1976). During the same 2 years, production of high-rank coals increased by only 5 percent, although still accounting for 88 percent of total production for the United States. In 1975, approximately 50 percent of the low-rank coal mined was produced in the northern Great Plains province and 13 percent in the Gulf province (Merritt, 1976).

The major reserves of low-rank coals are located in the northern Great Plains province (Montana, Wyoming, North Dakota, and South Dakota) and in the Gulf province (Texas, Louisiana, Mississippi, Alabama, and Arkansas). For lignites, the reserve base recoverable by surface mining is 16 billion tons in North Dakota and 3.3 billion tons in Texas (Averitt, 1975 and U. S. Bureau of Mines, 1974). Other estimates will differ somewhat from these figures. Total estimated resources are higher, in turn, by more than a factor of 10.

The program at GFERC on combustion includes projects on fireside ash fouling of boiler heat transfer surface, flue-gas desulfurization (FGD), electrostatic precipitation (ESP) of high-resistivity fly ash, and fluidized-bed combustion. These projects address aspects of both near-term problems of boiler availability and environmental control and long-range problems of developing improved methods of combustion. The state of the technology in these project areas and the current research at GFERC are discussed.

GENERATION OF ELECTRIC POWER

Nearly all of the lignite mined in the United States is burned for electric power generation. A small amount is used in industrial boilers for heating or steam generation. Pulverized-coal (PC) firing is the most popular method of firing for central power stations. However, in recent years three cyclone-fired boilers have been commissioned burning North Dakota lignite. For smaller industrial boilers, the usual firing method is spreader stoker with traveling grate ash discharge. There is also much interest in development of fluidized-bed combustion for application to lignite firing (Kinag and others, 1976). The alkali characteristics of lignite ash make the concept attractive for SO_2 reduction.

MODERN BOILER DESIGNS FOR BURNING LIGNITE

Special precautions must be taken in designing boilers to burn lignites. Although ignition characteristics are generally good, careful design consideration must be given to the higher moisture content, lower heating value, poorer pulverization characteristics (Ellman and others, 1962), and the variable and often troublesome ash contents.

In 1972, there was a total of about 2,300 megawatts (MW) of installed lignite-fired powerplant capacity in the United States. Since then, additional units have been placed in operation and others are under construction both in North Dakota and in Texas. By 1980, the lignite-fired powerplant capacity in the United States should have increased to an estimated 8,000 MW.

Some important design specifications are presented in table 1 for three recent lignite-fired boilers. These boilers were selected because they include both cyclone and pulverized-coal firing and because they are designed to burn high-fouling coals from North Dakota or Texas (Gronhovd and Sondreal, 1976). The two 550 MW Coal Creek boilers (fig. 1; table 1) are designed to burn high-fouling (high sodium) lignite from McLean County in North Dakota. The 450 MW Leland Olds cyclone furnace-fired boiler no. 2 (fig. 2; table 1) is designed to burn high-fouling lignite from Mercer County in North Dakota. Because of the expected fouling tendencies of these coals, the boilers were designed with considerable furnace height (205 ft) and low-volume heat-release rate (7,200 Btu/ft^3-hr for pulverized-coal firing and 12,100 Btu/ft^3-hr for cyclone furnace firing). Other special features for controlling ash fouling include wide tube spacing and shallow tube bank depths in the convection section, steeply sloped floors under the pendant surfaces for shedding deposits into the main furnace, and a large number of soot blowers. The Coal Creek plant will have a total of 252 soot blowers and 27-inch spacing on the secondary superheater pendants. The Leland Olds boiler is designed to have a flue-gas temperature entering the secondary superheater of 1,950°F at rated load. Fouling in the convection section is greatly influenced by flue-gas temperature as the ash-fusion temperature is approached. When burning high-moisture lignites in the cyclone burner, a predrying system is used to maintain the temperature in the cyclone high enough to insure continuous ash melting and slag tapping. Lignite from feeder is mixed with 750° F primary air and carried to and through the hammer-mill crusher where 10 to 12 percent of the total moisture is removed. This "cool" mix of moist air is vented into the furnace above the top row of cyclones. The dried lignite is picked up by a rotary-seal feeder and fed into another stream of 750° F air. An airlift from there to the cyclones completes the fuel-feed cycle. Characteristics of lignite used in design of these units are given in table 2.

The San Miguel plant (fig. 3; table 1) is designed to burn a very low grade of Texas lignite (table 2) having high ash (28 percent), low heating value (higher heating value (HHV, 5,000 Btu/lb), high sulfur content (2.4 percent), and high alkali metal content in the ash (5.0 percent). This lignite is probably the lowest quality coal that has been considered for a large power station in the United States, and the operating experiences of this plant will be watched with great interest by the power industry.

FIRESIDE BOILER-TUBE FOULING

Ash fouling of heat transfer surfaces is the

Table 1. Boiler and equipment specifications for some recent lignite-fired powerplants in the United States.

Plant name (Plant rating, MW)		San Miguel (400)		Coal Creek (2 boilers at 550; total of 1,100)		Leland Olds No. 2 (450)
Boiler specifications:						
Manufacturer		Babcock and Wilcox		Combustion Engineering		Babcock and Wilcox
Firing method		pulverized coal		pulverized coal		cyclone furnace
Rated capacity, lb/hr		3,054 x 10^3		3,730 x 10^3		3,250 x 10^3
Pressure, lb/inch^2 gauge		2,620 (178 atm)		2,620 (178 atm)		2,400 (163 atm)
Steam temperature °F (°C)		1,005 (541)		1,005 (541)		1,005 (541)
Reheat temperature °F (°C)		1,005 (541)		1,005 (541)		1,005 (541)
Balanced draft furnace		Yes		Yes		Yes
Heat release at rated capacity:						
Volume heat release, Btu/hr/ft^3 (kcal/hr/m^3)		*7,500 (66,744)*		*7,200 (64,074)*		*12,100 (107,681)*
Area heat release, Btu/hr/ft^2 (kcal/hr/m^2)		85,000 (230,562)		47,500 (128,843)		78,000 (211,575)
Furnace height, ft (m)		220 (57.1)		205 (62.5)		204 (62.2)
Furnace width, ft (m)		67 (13.7)		95 (28.9)		48 (14.6)
Furnace depth, ft (m)		45 (20.4)		43 (13.1)		45 (13.7)
Design flue-gas temp. and tube spacing:	Temp. °F (°C)	Tube spacing center-to-center inches (cm)	Temp. °F (°C)	Tube-spacing center-to-center inches (cm)	Temp. °F (°C)	Tube spacing center-to-center inches (cm)
Entering secondary superheater	1850 (1010)	24 (60.9)	DNA[1]	27 (68.6)	1950 (1066)	22 (55.9)
Entering reheater	1500 (815)	9 (22.9)	DNA	13.5(34.3)	DNA	9 (22.9)
Entering primary superheater	1110 (598)	4.5 (11.4)	DNA	4.5(11.4)	DNA	4.5 (11.4)
Entering economizer	825 (440)	4.5 (11.4)	DNA	4.5(11.4)	DNA	4.5 (11.4)
Soot blowers:						
Type		Steam		Steam		Steam
Number of short wall blowers		76		192		124
Number of long retractable blowers		80		60		157
Pulverizer, burner data:						
Pulverizer model		Babcock and Wilcox–MPS 89		Combustion Engineering–1043 RP		None
Capacity, tons/hr		86		69		—
Number per boiler		7		8		12 - 10ft (3.05 m) diameter cyclone burners
Number of burners per boiler		42		64		—

[1] Data not available.

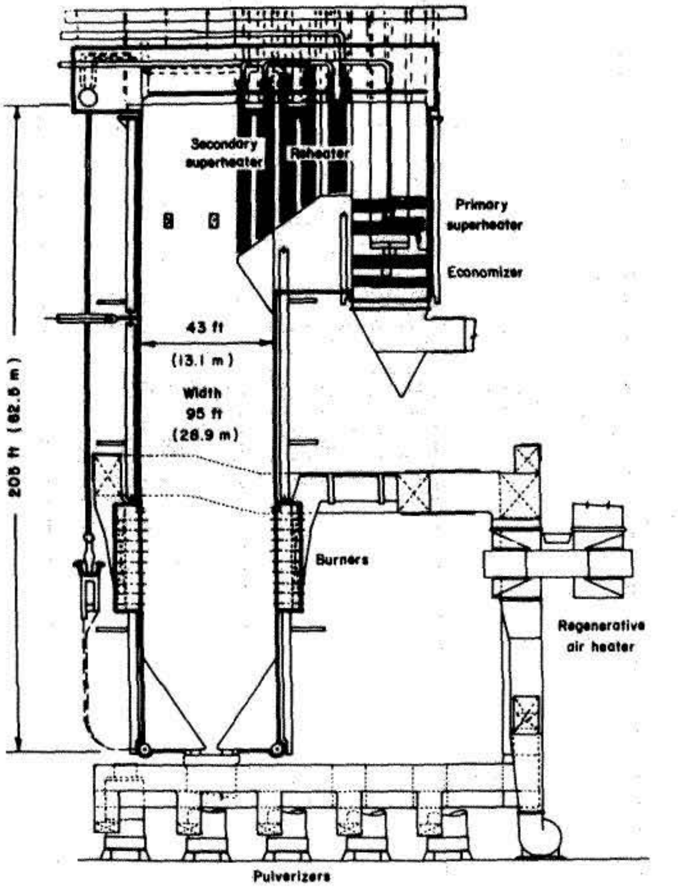

Figure 1. Cross-sectional view of 550MW pulverized coal-fired Coal Creek boiler, United Power Association Cooperation, Inc., Underwood, North Dakota. (High-fouling lignite from McLean County, North Dakota.)

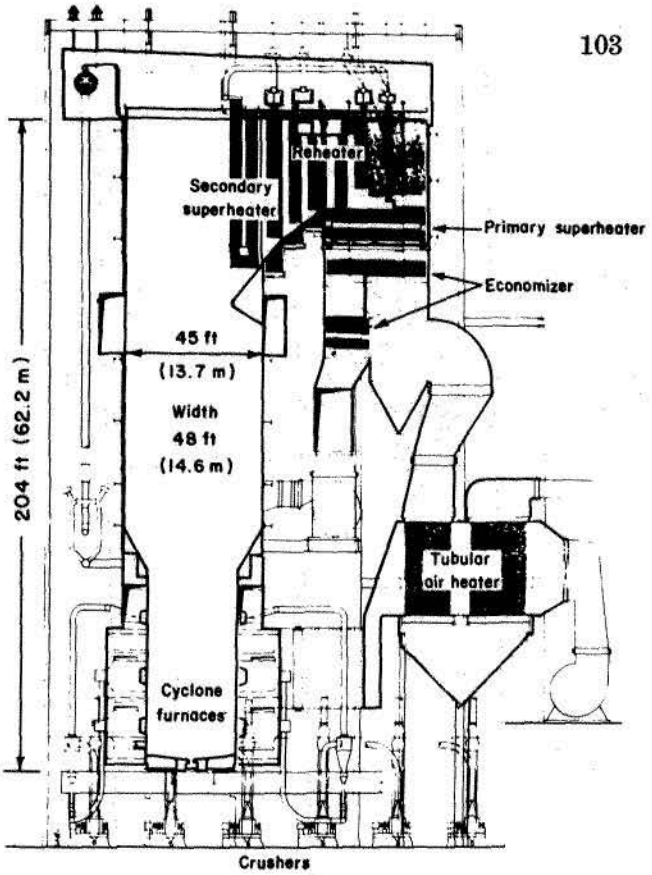

Figure 2. Cross-sectional view of 450MW cyclone-fired Leland Olds No. 2 boiler, Basin Electric Cooperative, Inc., Stanton, North Dakota. (High-fouling lignite from Mercer County, North Dakota.)

most serious problem encountered in operation of power boilers fired with low-rank coals. Fouling is often erratic with excessive ash deposition occurring rapidly and forcing unscheduled shutdown. Design modifications utilized to improve availability have consisted of low volumetric heat-release rates, wider tube spacing, and installation of numerous soot blowers.

The Grand Forks Energy Research Center has conducted research for many years on the properties of lignite and its ash which affect fouling. The research program has included testing of commercial installations, pilot plant work using a specially designed 75 lb/hr test furnace, and laboratory investigations of ash compositions and fusibility characteristics.

Ash Composition

Ash composition of coal varies depending on inherent and extraneous mineral contributions. In addition, there are characteristic differences between high-rank and low-rank coals. A decrease in rank is usually associated with increased concentrations of CaO, MgO, Na_2O, and SO_2, with reduced concentrations of SiO_2 and Al_2O_3. Usually the higher rank coals exhibit a higher content of extraneous ash which can be removed in part by physical separation methods such as that done in commercial washing plants. Table 3 indicates ash characteristics using data from 472 ash analyses (260 of bituminous ash and 212 of lignite ash) (Selvig and Gibson, 1956; Sondreal and others, 1968). Subbituminous coals exhibit intermediate ash compositions, but usually more closely resemble lignitic ash.

Despite differences in composition, the range of fusibilities of ashes from American lignites does not differ significantly from that for bituminous coals, as indicated by results of a study of the analyses of 338 lignite and 135 bituminous ashes (Sondreal and Ellman, 1975).

However, the effect of changes in ash analysis on fusibility is greatly different. Lignite ash is high in the major basic constituents, calcium, magnesium, and sodium, and is relatively low in the acidic constituents, silica and alumina. The fusion temperature of lignite ash is lowered by increas-

Table 2. Fuel specifications for some recent lignite-fired powerplants in the United States.

Plant Name	San Miguel	
Startup date	1979	
Plant location	Christine, Texas - Atascosa County	
Company	Brazos Electric Cooperative Inc. and Southern Texas Electric Cooperative Inc.	
Plant rating, MW	400	
Fuel specications:		
Rank of coal	Lignite	
Location of mine	Atascosa and McMullen Counties, Texas	
Proximate analysis, percent:	Design analysis	Range of analysis
Moisture	30.0	27.0 - 35.0
Volatile matter	23.2	21.4 - 26.2
Fixed carbon	18.4	18.3 - 18.6
Ash	28.4	24.0 - 29.0
Higher heating value, Btu/lb (kcal/kg)	5,000 (2,780)	4,200 (2,335) - 6,350 (3,530)
Ultimate analysis, percent dry basis:		
Carbon	41.5	40.3 - 45.4
Hydrogen	3.4	3.3 - 3.7
Nitrogen	0.73	0.68 - 0.84
Chlorine	0.08	0.04 - 0.14
Sulfur	2.39	2.2 - 2.7
Ash	40.6	34.9 - 41.6
Oxygen	11.3	10.7 - 12.6
Sulfur forms in coal:	Percent of as-mined coal	Percent of total sulfur
Pyritic	0.45	26.9
Sulfate	0.03	1.8
Organic	1.19	71.3
Total	1.67	100.0
Grindability of coal Hardgrove index	102	
Elementary analysis of ash, percent:	Design analysis	Range of analysis
SiO_2	62.9	61.1 - 65.1
Al_2O_3	17.5	16.0 - 19.5
Fe_2O_3	2.8	2.0 - 3.9
TiO_2	0.8	0.7 - 0.9
P_2O_5	0.06	0.04 - 0.12
CaO	4.8	4.0 - 5.5
MgO	0.7	0.5 - 0.8
Na_2O	3.1	2.8 - 3.7
K_2O	1.9	1.8 - 2.1
SO_3	4.6	3.3 - 5.9
Ash-fusion temperature °F (°C)		
Reducing atmosphere:		
Initial deformation	2,120 (1,160)	2,070 (1,132) - 2,170 (1,188)
Softening	2,386 (1,304)	2,360 (1,293) - 2,400 (1,316)
Hemispherical	2,430 (1,332)	2,400 (1,316) - 2,450 (1,343)
Fluid	2,700+ (1,482+)	2,700+ (1,482+)
Oxidizing atmosphere:		
Initial deformation	2,190 (1,199)	2,120 (1,160) - 2,220 (1,216)
Softening	2,430 (1,332)	2,400 (1,316) - 2,450 (1,343)
Hemispherical	2,480 (1,360)	2,450 (1,343) - 2,500 (1,371)
Fluid	2,700+ (1,482+)	2,700+ (1,482+)

[a] Data not available.

Coal Creek 1978 Underwood, North Dakota Cooperative Power Association-United Power Association 2 boilers at 550 MW; total, 1,100 MW		36 Leland Olds No. 2 1975 Stanton, North Dakota Basin Electric Power Cooperative 450	
Lignite McLean County, North Dakota		Lignite Mercer County, North Dakota	
Design analysis	Range of analysis	Design analysis	Range of analysis
39.9	27.8 - 52.6	39.6	33.6 - 40.0
27.6	21.4 - 32.9	27.5	—
25.4	11.4 - 31.5	26.6	—
7.1	3.9 - 11.6	6.3	4.3 - 9.5
6,258 (3,575)	3,068 (1,705) - 7,660 (4,255)	6,523 (3,624)	5,613 (3,118) - 7,320 (4,066)
61.4	43.2 - 66.1	63.5	57.1 - 66.2
4.6	3.1 - 5.2	4.5	3.9 - 5.3
1.1	0.8 - 1.5	1.1	0.88 - 1.4
0.03	0.0 - 0.14	0.02	0.0 - 0.04
1.03	0.4 - 2.4	0.7	0.55 - 2.54
11.9	6.5 - 27.1	10.8	7.2 - 15.8
19.7	16.5 - 25.8	19.4	15.3 - 27.4
Percent of as-mined coal	Percent of total sulfur	Percent of as-mined coal	Percent of total sulfur
0.27	26.1	DNA[a]	DNA
0.04	3.8	DNA	DNA
0.72	69.9	DNA	DNA
1.03	100.0		
36		25	
Design analysis	Range of analysis	Design analysis	Range of analysis
26.5	4.7 - 74.6	23.1	10.8 - 39.6
12.4	2.2 - 19.9	11.3	8.1 - 17.1
8.3	2.7 - 20.3	8.5	4.0 - 15.7
0.5	0.04 - 1.09	0.45	0.26 - 0.68
0.2	0.01 - 0.94	0.23	0.08 - 0.45
24.6	8.8 - 42.8	23.8	14.1 - 41.3
6.8	2.7 - 12.0	5.9	3.1 - 9.2
1.3	0.1 - 7.3	7.4	1.0 - 15.4
0.73	0.1 - 2.4	0.7	0.2 - 1.4
17.9	3.8 - 32.6	17.7	11.2 - 27.8
2,183 (1,195)	1,900 (1,038) - 2,820 (1,550)	2,077 (1,136)	1,910 (1,043) - 2,360 (1,293)
2,211 (1,210)	1,940 (1,060) - 2,820 (1,550)	2,139 (1,170)	1,950 (1,065) - 2,400 (1,315)
2,237 (1,225)	1,960 (1,071) - 2,820 (1,550)	—	—
2,263 (1,240)	1,990 (1,088) - 2,820 (1,550)	2,253 (1,233)	2,060 (1,126) - 2,560 (1,404)
2,247 (1,230)	2,000 (1,093) - 2,820 (1,550)	2,159 (1,181)	1,980 (1,082) - 2,380 (1,304)
2,271 (1,244)	2,020 (1,104) - 2,820 (1,550)	2,277 (1,247)	2,040 (1,115) - 2,400 (1,315)
2,296 (1,258)	2,050 (1,121) - 2,820 (1,550)	—	—
2,323 (1,273)	2,080 (1,138) - 2,820 (1,550)	2,364 (1,296)	2,180 (1,193) - 2,680 (1,971)

ing silica content and is raised by increasing calcium and magnesium contents. Bituminous coal ash, by contrast, is high in the acid constituents, and the effect of changes caused by variations in major individual constituents tends to be reversed. A regression equation on the individual oxide constituents in lignite ash expresses the American Society of Testing and Materials (ASTM) softening temperature as follows (Sondreal and Ellman, 1975).

$$ST_{°F} = 2326 - 6.9\ SiO_2 + 0.1\ Al_2O_3 - 4.3\ Fe_2O_3 - 128\ TiO_2 + 3.5\ P_2O_5 + 8.5\ CaO + 14.9\ MgO - 8.7\ Na_2O + 80\ K_2O - 5.1\ SO_3. \quad (1)$$

A similar equation for bituminous coal ash is:

$$ST_{°F} = 1164 + 12.1\ SiO_2 + 18.8\ Al_2O_3 + 7.2\ Fe_2O_3 + 83\ TiO_2 + 2.0\ CaO - 11.6\ MgO - 13.7\ Na_2O - 22.3\ K_2O. \quad (2)$$

Equations 1 and 2, because of their simple, linear form, best illustrate the influence of elemental constituents in lignite-type ash compared to bituminous-type ash. Other equations, also developed from data obtained at the GFERC include curvilinear effects, which allow a more precise prediction of fusion temperature.

Lignite and bituminous coal ashes are on different sides of the eutectic composition giving lowest ash-fusion temperature. Consequently, where low fusion temperatures are important, such as in slagging operations, addition of basic flux will reduce the melting temperature of bituminous ash, whereas an acidic flux is required to reduce the melting point of lignite ash. The Center maintains an open-file report on low-rank coal and ash compositions which is updated by inclusion of new analyses.

Ash-Fouling Research

Research on ash fouling at the Grand Forks Center has been primarily concerned with evaluation of fouling characteristics using a 75 lb/hr, pulverized-coal-fired pilot plant combustor. The furnace has a refractory lined combustion chamber 30 inches in diameter and 8 ft high. Figure 4 is a schematic arrangement of the furnace, and figure 5 is an overall view of the test facilities. Pulverized coal is fired through a bottom burner. The flue gases containing the particulate pass through three tube-bank sections. Conditions are maintained to simulate conditions at superheater and reheater levels by passing compressed air through the interior of the metal tubes. Temperatures of the flue gases entering the probe banks are controlled at 2000°, 1750°, and 1600°F.

A standard test procedure was developed in which coal was burned for a 5.25 hr test period. After cooling, the deposited ash was removed from the tubes, weighed and analyzed. Figure 6 shows

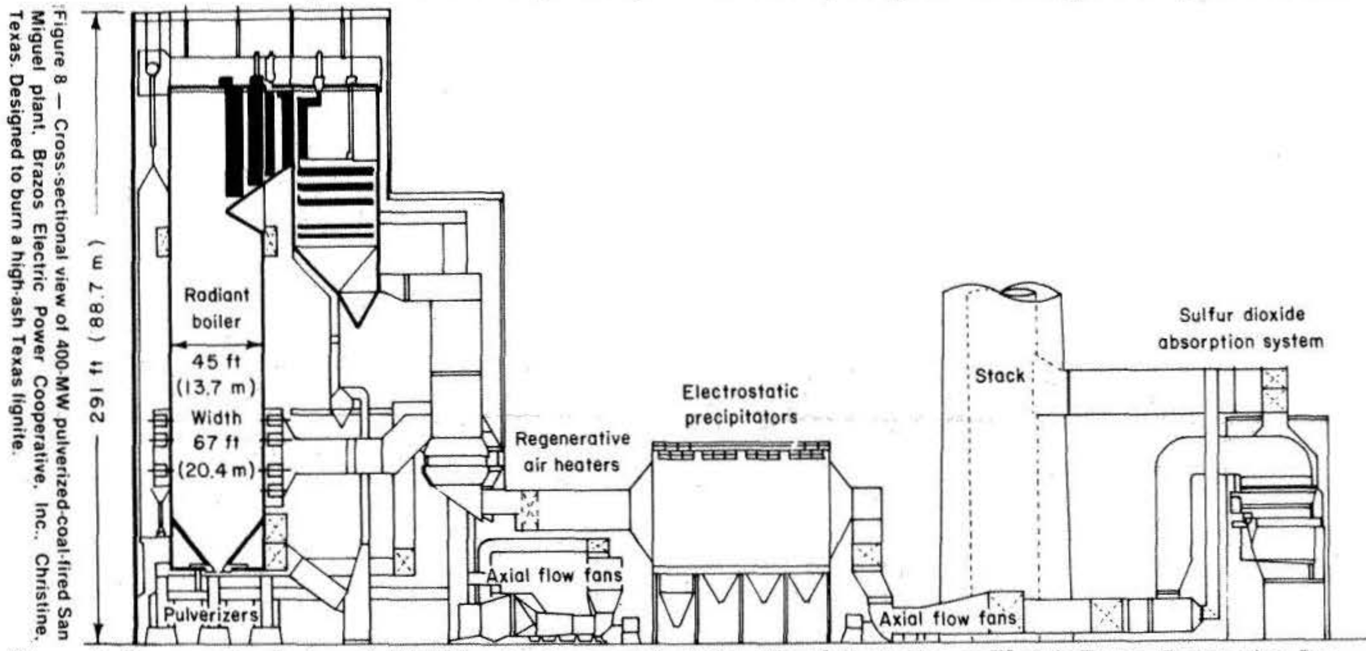

Figure 3. Cross-sectional view of 400MW pulverized-coal fired San Miguel plant, Brazos Electric Power Cooperative, Inc., Christine, Texas. (High-fouling Texas lignite.)

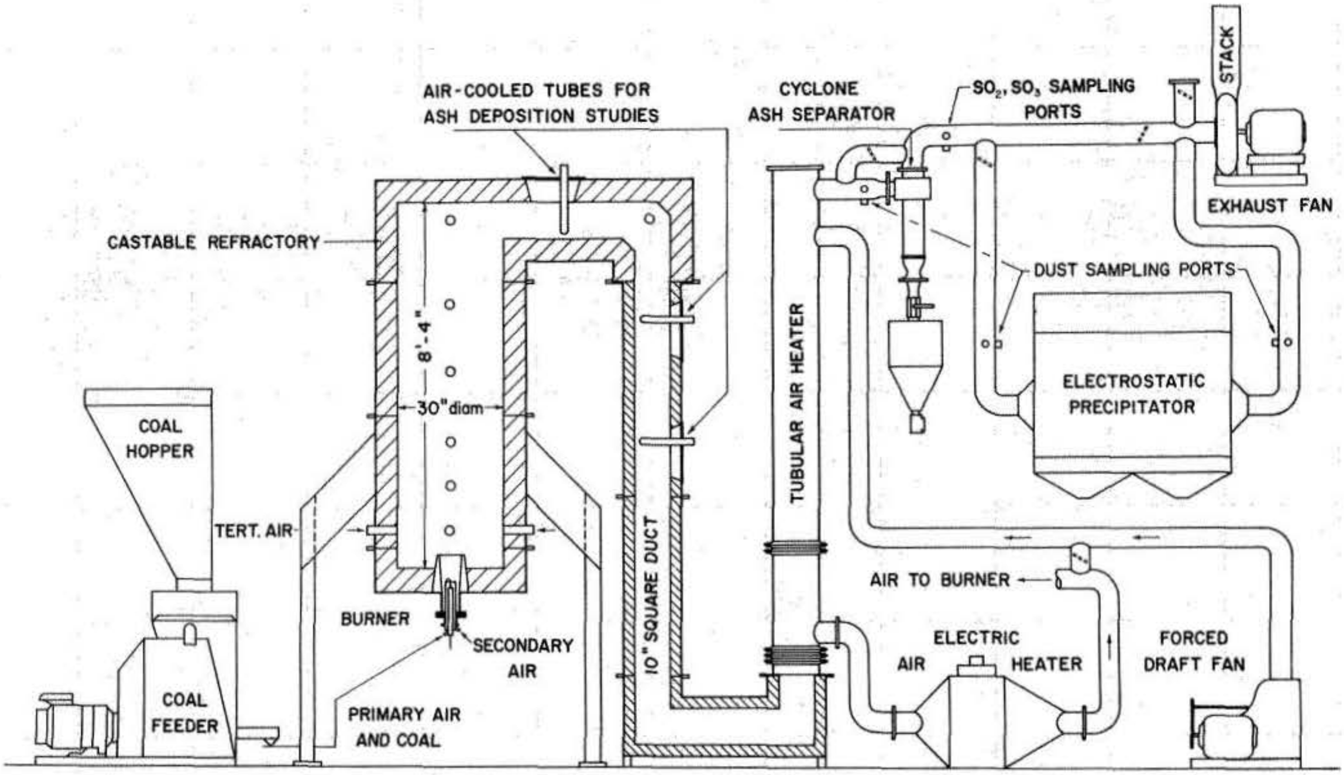

Figure 4. Schematic of 75-lb/hr test furnace and auxiliaries, Grand Forks Energy Research Center.

Table 3. Typical limits of ash composition of United States bituminous coals and lignites.

Component	Bituminous, percent	North Dakota lignite, percent
Silica, SiO_2	20 to 60	11 to 28
Aluminum oxide, Al_2O_3	10 to 35	8 to 14
Ferric oxide, Fe_2O_3	5 to 35	2 to 16
Calcium oxide, CaO	1 to 20	18 to 31
Magnesium oxide, MgO	0.3 to 4	2 to 9
Sodium oxide, Na_2O	0.2 to 3	1.4 to 6.5
Potassium oxide, K_2O	0.2 to 4	0.2 to 0.6
Titanium oxide, TiO_2	0.5 to 2.5	0.2 to 0.6
Phosphorous pentoxide, P_2O_5	0.0 to 3	0.0 to 0.6
Sulfur trioxide, SO_3	0.1 to 12	12 to 27

Ranges shown represent approximately 95 percent of the total variation in the data considered.
From Selvig and Gibson (1956).
From Sondreal and Ellman (1975).

Ash type	Range of ash-softening temperatures (°F)		
	Low	Medium	High
Lignite ashes	1,970	2,322	2,730
Bituminous ashes	1,940	2,355	2,930

the deposits on the tubes when burning a high-fouling and low-fouling lignite. (Note that deposit forms into the flow of stack gases.) The following classification of fouling potential was adopted after much testing and experience.

Deposit weight on first probe bank	Below 150 grams 150–300 grams
Above 300 grams Relative fouling potential	Low Medium High

Test furnace results have been verified by field tests on full-scale boilers. A study (Gronhovd and others, 1969) with various North Dakota lignites showed that the most important indicator of ash deposition was the sodium content of the lignite. The relationship between sodium content in the initial ash and the weight of deposited ash from burning lignite of a constant ash content is indicated in figure 7. Fouling is directly related to the concentration of sodium. Ash-fouling studies have also included investigation of subbituminous coals from Montana and Wyoming with similar results, provided that ash and sodium contents are

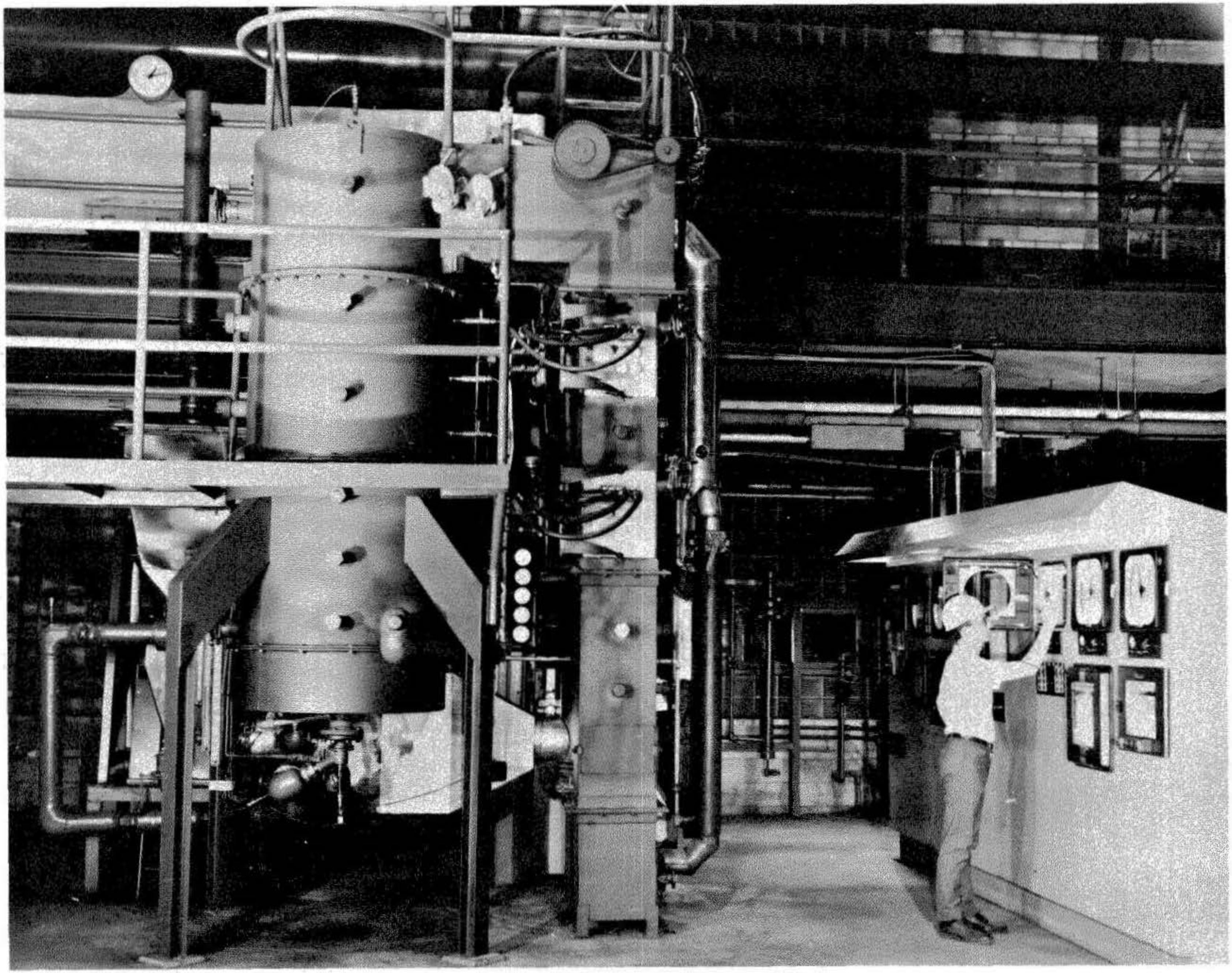

Figure 5. View of 75 lb/hr test furnace and control board, Grand Forks Energy Research Center.

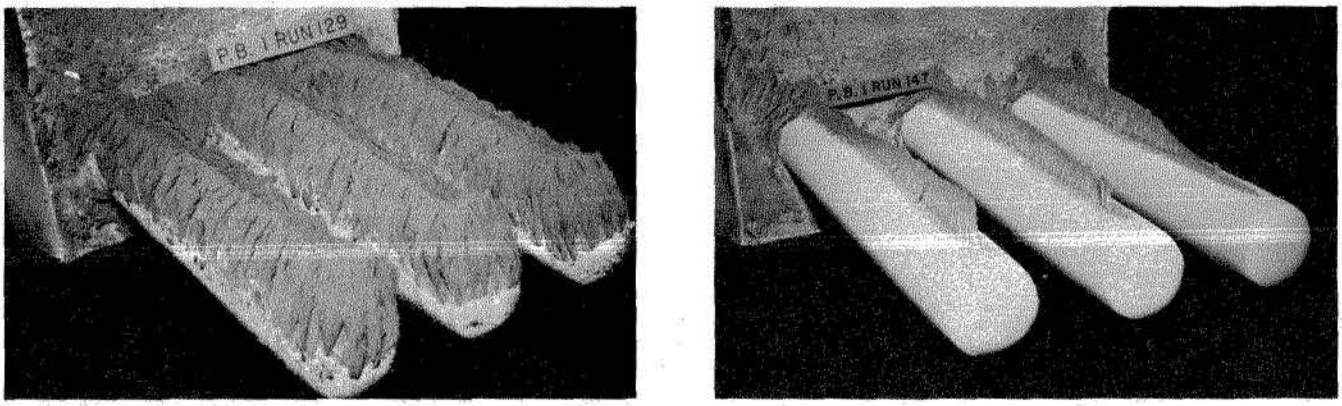

Figure 6. Comparison of probe deposits. (A) High-fouling lignite (weight, 315 g; ash, 10.3 percent dry basis; Na_2O in ash, 6.5 percent). (B) Low-fouling lignite (weight, 35 g; ash 11.8 percent dry basis; Na_2O in ash, 0.5 percent).

the same (Tufte and others, 1976). In figure 8, deposit weight is indicated as a function of ash content for subbituminous coal with sodium content as a parameter illustrating the typical combined effects of ash and sodium contents. Identification of sodium as an indicator of fouling has been applied in some instances by the blending of lignite to control average sodium content. High-sodium lignite is also reserved for periods of low boiler load.

An additional function of the test furnace is to evaluate fouling characteristics of coals from proposed mining areas prior to design of commercial boilers. An example of this activity is the Texas lignite to be used in the San Miguel plant which when tested was found to be the highest fouling lignite.

Mechanism of Ash Fouling

Additional investigations at the Grand Forks Energy Research Center are directed toward determination of the chemical and physical mechanisms responsible for ash deposition. The work includes studies of the mineral matter in the lignite and composition of ash deposits using X-ray diffraction and an electron microprobe (Tufte and Beckering, 1975). Much work has also been done on ash fouling by other investigators over the years, and, although no definitive explanation has been made, there is substantial evidence that the fouling mechanism of western coals differs from that of the eastern coals.

In the lignites studied there are three distinctive modes in which mineral elements occur. From 15 to 20 percent of lignite mineral content occurs

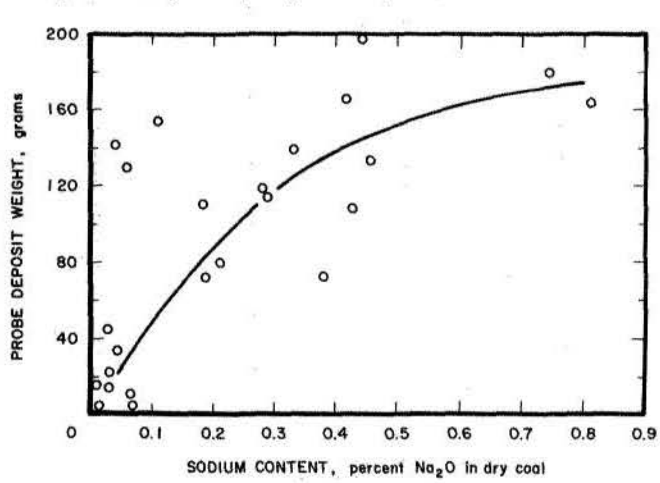

Figure 7. Probe deposit weight as a function of sodium content in ash (North Dakota lignite.)

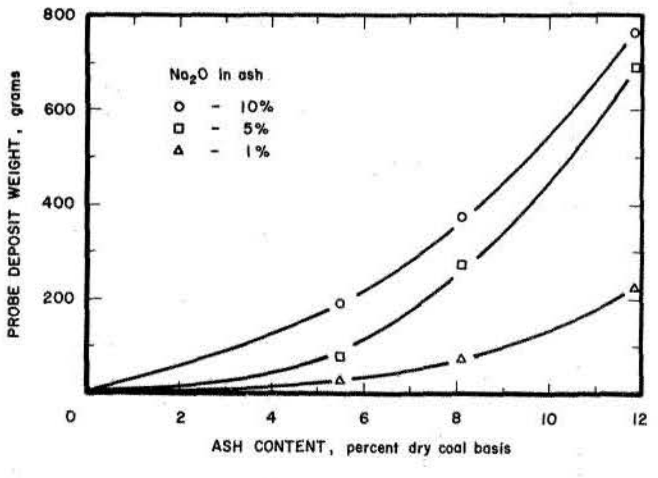

Figure 8. Probe deposit weight as a function of ash content for three subbituminous coals at three sodium levels.

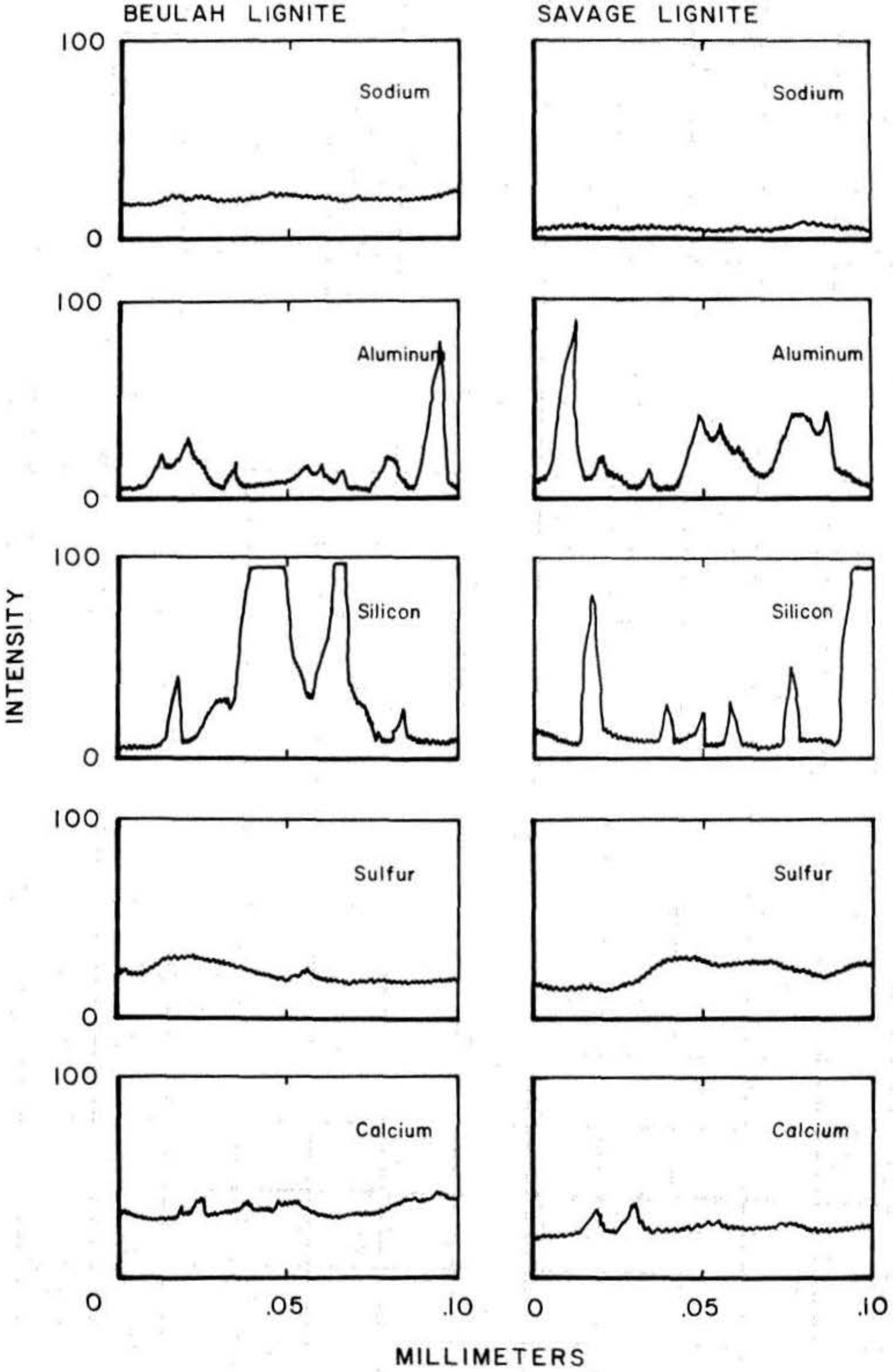

Figure 9. Distribution of mineral elements in lignite from electron microprobe scanning.

as mineral matter separable by CCl_4 float-sink techniques, 35 to 70 percent as organically bound elements, and 20 to 40 percent as finely divided nonseparable clay and SiO_2. Minerals identified in CCl_4 sink-fraction for two lignites are summarized in table 4. The float fraction ash has an analysis similar to the total coal ash.

The organically bound mineral elements (calcium, magnesium, sodium, sulfur, and possibly some iron and aluminum) are present primarily as salts of humic acids and are ion exchangeable. Frequently more than half the coal sulfur is present as organic sulfur. Microprobe examination of both Beulah and Savage lignite samples indicates a relatively uniform distribution of calcium, magnesium, sodium, and sulfur in the coal (fig. 9). Some iron and aluminum may also be distributed in a similar fashion. Because of their abundance and uniform distribution, the organically bound species assume an important role in the fouling mechanism. Finely divided SiO_2 and clay (< 3 micrometers) are dispersed throughout the lignite as shown by the microprobe tracing. The organically bound mineral elements and finely divided clay and SiO_2 are termed "inherent ash," as opposed to the "extraneous ash" separable by float-sink techniques.

Table 4. Minerals identified in CCl_4 sink fraction.
[Beulah and Savage lignites.]

DESCRIPTION	FORMULA OR MAJOR ELEMENTS	ESTIMATED FREQUENCY
	BEULAH LIGNITE	
Magnetite	Fe_3O_4	High
Hematite	Fe_2O_3	High
Pyrite	FeS_2	High
Nacrite	$Al_2Si_2O_5(OH)_4$	Medium-high
Quartz	SiO_2	Medium
Calcite	$CaCO_3$	Low
Dolomite	$CaCO_3 \cdot MgCO_3$	Low
Albite	$NaAlSi_3O_8$	Very low
Unknown	Ca-Si	Very low
Unknown	Ca-Mg-Si	Very low
Unknown	Fe-Al-Si	Very low
Unknown	K-Al-Si	Very low
	SAVAGE LIGNITE[a]	
Halloysite Nacrite Dickite	$Al_2Si_2O_5(OH)_4$	High
Quartz	SiO_2	High
Calcite	$CaCO_3$	Medium
Unidentified	Ca-S-Si	Low
Unidentified	Ca-S	Low
Rutile	TiO_2	Very low

[a] Iron as hematite and pyrite are believed to be present but not isolated.

Examination of pilot plant probe deposits shows them to be of three distinct parts (fig. 10): (1) an inner white layer occurring all around the tube, (2) an inner sinter layer on the upstream face of the probe, and (3) an outer sinter built upon the inner sinter. The vast bulk of the total deposit occurs in the outer sinter layer. It is this layer that characterizes a severe fouling condition.

The white layer consists of a fine fly ash enriched in Na_2SO_4 but otherwise having an analysis similar to the original ash. The mechanisms of Na_2SO_4 enrichment may be vapor condensation or small particle and eddy diffusional processes. The white layer is nonwetting, easily removed, and not considered an important part of the mechanism of forming the large bulk deposits.

The inner sinter layer exhibits particle-to-particle bonding and particle-to-tube bonding of relatively low strength. Surface stickiness of particles appears to be all that is necessary to form this part of the deposit because there is no appreciable melt phase. The mechanism of deposition is impaction of the larger fly-ash particles around the tube stagnation point. In low-sodium, low-fouling lignite deposits, the entire deposit has a structure similar to the inner sinter.

The outer sinter layer consists of fly-ash particles cemented together by a semicontinuous melt phase termed matrix material. The presence of this melt phase is instrumental in the formation of large, strong deposits, and understanding of its deposition is essential for explanation of the fouling mechanism for lignite.

Microprobe analyses of matrix material from the deposits of five lignites have indicated no significant enrichment or depletion relative to coal ash for any element except iron, which is depleted. X-ray diffractions of matrix particles from two lignites have shown two different but repeatable patterns, indicating a crystalline form for the matrix which may be specific to the particular coal studied. The spacings of the diffraction patterns are similar to those for the mineral gehlenite and akermanite which belong to the melilite group of silicates. It is known that gehlenite will form solid solutions with akermanite, and that $NaCaAlSi_2O_7$ will form crystal solutions up to 30 percent with

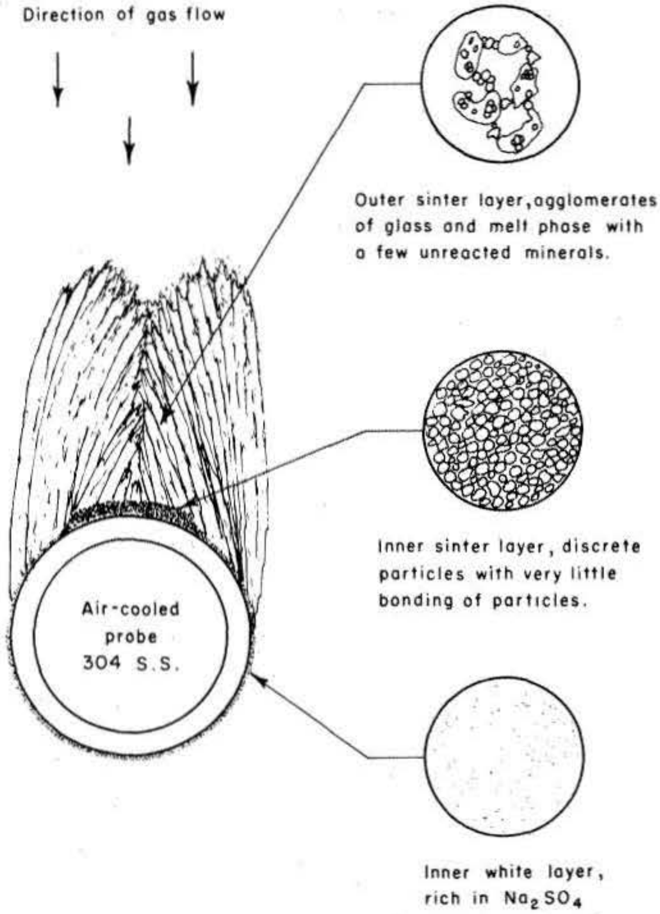

Figure 10. Typical structure of ash deposit from burning high-fouling lignite.

gehlenite. Mixtures of these minerals with amorphous material may comprise the melt phase which cements deposits together.

A fouling mechanism for lignite should explain formation of the "matrix material" from complex ash particles and sodium. Examination of deposits shows that sodium acts to flux a portion of fly-ash particles, termed matrix parent, causing it to soften and flow into a continuous melt phase (matrix), which collects and cements nonreactive fly-ash particles into a strong deposit. Matrix parent particles are derived from the inherent ash in the coal, although not all particles derived from inherent ash are fluxed. Microscopic examination has resulted in the classification of deposit fly-ash particles into the eight descriptive categories shown in table 5. Matrix parent is believed to be that subfraction of category "C" whose elemental composition renders it highly fluxable by sodium. Category "C" particles are found in both high- and low-fouling ashes, but behave differently depending on the presence of sodium. In the absence of sodium, category "C" particles are found throughout the small deposit formed, but no fluxed matrix is present.

In the presence of sodium, category "C" particles are found in the inner sinter layer next to the cool tube surface and fluxed matrix particles are not. In the outer sinter layer, fused matrix is found but no category "C" particles, implying a reaction between sodium and category "C" particles to form matrix material in the hot outer sinter layer.

The sodium, which fluxes the matrix parent, originates from the organically bound sodium in the coal, which is volatilized as a coal particle burns. If sulfur is present in the flue gas as SO_2 or SO_3, Na_2SO_4 will be rapidly formed in the flue-gas stream. If sulfur species are not present, Na_2CO_3 will be formed. Either species will act to flux deposits based on the observed fouling behavior of pure compounds injected into a gas flame.

Two ways to alleviate fouling in lignite may be suggested based on the proposed mechanism. The first is an additive to tie up sodium in an unreactive form, thus inhibiting its fluxing action. The second is an additive which would react with inherent ash to raise the fusion temperature of the matrix parent or otherwise inhibit the fluxing action of sodium.

FLUIDIZED-BED COMBUSTION — THE FUTURE METHOD OF FIRING

The problem of ash fouling and the problem of controlling sulfur emissions are both potentially solved by fluidized-bed combustion (FBC). This FBC involves the combustion of minus ¼-inch coal at a controlled temperature of 1,500° to 1,800°F in a bed of inert material held in suspension (fluidized) by a flow of air up through the bottom of the bed. The relatively low temperature of the bed, lower than the fusion of the ash, should greatly reduce or eliminate the ash-fouling problem. Also, at this temperature the sulfur dioxide generated from the coal can be absorbed on limestone, or in the case of lignite, at least partially on the alkaline coal ash. The capability of absorbing sulfur dioxide during combustion eliminates the need for flue-gas desulfurization, which is the primary incentive hastening the development of FBC. Other envisioned advantages are a reduced emission of NO_x and the possibility of building smaller and less costly boilers because of the inherently high heat-transfer rates between the bed and immersed heat-transfer surfaces.

The ERDA program on FBC has the objective of rapid development for both utlility and industrial applications, with commercialization targeted for the 1980's. Atmospheric fluidized-bed combustion (AFBC), which is farthest advanced, is a natural successor to pulverized-coal firing for steam generation. Pressurized fluidized-bed combustion (PFBC), at a less advanced stage of development, is envisioned to be applied to combined-cycle power generation provided that the hot pressurized combustion gas can be economically cleaned sufficiently to permit expansion through a gas turbine. The ERDA FBC program includes AFBC projects up to pilot plant scale, with the 30 MWe AFBC boiler at Rivesville, West Virginia, to be operational in July 1976. The Curtis Wright Company has been selected (January 1976) to build a 13 megawatts electrical (MWe) PFBC combined cycle pilot plant to be completed by 1980. Demonstration plants of nominally 200 MWe are projected beyond the pilot plant projects to establish FBC technology as a viable option for the power industry.

A small FBC project recently started at GFERC has the objective of determining the extent of retention of SO_2 on the alkaline ash formed from burning lignites and western subbituminous coals in an AFBC. The test facility shown in figure 11 has a 6-inch inside diameter combustion chamber and is cooled both by air flowing through an outer annulus and by water flowing through tubes immersed in the bed. Tests scheduled for this unit involve the determination of sulfur retention for a number of coals selected to represent the full range of variation in ash analysis for lignites and western subbituminous coals, and determination of the effect of temperature and ash-residence time on sulfur retention.

Table 5. A comparison of chemical analysis of various particle categories for two lignites.

Category designation[a]	A	B	C	D	E	F	G	H	I
			BEULAH LIGNITE						
Number of particles analyzed	23	12	34	24	29	12	2	2	8
Element, percent:									
SiO_2	30±7	28±5	16±12	40±23	12±10	12±18			9±9
Al_2O_3	11±4	17±4	14±9	14±9	10±4	10±5			14±7
Fe_2O_3	3±2	1±1	1±1	2±1	4±2	4±2	85+	70+	5±4
CaO	32±8	28±4	31±12	24±17	42±9	44±15			47±8
MgO	10±5	5±2	12±7	6±4	15±7	10±3			21±5
Na_2O	4±2	7±4	3±4	8±5	3±4	1±3			1±1
SO_3	11±5	12±7	22±12	5±4	14±7	19±9			5±2
			SAVAGE LIGNITE[b]						
Number of particles analyzed	19	7	4	7	24	17	0	0	2
Element, percent:									
SiO_2	23±6	NA	10±7	24±33	8±13	5±9			13±2
Al_2O_3	11±3		9±6	17±20	5±4	2±2			9±3
Fe_2O_3	1±2		0±0	0±0	0±0	0±0			1±1
CaO	23±5		25±2	31±20	43±9	46±9			29±6
MgO	8±3		15±5	7±6	6±6	2±3			22±5
Na_20	12±5		9±3	0±0	0±0	0±0			0±0
SO_3	21±6		34±9	20±7	34±15	45±9			4±1

[a] Key to category designations:
A: Matrix or binding material.
B: Opaque white angular solid particles. (Believed to be a pure form of matrix.)
C: Opaque white or yellow angular agglomerated particles.
D: Transparent colorless spherical solid particles.
E: Transparent yellow spherical solid particles.
F: Opaque yellow spherical solid particles.
G: Opaque black spherical solids.
H: Opaque red angular solids.
I: Ash residue from float coal particles in CCl_4 when ignited over a bunsen burner.

[b] Note: Particle categories A and F for Savage are from a test where sodium nitrate was added to the coal. The other particles are from Savage without Na_2O in the coal ash.

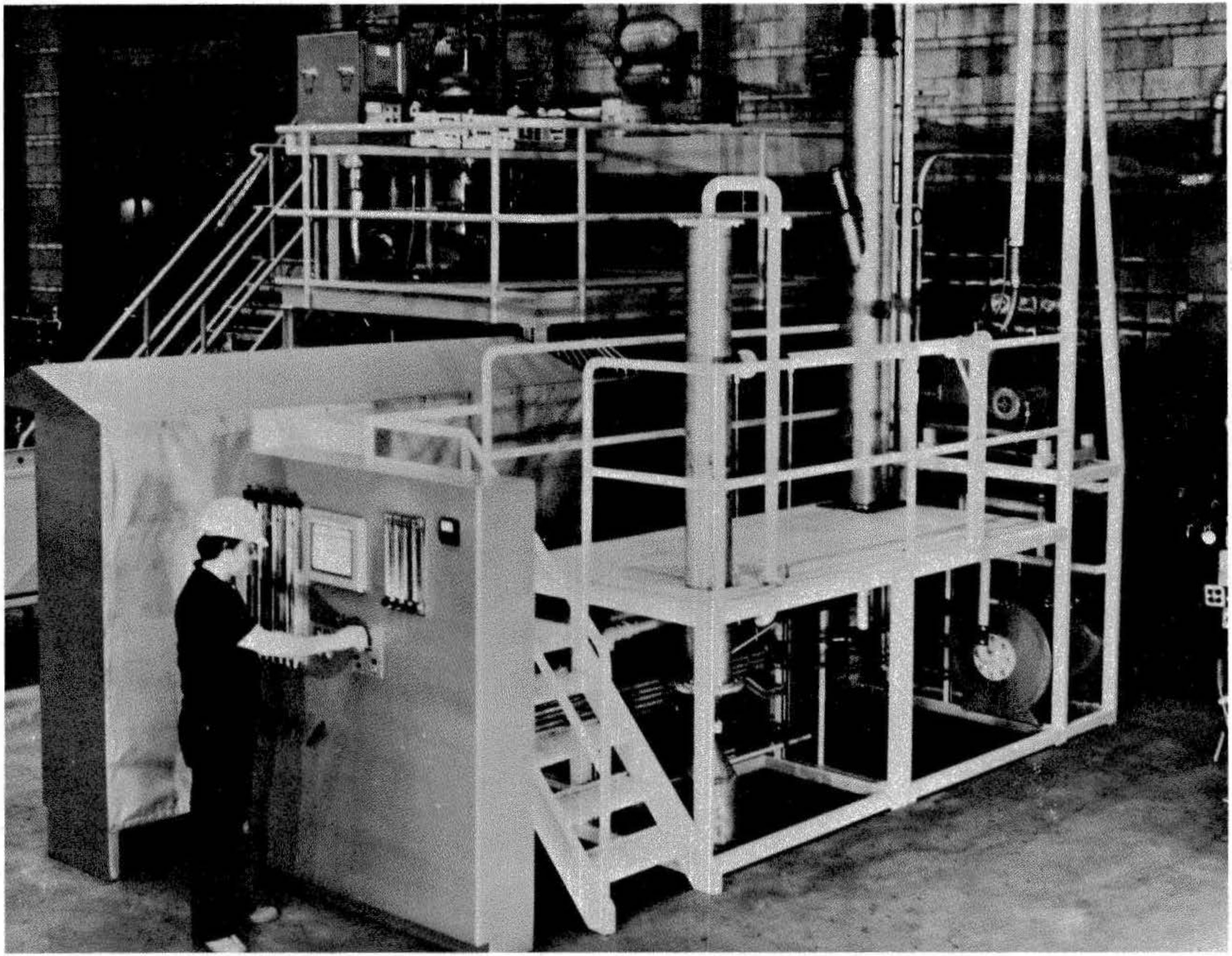

Figure 11. Experimental fluidized-bed combustor, Grand Forks Energy Research Center.

EMISSION CONTROLS

The commitment for reduction and control of air pollution has become one of the most important influences on power production in the United States. This concern dominates the planning of all new power projects and necessitates changes in fuel or plant equipment for many existing operations. It largely determines choice of fuel, plant siting, selection of emission control equipment, and reliability and availability of plant operations.

New source performance standards, applying to all new construction or modifications of units more than 25 MW capacity began after August 17, 1971, require that stack-gas-cleaning equipment be installed on all new coal-burning power stations. These standards (from EPA) are as follows:

	lb/10^6 Btu Input
SO_2	1.2
NO_x	0.7
Particulate	0.1

Compliance without the use of stack-gas-cleaning equipment would require an ash content below 0.1 percent and sulfur content below 0.5 percent based on the heating value of lignite and 80-percent emission of the coal's ash and sulfur. The required ash content, of course, cannot be met by any coal, and the required sulfur content can be met only by a few subbituminous coal deposits.

The new source performance standards were adopted largely on the basis of the best technology available at the time the standards were issued. The standard of 0.7 lb $NO_x/10^6$ Btu was applied only to coal of subbituminous rank and higher, because no data were available at the time of issuance to establish the best technology available for lignite. The EPA has since issued a draft regulation for lignite, requiring an emission below 0.6 lb $NO_x/10^6$ Btu. The EPA justifies the lower emission standard for lignite based on an alleged lower fuel nitrogen content and a lower flame temperature for lignite compared to other coals.

Some state and local governments have adopted emission standards which are stricter than the Federal standards. Six western states have SO_2 standards lower than the Federal standard of 1.2 lb $SO_2/10^6$ Btu. The State of New Mexico, with an NO standard of 0.45 lb $NO_x/10^6$ Btu, has the only regulation that is stricter than the Federal standard of 0.7 lb $NO_x/10^6$ Btu. No statewide standard on particulate is lower than the Federal standard of 0.1 lb/10^6 Btu. The most stringent standards existing anywhere in the United States are the local regulations of Clark County, Nevada, which require an SO_2 emission below 0.15 lb $SO_2/10^6$ Btu and an opacity corresponding to a particulate emission of about 0.02 lb/10^6 Btu.

EMISSION CONTROL TECHNOLOGY FOR FLY-ASH PARTICULATE

Wet scrubbers and ESP's are the devices currently used to reduce fly-ash particulate emissions down to the level required by the new source performance standards. Both require recognition of the special properties of low-rank coals if they are to be designed to operate effectively.

Electrostatic Precipitation

The special properties of low-rank American coals which influence the design and operating efficiency of electrostatic precipitators are (1) low sulfur content and an alkaline ash, which yield a negligible SO_3 content in the flue gas, (2) an ash composition which leads to high electrical resistivity for some fly ashes, (3) often moderate to high sodium contents which are instrumental in lowering the resistivity of fly ash, and (4) a high moisture content. The first two factors are detrimental, and the last two are beneficial. Because of uncertainty regarding the effects of these variables, ESP's recently constructed for use with lignite and subbituminous coals are generally oversized.

The resistivity of fly ash is controlled by surface conduction at temperatures below about 350°F and by conduction through particles above 450° to 500°F. A gradual change in the dominant conduction mechanism from surface to volume occurs in the range from 300° to 500°F. Resistivity is maximum at about 400°F and is reduced at either lower or higher temperatures. Hot precipitators operating at nominally 600°F can be operated efficiently on problem fly ashes; however, only two such precipitators have been constructed for low-rank coals in the United States.

Sodium content has been shown by tests at GFERC (Selle and others, 1972; Selle and others, 1975) to have an overriding effect in lowering the resistivity of fly ash from low-rank coals at both high and low temperatures (fig. 12). Also, the

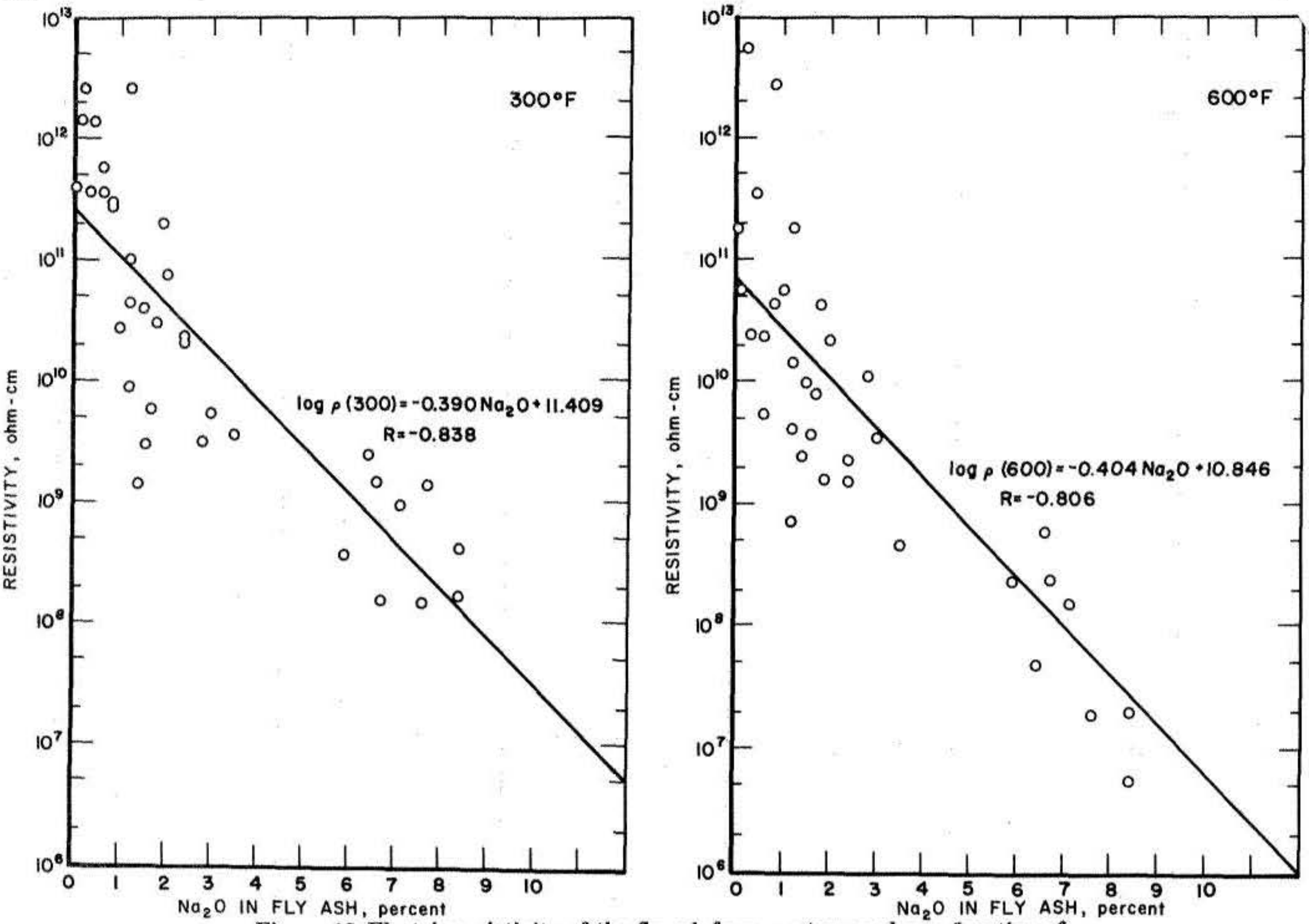

Figure 12. Electric resistivity of the fly ash from western coal as a function of Na_2O *content at* 300°F and 600°F (laboratory measurements).

addition of small amounts of sodium has been shown to improve ESP efficiency in both pilot plant tests (Selle and others, 1975) and field tests (White, 1974). The improvement in collection efficiency with added sodium is greatest at low levels of sodium between 0 and about 1 percent; further addition of sodium continues to reduce fly-ash resistivity, but does not further improve efficiency at a fixed power setting.

Many of the first ESP's installed on boilers burning subbituminous coals failed to meet guaranteed efficiencies. These were low-temperature collector units designed with specific collecting areas of 90 to 214 ft^2/1,000 actual ft^3 for removals in the range of 87 to 98 percent. Gas conditioning by injection of about 20 parts per million (ppm) SO_2 into the flue gas increased removal efficiencies, but not to the level of the guarantee for all units. One utility was able to overcome a high resistivity problem by lowering ESP operating temperatures by diluting the flue gas with fresh air.

Recent experience with ESP's on powerplants burning North Dakota lignites has been good. All operating units, for which data are shown in table 6, have met or exceeded design efficiencies. These units were designed with specific collecting areas from 235 to 375 ft^2/1,000 actual ft^3 for removals in the range of 97 to 99.5 percent. The design is only slightly more conservative than that of the earlier units operated on subbituminous coals, considering similar removal efficiencies. The superior performance of units operating on lignite, at least partially, is caused by differences in the properties of the coals, with lignite having a higher moisture content and sodium in the ash. The operating problems of ESP's on boilers burning lignite are concerned mainly with removal of fly ash from the hoppers. High-sodium fly ash has a tendency to cake in the hopper and on spreader-stoker units, combustion of carbon carryover in the ESP hopper can cause ash clinkers.

Research on ESP at the Grand Forks Energy Research Center has the short-term goal of determining a reliable means of sizing ESP's so that they will meet the new source performance standards in burning western coals. This problem was first approached by developing information on the resistivity of western coal fly ash and correlating the results with elemental analysis. Since this resistivity research has not provided a sufficient criterion, present work is focused on the design and construction of a new pulverized-coal-fired pilot plant furnace that will allow fly ash to be generated under controlled conditions of temperature and residence time without loss of ash from the flue gas. This furnace will be attached to a new pilot ESP, and tests will be run to rank the precipitability of fly ashes from lignites and western subbituminous coals. By collecting pilot plant data on known coals and corresponding data from commercial ESP's operating on the same coals, the significance of the pilot plant ranking will be determined. Data for unknown coals can then be compared with the ranking to provide a design criterion relative to past commercial experience. In addition, work will be performed on theory and computer modeling to develop a more generalized approach to design. The pilot facility will also be used to evaluate methods of conditioning to improve ESP performance, including use of sodium for conditioning.

Longer term research on ESP's will be concerned with the study of formation and capture of ultrafine submicron particulate. Western coals, particularly those high in sodium, produce a fraction of very fine fly ash owing to the dispersion of the mineral matter in the coal and to its partial volatilization during combustion. The pilot furnace at GFERC will be used to study the formation of fine particulate with the aid of an analyzing and scanning electron microscope. Collection efficiency will be studied as a function of particle size range and ESP design.

Wet Scrubbers for Particulate Control

Wet scrubbers for particulate control have been installed on 10 boilers burning low-rank coals in the United States. A summary of design and operating data is presented in table 8. The designs represented are of three types: (1) venturi scrubbers, (2) high-pressure spray impingement scrubbers, and (3) turbulent contact absorbers (TCA's), in which flue gas is passed countercurrent to scrubber liquid through a bed of light plastic balls.

All of the scrubbers operating on low-rank coals have successfully met applicable emission standards and, in addition, have removed some portion of the SO_2 entering in the flue gas. The SO_2 removed is oxidized to sulfate in the recirculating scrubber liquor and is reacted with calcium from the fly ash to form precipitated gypsum ($CaSO_4 \cdot 2H_2O$). The precipitation of calcium sulfate causes formation of scale which plugs piping and reaction vessels and seriously reduces the reliability and availability of a scrubber. The scaling problem has forced most scrubber operations to continuously dilute recirculating liquor to remain below saturation with respect to calcium sulfate and to remove a corresponding amount of blowdown which must be disposed of by discharge to streams or by evaporation in ponds.

In the past 10 years, the trend in technology for particulate removal for plants burning low-rank coals has been first from ESP's to scrubbers and later from scrubbers back to ESP's. Currently, conservative design includes both an ESP for particulate removal and a scrubber for SO_x removal.

EMISSION CONTROL TECHNOLOGY FOR SO_2

The emerging technology for FGD includes both byproduct and throw-away processes. The throw-away wet processes are lime/limestone scrubbing, soda-ash scrubbing, sodium scrubbing with lime or limestone regeneration, and ash-alkali scrubbing. Regenerative wet processes for producing product sulfur, sulfuric acid, or gypsum are based on scrubbing with magnesium oxide, sodium sulfite, dilute sulfuric acid, or sodium citrate, or on catalytic oxidation. Dry processes under study are based on the use of coal chars (regenerative) or nahcolite (a mineral containing sodium bicarbonate used for once-through dry absorption of SO_2).

The three most significant factors to be considered in selecting and designing FGD systems for low-rank coals are: (1) the relatively low sulfur content, (2) the alkalinity of the coal fly ash, and (3) the tendency for sulfite to be rapidly oxidized to sulfate in wet scrubbers operating on these coals. Most projects involving low-rank coals are in the western United States where throw-away processes are favored over processes producing saleable products, because of remoteness from large chemical markets. Process water is

Table 6. Design and test data for electrostatic precipitators in operation or planned for powerplants burning North Dakota.

Utility Company	Basin Electric Power Cooperative		Minnkota Power Cooperative		Otter Tail Power				Montana Dakota Utilities		United Power Association
Station	Leland Olds No. 1 Stanton, North Dakota	Leland Olds No. 2	Milton R. Young No. 1 Center, North Dakota	Milton R. Young No. 2	Hoot Lake No. 2 Fergus Falls, Minnesota	Hoot Lake No. 3	Ortonville Ortonville, Minnesota	Big Stone Milbank, South Dakota	Heskett No. 1 Mandan, North Dakota	Heskett No. 2	UPA - Stanton Stanton, North Dakota
ESP installation on new or existing boiler	Existing	New	Existing	New	Existing	Existing	Existing	New	Existing	Existing, ESP in series with mechanical collector	Existing
ESP vendor	Research Cottrell	Western	Research Cottrell	Wheelabrator	Research Cottrell	Research Cottrell	Research Cottrell	Wheelabrator	Research Cottrell	Research Cottrell	Research Cottrell
Completion date	11/74	9/75	6/75	5/77	5/72	4/72	6/72	5/75	6/75	6/75	5/76
Boiler capacity, MW	215	440	235	438	61	79	21	440	25	66	160
Firing method	PC	cyclone	cyclone	cyclone	PC	PC	spreader-stoker	cyclone	spreader-stoker	spreader-stoker	PC
Number of transformer-rectifier sets	16	40	16	32	4	4	4	24	6	10	12
Flue gas											
Temperature, °F	360	373	385	380	330	310	345	288	418	333	350
°C	(182)	(189)	(196)	(193)	(166)	(154)	(174)	(142)	(214)	(167)	(177)
Velocity, ft/sec[a]	5.01	5.00	5.55	5.00	4.23	5.07	4.25	5.25	3.80	4.28	5.17
(m/sec)	(1.53)	(1.52)	(1.69)	(1.52)	(1.29)	(3.28)	(1.30)	(1.60)	(1.16)	(1.30)	(1.58)
Flow, Ft^3/min[b]	1,000,000	2,100,000	1,170,000	2,200,000	280,000	390,000	133,000	2,330,000	189,300	451,800	853,750
(m^3/min)	(28,300)	(59,500)	(33,100)	(62,300)	(7,900)	(11,000)	(3,800)	(66,000)	(5,400)	(12,800)	(24,200)
Specific collecting area											
ft^2/1000-ft^3/min[b]	320	267	288	375	252	236	280	355	352	280	235
(m^2/1000-m^3/min)	(1050)	(876)	(945)	(1230)	(827)	(774)	(919)	(1165)	(1155)	(919)	(771)
Inlet loading, gr/ft^3[b]	2.30	1.30	1.00	1.0 to 2.7	1.87	2.09	0.97	1.17	2.5 to 4.1	0.3 to 0.6	DNA
(g/m^3)	(5.26)	(2.97)	(2.29)	(2.29 to 6.18)	(4.28)	(4.78)	(2.22)	(2.68)	(5.72 to 9.38)	(0.69 to 1.38)	DNA
(g/m^3)											
Outlet loading, gr/ft^3 [b]	0.0125	0.0125	0.01	0.006	0.015	0.015	0.0042	0.014	0.0225	0.021	DNA
(g/m^3)	(.0286)	(.0286)	(.0229)	(.0137)	(.0343)	(.0343)	(.0096)	(.0320)	(.0515)	(.0480)	DNA
Design efficiency, percent	99.50	99.05	99.00	99.40	98.50	98.50	98.90	98.80	99.45	97.00	98.0
Measured efficiency	99.45	DNA[c]	99.82	DNA	99.00	99 +	99 +	99.63	0.1 gr/ft^3	0.1 gr/ft^3	DNA
Migration velocity, cm/sec[a]	8.26	DNA	11.15	DNA	9.28	9.9	8.4	8.01	DNA	DNA	DNA

[a] Volume flow rate at the entering flue gas temperature divided by cross-sectional area of precipitator.

[b] Flue gas volumes are computed at the entering flue gas temperature.

[c] Data not available.

Table 7. Summary data on particulate scrubbers operating on boilers burning low-rank western U. S. coals.

Utility Company	Arizona Public Service Company	Pacific Power and Light Company	Public Service Company of Colorado		Minnesota Power and Light Company		Montana Dakota Utilities
Station	Four Corners,	Dave Johnston,	Valmont,	Arapahoe,	Clay Boswell,	Aurora,	Sidney,
Location	Farmington, New Mexico	Glenrock, Wyoming	Boulder, Colorado	Denver, Colorado	Cohasset, Minnesota	Aurora, Minnesota	Sidney, Montana
Scrubber startup date	12/71	4/72	11/71	9/73	5/73	6/71	12/75
Reagent	None	None	None	None	None	None	Limestone for pH control
Vendor	Chemico	Chemico	UOP	UOP	Krebs	Krebs	Research Cottrell
Design and Operating Parameters:							
Scrubber type	Venturi	Venturi	3 stage TCA	3 stage TCA	High-pressure spray	High-pressure spray	Flooded disk venturi
No. of equipped boilers	3	1	1	1	1	2	1
No. of scrubber modules per boiler	2	3	2	1	1	1	1
Total capacity equipped with scrubbers, MW	575	330	118	112	350	116	50
Reheat	yes	no	yes	yes	no	no	no
Bypass	no	no	yes	yes	no	no	yes
Capital cost, \$/kW	52	24	30	41	DNA[b]	DNA	90
State	New Mexico	Wyoming	Wyoming	Wyoming	Montana	Montana	Montana
Rank of Coal	subbituminous	subbituminous	subbituminous	subbituminous	subbituminous	subbituminous	lignite
Sulfur in coal, percent	0.7	0.5	0.6	0.6	0.8	0.8	0.7
Ash in coal, percent	22	12	5.2	5.2	9	9	8.5
Calcium oxide in ash, percent	4	20	20	20	11	11	25
L/G, gal/1,000 actual ft^3	9	13	50	50	8	8	15-25
ΔP total inches H_2O	28	15	10-15	10-15	4	4	13
Capital cost, \$/kW	open	intermittent open	open	open	open	open	closed
Water requirement, acre-ft/MW-yr.	5.91	2.42	2.88	2.68	4.29	30.2	1.46
Scrubber power consumption, percent of generating capacity	3-4	2.3	5.09	4.02	0.86	0.86	1.2
Inlet dust load gr/ft^3[a]	12	4	0.8	0.8	3	2	1.25
(g/m^3).	(27.5)	(9.15)	(1.83)	(1.83)	(6.86)	(4.58)	(2.86)
Inlet SO_2 ppm, v/v dry.	650	500	500	500	800	800	700
Particulate removal	99.2%	.04 gr/ft^3 exit[a]	.02 gr/ft^3 exit	.02 gr/ft^3 exit	99%	98%	98%
SO_2 removal, percent	30	40	40	40	20	20	NA
Availability, percent	80	NA	80	20-40	DNA	DNA	DNA

[a] Volume at one atmosphere and 60° F for dry gas.
[b] Data not available.

Table 8. Operating and planned ash-alkali scrubbers for SO_2 removal on boilers burning low-rank United States coals.

Utility Company	Montana Power Company		Northern States Power Company		Square Butte Electric Cooperative
Station	*Colstrip No. 1*	Colstrip No. 2	Sherburne No. 1,	Sherburne No. 2,	Milton R. Young No. 2,
Location	Colstrip, *Montana*	Colstrip, *Montana*	Becker, *Minnesota*	Becker, *Minnesota*	Center, North Dakota
Scrubber startup date	5/75	5/76	5/76	3/77	5/77
Vendor	Combustion Equipment Associates		Combustion Engineering		Combustion Equipment Associates
Design	Venturi and spray tower	Venturi and spray tower	Venturi and marble bed	Venturi and marble bed	Spray tower (ESP for particulate)
Auxiliary reagent	lime	lime	limestone	limestone	lime
Boiler capacity, MW	362	362	680	680	450
Reheat	yes	yes	yes	yes	yes
Coal	Montana subbituminous	Montana subbituminous	Montana subbituminous	Montana subbituminous	North Dakota lignite
Sulfur in coal, percent	0.8	0.8	0.8	0.8	0.4 to 1.3
Ash in coal, percent	8.6	8.6	9	9	8.6
Calcium in ash, percent	22	22	16-20	16-20	25
$\triangle$P, inches of water	17	17	13	13	6
L/G gal/1000 ft^3	15 to 20 *in tower*	15 to 20 *in tower*	32	32	80
Suspended solids in scrubber liquor, percent	12	12	10	10	12
pH	5-6	5-6	5-6	5-6	5-6.5

limited in some affected locations, which may make dry processes advantageous as they become fully developed.

The average sulfur content of low-rank coals, including North Dakota lignite, is slightly in excess of 1 percent on a dry-coal basis. The corresponding sulfur oxide emission without control is 840 ppm, or 1.8 lb $SO_2/10^6$ Btu. This does not allow for retention of sulfur in the ash during combustion, which can vary from near zero to about 40 percent, depending on ash composition. A removal of 30 to 40 percent is required to bring the average emission below the Federal new source performance standard of 1.2 lb $SO_2/10^6$ Btu. Higher removals are required where coal sulfur is above the average or where local standards require lower emissions. There are very few subbituminous coal deposits that meet the Federal standard without flue-gas desulfurization.

The FGD systems for low-rank coals in the United States use wet scrubbing and produce a throw-away product. The reagents used are lime, limestone, and the alkaline fly ash produced by firing the coal. At these low levels of SO_2, scrubbers are designed to maximize gas film diffusion using either a multiple-spray tower or internal surface in devices like a marble bed or a turbulent contact absorber.

An important property of low-rank coals is that they contain, on an average, more alkali in the form of calcium, magnesium, and sodium, than sulfur. This alkali can be used as a reagent for removing SO_2 in a wet scrubber, as shown in pilot plant tests at GFERC (Sondreal and others, 1974; Sondreal and Tufte, 1975; and Ness and others, 1976) and more recently in a full-scale scrubber operated by Montana Power Company (table 8, figs. 13 and 14). The range of stoichiometric ratios of alkali to sulfur from 0.5 to 2, shown in figure 14, is representative of most low-rank coals. Selected lignites have alkali to sulfur ratios as high as 5:1.

Pilot plant tests on scrubbing with ash alkali have demonstrated SO_2 removals in the range of 40 to 95 percent for a range of feasible operating conditions. (See fig. 14.) The utilization of the partially vitrified fly ash can be improved by designing to operate at a pH lower than the current range of 5 to 6; however, the resulting increased solution of iron, aluminum, and various lesser elements must first be investigated to determine any adverse effects on scrubber operability or on the properties of the waste produced. The waste produced currently is a sulfate-enriched fly-ash sludge containing varying amounts of soluble salts, primarily sodium and magnesium sulfates. The sludge has good settling properties under most conditions.

The most serious problem in wet scrubbing with calcium-containing reagents is the plugging which occurs because of calcium sulfate scaling. If fresh-water makeup is used to keep the scrubber solution below saturation, the absorbed SO must be discharged in blowdown as a soluble sulfate waste, which is not permissible in most circumstances. Operation under closed loop conditions (no blowdown) is difficult, and scrubber reliability under these conditions is still debated. For the conditions of low-rank coals, scaling is controlled by recirculation of a high level of suspended solids in the scrubber liquor (12 percent), by designing for a high liquid-to-gas ratio, and by controlling pH at a constant level.

The cost of scrubbing adds substantially to the capital cost of a new powerplant and to operating costs. The installed cost, including contingencies, for an ash-alkali scrubber presently being built for a 450 MW plant is about $30 million. Operating cost, including capital changes, will be close to $4 million annually. This operating cost is

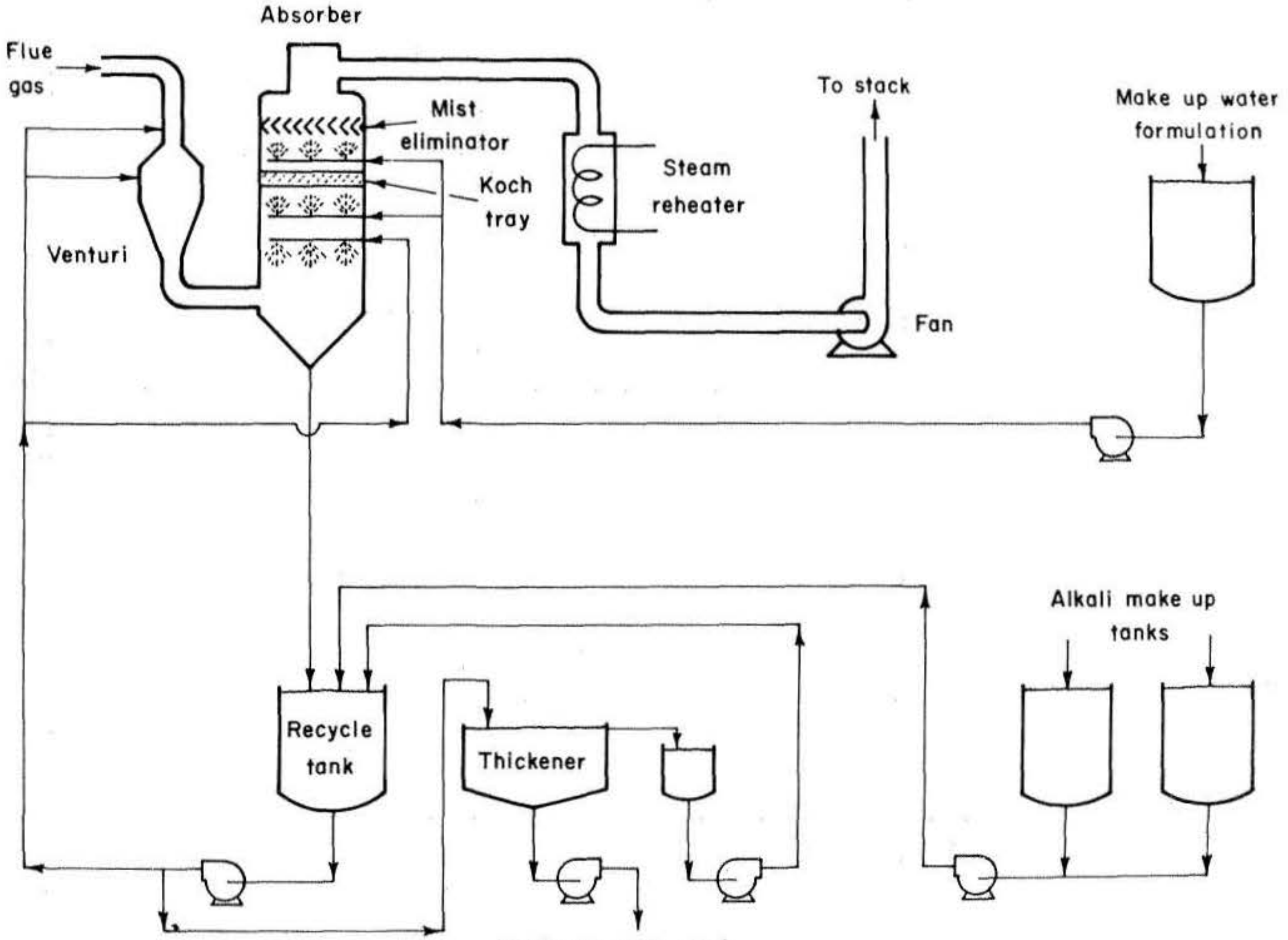

Figure 13. Flow diagram of ash-alkali pilot plant scrubber. Corrette Station, Montana Power Company, Billings, Montana, representative of a 362 MW unit placed in operation May 1975 burning subbituminous coal.

$\$0.125/10^6$ Btu input, which is equivalent to about two thirds of the fuel cost for this plant.

Research on FGD by ash-alkali wet scrubbing is being carried out by GFERC in a 120 scf/minute pilot scrubber at the Center and in a 5,000 cfm pilot plant operated on a slip stream of stack gas from a cyclone-fired boiler operated by the Minnkota Power Cooperative. Tests on the 5,000 cfm plant are being carried out under a cooperative agreement between ERDA, the Square Butte Electric Cooperative, and Combustion Equipment Associates. The utility has started construction on an ash-alkali scrubber for a 450 MW cyclone-fired lignite plant to be operating in May 1977 (table 8). Continuing research at GFERC will be concerned with (1) scrubbing with fly ashes which contribute high levels of Na and Mg to the scrubbing liquid, (2) scrubbing at low pH to improve alkali utilization from fly ash, (3) use and disposal of scrubber waste, (4) use of dry sorbents, and (5) separation of pyrite from lignite to bring it into compliance with the new source emission standard.

EMISSION CONTROL TECHNOLOGY FOR NO_x

The reaction of oxygen with nitrogen in the combustion air and with fuel nitrogen produces NO_x. Fuel-derived NO_x is controlled by the level of coal nitrogen and the amount of oxygen available during volatilization; the contribution of fuel nitrogen to the total NO_x emission has not been

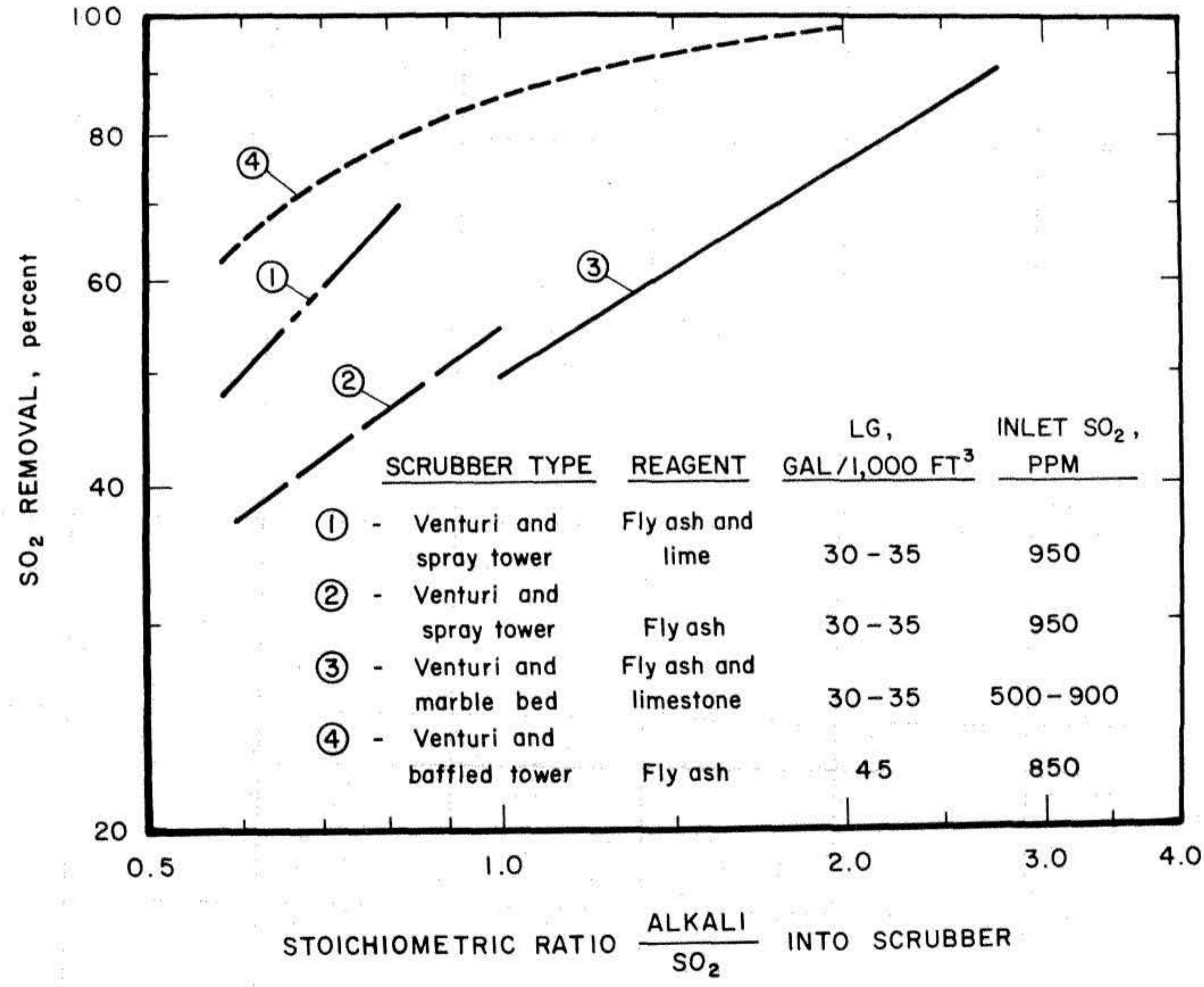

Figure 14. Sulfur dioxide versus stoichiometric ratio of alkali to SO_2 for pilot scrubbers, low-rank coals.

definitely established. The emission derived from combustion air, termed "thermal NO_x," is directly determined by the peak temperature occurring during combustion.

The Federal new source performance standard for NO_x is 0.7 lb/10^6 Btu for coals of subbituminous rank and higher. A standard of 0.6 lb/10^6 Btu has been proposed for lignite but has not yet been adopted.

Emissions from existing boilers burning lignite differ substantially, depending on method of firing. Limited testing performed at GFERC (Gronhovd and others, 1974) has established emission of 0.29 lb/10^6 Btu for spreader-stoker firing, 0.38 to 0.66 lb/10^6 Btu for pulverized coal firing, and 0.73 to 0.89 lb/10^6 Btu for cyclone firing.

Methods for reducing production of NO_x during combustion are concerned with controlling the distribution of fuel, oxygen, and temperature in the furnace. The methods that are applicable to low-rank coals are low excess air, staged combustion, and low emission burners.

Low excess air reduces NO_x production by limiting the amount of oxygen available to react with nitrogen from either the fuel or the air. Staged combustion, which is accomplished either by reducing primary air while increasing secondary overfire air or by maldistributing the fuel by taking burners out of service, reduces NO_x formation (1) by making less oxygen available in the burner zone where fuel nitrogen is volatilized and (2) by causing combustion to be extended over a longer time and space so that heat losses reduce the peak temperature. Low-emission burners are designed to optimize the distribution and mixing of fuel and air at the burner to effect reduced NO_x formation.

Different methods of firing are not equally amenable to modifications for reducing NO_x. Spreader-stoker firing produces the least NO_x but is not considered practical for large boilers. Limited testing by the EPA on pulverized-coal-fired boilers burning lignite has shown that the techniques for controlling the distribution of oxygen and temperature are apparently successful in reducing NO_x emissions below the level of 0.6 lb/10^6 Btu. Cyclone firing produces the highest emission of NO_x, and modifications in the distribution of combustion air have not been successful in sufficiently reducing emissions. Adoption of the proposed standard for lignite would, therefore, have the effect of eliminating cyclone firing in future power projects burning lignite.

The lignite industry is concerned that the proposed NO_x standard may have an adverse effect on boiler reliability and particularly on ash fouling. Cyclone firing is believed by some to reduce the rate of fouling owing to the smaller amount of fly ash reaching the convection sections of the boiler; this has not been substantiated in controlled tests, but such tests are currently underway. It is also believed that reducing excess air may aggravate ash fouling for pulverized-coal firing because of reduced cooling of fly ash by excess air, which could result in requirements for larger boilers and still lower heat-release rates. Industry consensus is in favor of a delay in the standard to permit further study of the problem.

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MEASURING THE COMBUSTION RATE OF PULVERIZED LIGNITE

M. E. Leesley[1] and C. E. Jones[1]

ABSTRACT

The renewed interest in lignite utilization has caused a reevaluation of existing data on the behavior of lignite in combustion and gasification systems. A lack of knowledge exists concerning the combustion mechanism and the kinetics of burning. We review the methods of obtaining these data and show how in all cases but one, the results may be seriously affected by the experimental method. The exception, known as the one-dimensional furnace method, is described with an example of its use.

We further show how the wide-range particle-size distributions of pulverized lignite need not cause difficulties in obtaining specific reaction-rate equations from the experimental data.

INTRODUCTION

With oil prices rising as rapidly as they are, it is inevitable that developers will look to the vast lignite resource of Texas for exploitation. Conversion processes will use a portion of the fuel but the majority will be burned directly to produce steam. Until the fluidized-bed combustor becomes commercially viable for lignite, economics will continue to favor the well-proved direct-combustion technology of conventional pulverized fuel (PF) firing. Designers of PF-fired systems will find a gap in the information they need to calculate length, speed, and heat release profile of a PF flame. They will need to know the combustion or burning rate of the lignite, expressed as a function of temperature, oxygen concentration, and initial particle-size distribution.

Thus, if the specific reaction rate, dm/dt, can be expressed as:

$$\frac{1}{A} \cdot \frac{dm}{dt} = f(p_{O_2}, T) \qquad (1)$$

then they need to know the format of the function, f, of partial oxygen pressure (p_{O_2}) and temperature, T. In addition, the area A at time t needs to be calculable from the initial particle-size distribution of the fuel.

Since an expression such as equation 1 cannot meaningfully be derived theoretically, an experimental method must be devised to measure burning rate under a range of conditions to give data that can be used to provide an empirical relationship. Several methods have been researched in the past and these are briefly reviewed in the following paragraphs.

THE SINGLE-PARTICLE METHOD

This method, popular approximately 30 years ago, has only one purpose now and that is to find order-of-magnitude data to enable the design of more accurate equipment. It involves suspending a particle by silica thread (or some similar device), exposing it to conditions which simulate a real flame, and photographing its burnaway. Burning rate can be deduced from the rate of decrease of diameter measured from the photographic record. Researchers discovered the following disadvantages.

1. It is almost impossible to simulate real flame radiation and convection of heat to and from the particle.
2. The suspension medium (silica thread or similar) conducts heat to and from the particle.

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3. The glue may also react and affect the experiment.
4. The particle does not have all its surface area available for combustion.
5. Only larger particles can be used because of the difficulties of attaching realistically sized particles (< 80 microns) to a suspension medium.

The main advantages of the single-particle method are its low cost (only a few grams of fuel are required), its simplicity of experimentation, and its speed of acquiring results.

However, to understand better the mechanism of combustion of a PF flame, experimentation must be carried out using actual flames. (Griffin and others, 1929; Essenhigh, 1959, 1961; Tu and others, 1934; Traustel, 1941; Parker and Hottel, 1936.)

INDUSTRIAL FLAME MEASUREMENTS

An obvious approach to a deeper understanding of the processes occurring in a PF flame is to make measurements on a real flame. Some work has been done on existing utility boilers, but the problems are immense.

Trials must be conducted in such a way as not to affect the production of steam. This limits the range of changes that can be made to combustion parameters such as fuel/air ratio, operating temperature, and particle-size distribution. The scope for flame measurements is limited. It would be highly impracticable, for example, to attempt deep in-flame sampling because of the sheer size of the flame. The gathered data depend on the three-dimensional position of the sampling probes. This positioning may not be easy to ascertain in a huge industrial flame. The complex geometry of a modern industrial burner and boiler system causes extreme problems in collating data. Recirculation of hot products to the preignition and early combustion zones has a masking effect on measured data. If a solid sample is taken at some early point in the flame, are all the particles freshly introduced into the flame? If not, how many have been recirculated? From where? A 40-micron particle in the sample may be one which started off at 50 microns and is in its first and perhaps only pass through the flame, or it may be one which started off at 200 microns and has been recirculated a number of times. These various problems led to the development of small- and medium-sized experimental furnaces. (Cutress and Pierce, 1964; Pierce, 1966.)

MEDIUM-SIZED EXPERIMENTAL FURNACES

These are customized rigs usually with easily exchangeable burner heads and a controllable heat load. In order to approximate real conditions they operate at 1,500 lbs of coal per hour and are fitted with gantry-mounted sampling systems to carry solid- and gas-sampling devices in addition to suction pyrometers and Pitot probes. This type of equipment is easy to manage and operate but, as in the industrial-sized flames, problems of recirculation make it difficult to analyze the data to obtain a true reaction-rate equation. (Flame Research Foundation, 1960, 1962; Beer, 1964; Baker, 1969.)

ONE-DIMENSIONAL EXPERIMENTAL FURNACES

Again, these are purpose-built rigs with an extremely wide operating range. They can be built to operate at as low as 30 lbs of coal per hour. They are designed as plug-flow reactors with a conical feed section which prohibits recirculation (fig. 1). A typical one-dimensional furnace could be a 24 ft high, 18-inch internal diameter, vertical refractory tube with sampling ports provided at 1 ft intervals down its length. The flat flame front profile and the plug-flow design ensure that flame properties vary in one dimension only, thus making sampling easy and giving data which can be used to compute burning rate without the masking effects of geometry, radial transport, and recirculation. The low feed rate means that relatively small amounts of the fuel under investigation are needed. City gas is used to heat the furnace and, as soon as wall temperatures, monitored by platinum-platinum: rhodium thermocouples, are stable, the fuel/air feed can be introduced. A further 4 to 6 hours are needed to reach a steady state when sampling can begin working from the end of the flame so as not to disturb upstream conditions. Gas samples may be withdrawn using a suction probe and analyzed for CO, CO_2, and O_2 to compute burnaway. Solid samples may be taken by withdrawing furnace gases through a sintered

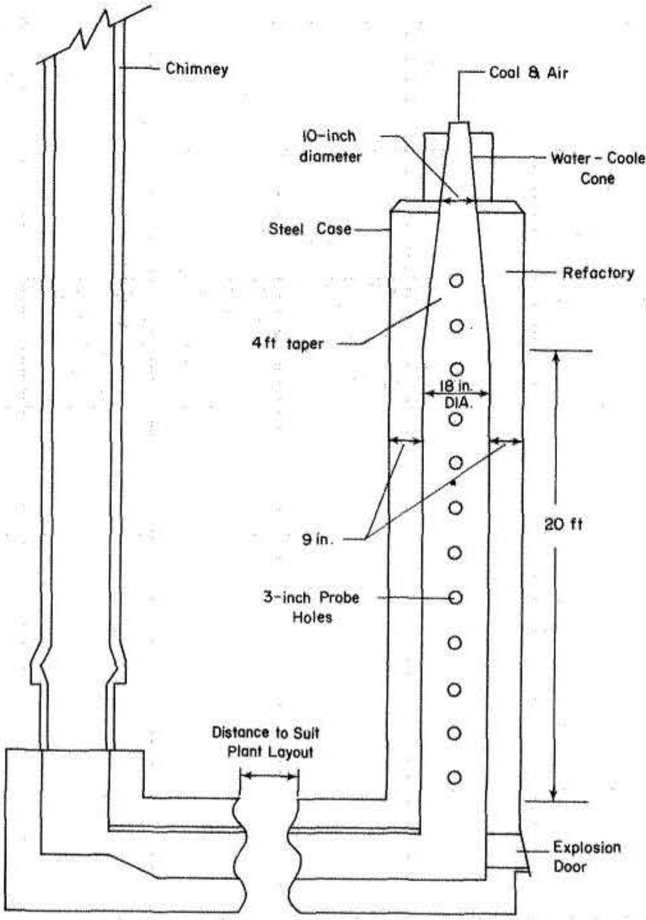

Figure 1. The one-dimensional furnace.

bronze filter mounted in a water-cooled probe and later analyzed for unburned carbon as an extra calculatory method for burnaway. Wall temperatures may be constantly monitored in a multipoint recorder and flame temperatures taken using a suction pyrometer. Velocity measurements are superfluous owing to the plug-flow design which enables a velocity calculation to be made from the initial feed rates and the local flame temperature. About 2 to 4 hours of running time are required to achieve a full set of trial data for each set of flame parameters. At 50 lbs/hr feed rate, 600 lbs of the fuel under investigation, at most, are consumed. (Beer, 1960; Marsden, 1964; Guldenpfennig, 1964; Leesley, 1967, 1975.)

Results can be fitted by multiple correlation to an equation of the form:

$$\frac{1}{A} \cdot \frac{d}{dt}\left(\frac{m}{m_o}\right) = -kf(p_{o_2}, T) \qquad (2)$$

where
m_o = initial fuel rate, lbs/hr
m = unburned fuel at sampling point
p_{o_2} = partial oxygen pressure lbs/hr at that point, psia
T = flame temperature at that point, °R
A = surface area available for combustion at that point, ft^2
k = a constant.

RANGE OF EXPERIMENTATION USING THE ONE-DIMENSIONAL FURNACE

To provide sufficient data to achieve a meaningful rate equation (equation 2), a series of trials with fuel/air ratio set to 0, 10, 20, 30, and 40 percent excess air are required with three repeated runs to establish reproducibility. Thus, a total supply of approximately 4.5 tons of fuel is needed. The low fuel demand means that sized fractions of fuel can be prepared to determine the effect of initial size distribution.

THE AREA OF A CLOUD OF PULVERIZED FUEL PARTICLES

Equation 2 contains an area term which must be evaluated before the multiple correlation can be attempted. Assuming uniformly sized, spherical particles, Beer and Thring (1961) derived the following expression for the area at any point in the flame.

$$\frac{1}{A} = \frac{\rho \overline{x}_i}{6}\left(\frac{m}{m_o}\right)^{-2/3} \qquad (3)$$

where
ρ = fuel density, lbs/ft^3
$\overline{x}_i$ = mean particle diameter, ft.

This expression assumes that the combustion rate is controlled by the chemical kinetics at the particle surface. A similar expression can be developed assuming that the diffusion of reactants to the surface is a rate-controlling step. For completeness, the difference could be described, but in this paper which is concerned with experimental techniques, a discussion of the rate-controlling mechanisms has been omitted. (See Leesley, 1975, for discussion.)

Leesley (1975) found that equation 3 was inadequate when dealing with sized fractions of anthracite and the particle-size distribution could be expressed by the Rosin-Rammler equation (Rosin and Rammler, 1933).

$$W_x = e^{-bx^n} \tag{4}$$

where

W_x = weight fraction of particles with size x
x = particle diameter, ft
b,n = constants.

This led to the development of the following area term:

$$\frac{1}{A} = \frac{\pi\rho\bar{x}_i}{2k_1}\left(\frac{m}{m_o}\right)^{-k_2} \tag{5}$$

where

k_1, k_2 = constants.

The constants k_1 and k_2 replace the values $3/\pi$ and ⅔, respectively, and are complex functions (Leesley, 1975) of the constants b and n in equation 4 only and vary along the flame length. The reference contains explicit instructions on the derivation of k_1 and k_2, and table 1 gives values of k_1 and k_2 for a range of b and n which encompasses the most commonly met values. Note that two values each of k_1 and k_2 are given for each pair of values of b and n.

Figure 2 shows how the slope (k_2) and intercept (k_1) vary with flame length and how, for simplicity, two straight lines have been drawn. The explanation of the axes is beyond the scope of this paper, however more information concerning these axes is available from Leesley (1975).

COMPUTATION OF A COMBUSTION-RATE EQUATION

With values of m, A, p_{O_2}, and T at known sampling points and the time, t, from ignition calculable from the velocity and distance, the determination of a combustion-rate equation is relatively simple. First the burnaway curve, m/m_o versus t, is differentiated at the sampling points

Table 1. Values of constants k_1, k_2 for various size distributions.

		Chemical (B = 2)				Diffusion (B = 1)			
		upper		lower		upper		lower	
n	b	k_1	k_2	k_1	k_2	k_1	k_2	k_1	k_2
0.8	0.0005	5.2307	0.9613	4.6072	.77567	10.198	1.9566	8.3645	.7293
	0.001	4.7330	1.2390	4.2570	.91912	9.661	4.3073	7.9322	1.4218
	0.0015	4.4280	1.4831	3.9849	1.04449	9.183	5.8686	7.0539	1.5066
	0.002	4.2104	1.7059	3.7221	1.10345	8.451	5.6769	6.3891	1.5405
	0.0025	4.0427	1.9129	3.5175	1.14624	8.117	6.2817	5.8816	1.5695
0.9	0.0005	4.6424	1.2233	4.2204	.91692	9.399	4.4782	7.7969	1.3939
	0.001	4.1400	1.6103	3.7108	1.06498	8.152	5.1913	6.3319	1.4381
	0.0015	3.8483	1.9317	3.3727	1.13245	7.317	5.2621	5.5025	1.4767
	0.002	3.6469	2.2132	3.1016	1.15936	6.817	5.4918	4.9307	1.5112
	0.0025	3.4581	2.2914	2.8855	1.17332	6.378	5.4891	4.4892	1.5336
1.0	0.0005	4.0988	1.5103	3.7276	1.03354	7.840	4.4386	6.3365	1.3446
	0.001	3.6236	1.9857	3.1643	1.10851	6.649	4.7392	5.0499	1.3979
	0.0015	3.3219	2.1468	2.8088	1.12858	6.702	4.9798	4.3429	1.4463
	0.002	3.1155	2.2396	2.5738	1.15036	5.542	4.9536	3.8827	1.5035
	0.0025	2.9286	2.2102	2.4040	1.17233	5.279	5.2036	3.5487	1.5550
1.1	0.0005	3.4552	1.8517	3.0538	1.07014	6.189	4.1469	4.8293	1.3125
	0.001	2.9371	1.9550	2.5068	1.10410	5.193	4.4336	3.7448	1.3986
	0.0015	2.6650	1.9997	2.2228	1.13638	4.692	4.6487	3.1877	1.4822
	0.002	2.5199	2.1161	2.0508	1.17016	4.381	4.7627	2.8506	1.5612
	0.0025	2.4008	2.1204	1.9346	1.19846	4.167	4.8209	2.6338	1.6366
1.2	0.0005	2.8305	1.8191	2.4531	1.06355	4.891	3.9241	3.6408	1.3115
	0.001	2.4071	1.8877	2.0187	1.11744	4.106	4.1951	2.7868	1.4481
	0.0015	2.2276	1.9621	1.8275	1.16603	3.779	4.3968	2.4231	1.5720
	0.002	2.1391	2.0209	1.7302	1.20600	3.606	4.4916	2.2520	1.6778
	0.0025	2.0962	2.0792	1.6808	1.23818	3.510	4.5466	2.1680	1.7575
1.3	0.0005	2.3352	1.7460	1.9989	1.07483	3.901	3.7490	2.7495	1.3558
	0.001	2.0534	1.8344	1.7085	1.15076	3.396	4.0361	2.2019	1.5553
	0.0015	1.9735	1.9098	1.6214	1.20125	3.238	4.1401	2.0574	1.6872
	0.002	1.9356	1.9075	1.5953	1.22968	3.177	4.1661	2.0196	1.7565
	0.0025	1.9275	1.9266	1,5865	1.24249	3.156	4.1787	2.0088	1.7865

either by hand or preferably by fitting a curve of the form

$$\frac{m}{m_o} = a_o + \frac{a_1}{a_2 + t} \qquad \textbf{(6)}$$

and differentiating mathematically.

Second, the values of $\frac{d}{dt} \frac{m}{m_o}$, A, p_{o_2}, and T are subjected to multiple correlation analysis using the theoretically (Moore, 1960; Glasstone, 1962) suggested expression:

$$\frac{1}{A} \cdot \frac{d}{dt}\left(\frac{m}{m_o}\right) = \frac{-k}{T^{1/2}} \cdot p_{o_2}{}^{n1} \exp\left(\frac{-E}{RT}\right) \qquad (7)$$

where
E = an activation energy, Btu/mole
n_1 = order of reaction
R = gas constant.

Other rate equation types have been suggested (Marsden, 1964) and one such alternative, which can also be used in a multiple correlation analysis, is

$$\frac{1}{A} \cdot \frac{d}{dt}\left(\frac{m}{m_o}\right) = -k\, p_{o_2}{}^{n1}\, T^{n}_{2} \qquad (8)$$

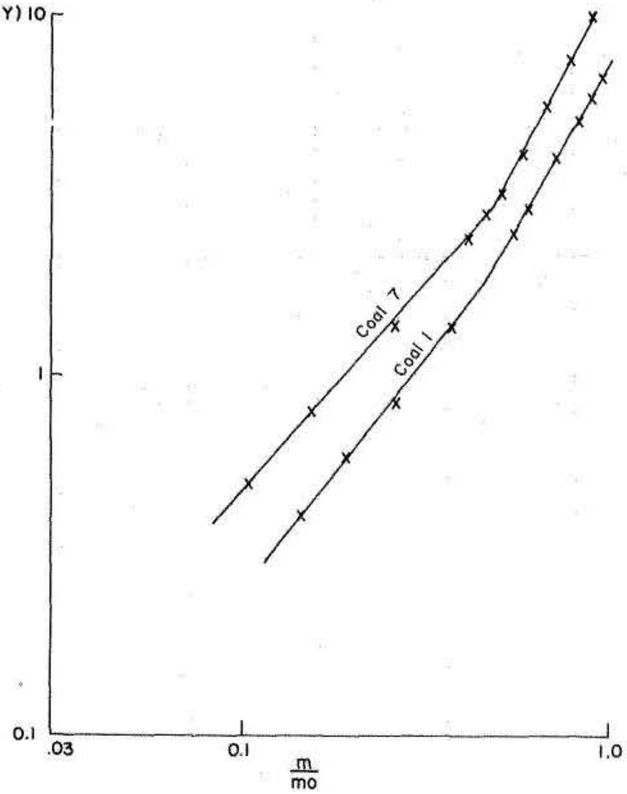

Figure 2. Graph showing F(Y) plotted against m/m_o for polydisperse coals assuming chemical control.

AN EXAMPLE OF THE USE OF THE ONE-DIMENSIONAL FURNACE

Leesley (1975) prepared a number of discretely sized fractions and a number of polydisperse samples of pulverized anthracite. A series of trials was conducted as described, and the best two rate equations which resulted from multiple correlation analyses were as follows:

$$\frac{1}{A} \cdot \frac{d}{dt}\left(\frac{m}{m_o}\right) = \frac{-6.34 \times 10^7}{T^{1/2}}\, p_{o_2}{}^{0.887} \exp\left(\frac{-29230}{RT}\right) \qquad (9)$$

$$\frac{1}{A} \cdot \frac{d}{dt}\left(\frac{m}{m_o}\right) = -k\, p_{o_2}{}^{0.932}\, T^{8.305} \qquad (10)$$

CONCLUDING REMARKS

The cheapest, most accurate method of obtaining a combustion-rate equation for pulverized fuel is to use the one-dimensional experimental furnace. The rate data are not masked by the effects of geometry, radial transport, and recirculation. With an equation derived in this way, the effects of geometry, radial transport, and recirculation can then be modeled to aid the designer to compute flame lengths and heat-release profiles for various fuel/air ratios and initial particle-size distributions. Allowing for experimental difficulties, this modeling can be done using the one-dimensional furnace using less than 10 tons of fuel.

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THE POTENTIAL OF IN SITU GASIFICATION FOR TEXAS LIGNITE

T. F. Edgar[1]

ABSTRACT

A brief history of underground gasification of coal along with a status report on current field-testing programs is given in this paper. The application of underground gasification to Texas lignite is discussed in detail; applicable resources and their chemical and physical properties pertaining to this process are delineated. The recovery of deep-basin Texas lignite by in situ gasification does appear to be both technically and economically feasible; data supporting these conclusions are presented. Engineering aspects of the Russian system for in situ gasification, which is suitable for use in Texas, are discussed.

INTRODUCTION

Underground coal gasification (UCG) has as its objective the recovery of the energetic and chemical content of coal without mining. A gaseous mixture composed of nitrogen, oxygen, steam, and carbon dioxide in variable proportions is introduced in a coal seam prepared for gasification; combustion and gasification reactions occur in situ. The products, carbon monoxide, carbon dioxide, hydrogen, water vapor, methane, nitrogen, and other hydrocarbons are obtained in a readily usable form for the production of electric power or the manufacture of chemicals.

In situ coal gasification is a process that should be considered as a competitor with shaft mining but not with surface mining. The successful application of this method would provide a low-Btu gas which is relatively easy to clean (for sulfur compounds) and at the same time eliminates many of the health, safety, and environmental problems associated with conventional deep mining of coal. The in situ method also has the potential to recover the energy from deep coal deposits which are not economical to mine using conventional schemes.

The idea of underground coal gasification dates back a century. Historical reviews of the pre-1965 technology for UCG can be found in several references: U.S. Bureau of Mines (1972), Wang (1969), Capp and others (1963), and Elder (1963). However, the review of worldwide literature in UCG as performed in these four reports has not been complete because of general lack of information about Russian contributions to the technology. Only recently has a complete picture of the Russian UCG experience been obtained; aspects of the recently discovered Russian contributions will be given in this paper.

The Russian interest in this utilization method can be traced to the ideology of Lenin, since it was a way to liberate the workers from the drudgery of coal mining. Lenin also pointed out that this approach would not be attractive to the "capitalist mine bosses" in Europe and the United States, since constant unemployment there always made certain that the manpower required for conventional mining was always available.

UCG FIELD TESTS AND COMMERCIAL OPERATIONS

In previous applications of UCG, two classes of methods were used: shaft and shaftless. Shaft methods require underground work to prepare the seams for gasification; shaftless methods require no underground work since the seams are reached by boreholes. It appears that the shaft gasification methods offer no economic advan-

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tages over conventional deep mining and do not eliminate underground labor. Therefore they have been discarded as unfeasible for new applications.

Shaftless methods, on the other hand, require no underground labor, as in recovery of gas and oil. By using surface equipment, however, the underground work, such as fracturing, can be performed. The basic shaftless method, the method most applicable to Texas lignites, is the so-called percolation or filtration method (fig. 1), in which numerous variations involve different borehole diameters, number of boreholes, location patterns, methods of linking, and gasification procedures. The coal seam is penetrated by vertical boreholes spaced 50 to 100 ft apart and located in various geometric patterns or by long, horizontal boreholes. Gasification takes place between different pairs of linked boreholes, with offtake and intake holes depending on the locational pattern and gasification procedure. High-rank coals usually must be fractured to obtain requisite permeability; lignites generally have sufficient natural permeability.

Large-scale experiments have been conducted in the U.S.S.R. since the 1930's, and the process is in commercial use at present. Tests on underground gasification were also carried out in the 1950's and early 1960's in several other countries including the United States, United Kingdom, Poland, Belgium, Czechoslovakia, Japan, Italy, and Morocco. The most significant efforts besides those in U.S.S.R. were in Great Britain and in the United States. Experimental work in England was begun in 1949, and the field test results have been well documented by Gibb (1964). The coal seam studied was horizontal but only 3 ft thick; the average heating value obtained over a 4-month period was only 75 Btu/standard cubic feet (scf). The project experienced many problems, including excessive water leakage into the system and oxygen bypassing and recycling of gases in the cavity, which caused oxidation of CO to CO_2 and excessive gas outlet temperatures. Injection of steam reduced the high temperatures, but this was not considered to be a very productive operating strategy. Coal recoveries as high as 84 percent were obtained, but the average heating value of the gas still did not exceed 75 Btu/scf.

The tests in the United States were performed in Alabama by the U.S. Bureau of Mines from 1948 to 1962. Test results have been summarized by Elder (1963). The coal gasified was high-volatile "A" bituminous in a horizontal seam. Leakage of gases to the surface was quite excessive due to the shallow depths, high operating pressure, and

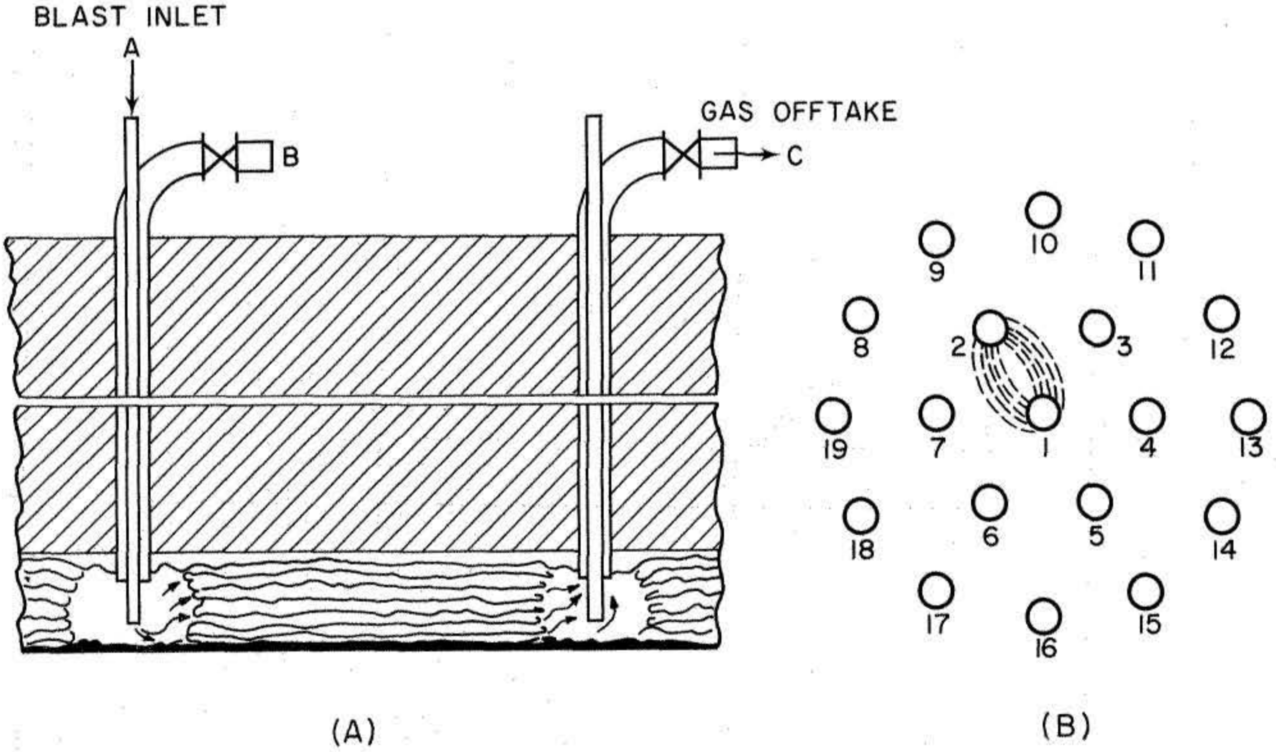

Figure 1. The percolation method. (A) Section through boreholes. (B) Plan of boreholes.

an extensive fracturing program. Typical heating values with different injected species included air (45 Btu/scf); 34-percent oxygen-enriched air (50 Btu/scf); 34-percent O_2, 43-percent N_2, 25-percent steam (110 Btu/scf); 65-percent O_2, 30-percent steam (135 Btu/scf); and steam only (150 Btu/scf). Various gasification and seam-preparation methods were attempted, including electrolinking, hydraulic fracturing, and reverse combustion. Heating values of 100 Btu/scf were obtained, but 30-percent gas losses were reported.

The effort expended by Soviet engineers in UCG greatly exceeds that of other countries. The first field tests were performed in 1933, and their efforts peaked in the late 1960's. It has been estimated that as many as 3,000 people were employed in these efforts in the 1960's. The Soviets arrived at a UCG system design that could be operated successfully in a predictable manner. This system operated not only in one area, but also was able to be transferred successfully from one geological area to another (and from one coal type to another). They developed a large quantity of field data for all coal types, strata, and operating conditions, as recently discussed by Gregg and others (1976). Examples of the field data will be presented and discussed later.

The Soviet system of UCG is based on two steps, pregasification and gasification. The pregasification step is probably the most critical one because proper seam preparation increases successful gas production. The main step in the preparation of the coal seam is the "linking" of definable points within the coal deposit. Some coal seams in their natural state (for example, some lignites) may be permeable enough so that gasification between definable points can be initiated and progress without any man-made link. However, most coals require a better link than that provided by the natural permeability in order to speed up the gasification process. One method is to drill a horizontal hole in the coal between the gas inlet and outlet boreholes. Other linking techniques are electrolinking, hydraulic linking, and pneumatic linking. These last three procedures result in the formation of low resistance paths of gas flow which are less definable than a drilled hole. In the process of electrolinking, electrodes are installed within the coal bed. Passing an electric current between the electrodes carbonizes the coal and forms a path of increased permeability. Hydraulic linking involves the injection of a fluid under high pressure to cause fracturing of the coal deposit. Pneumatic linking consists of using the natural cleat system of the coal seam and pumping air under pressure; this was the most popular Soviet method.

Once an adequate linking is established in the seam, two further steps can be undertaken before gasification which help insure the success of gasification. The first is drying the seam (with heated air or combustion gas) to further enhance the seam permeability. This process is usually only recommended for so-called "shrinking" coals, such as those found in the western United States. The second step is increasing the permeability of the air path by burning part of the coal using an approach called reverse combustion or backward burning. Reverse combustion involves the injection of the oxidant blast in a direction countercurrent to the movement of the combustion front; this method is contrasted to that of forward burning, where the gases and combustion front move in the same direction.

The effect of volatiles from the coal and allowable operating pressures are two of the important reasons that backward burning is utilized for permeability enhancement prior to application of forward combustion. In forward burning, volatiles are produced ahead of the combustion front; these volatiles are cooled with the product gases and begin to condense at about 150°C, according to Soviet experience. However, in backward burning, the volatiles must pass through the flame front, thus cracking many of the components. The volatiles then pass through the high permeability path already created, which minimizes the potential for plugging.

High flow rates at high pressure drops are not economically feasible. In general, it is necessary to operate at low pressure drops and high flow rates or at high pressure drops and low flow rates. This latter condition obtains prior to gasification of the seam, hence low flow rates are expected initially. In this case a heat-conduction-driven phenomenon, such as backward burning, is preferred over one which is convection driven. As described by Schrider and others (1974), after a period of time of operating at high pressure drops and low flow rates, a sudden, sharp decrease in pressure occurs, signifying breakthrough of the backward combustion process from one borehole to another. At this point it is feasible to use backward burning.

In UCG, it is important to minimize the loss of both the injected blast and the product gas, which can leak through cracks to the surface or other surrounding formations. Since the extent of such leakage cracks is unpredictable as the combustion zone moves across the coal seam, the system must be designed so that gas leakage is minimized. The only way this can be done is to operate the system at the lowest possible pressure and be certain that the permeability in the coal between the injection and exhaust holes is always much higher than the permeability from the reaction zone to the surface through subsidence. The reverse combustion step insures that this will happen.

In UCG, the reaction rate and high thermal efficiency depend on efficient gas-solid contact, or the presence of maximum surface area of the coal. The Soviet system for horizontal coal seams establishes a rubble zone of fractured coal in the channel because the flame front undercuts the coal at the bottom of the seam, and the overlying coal falls into the void (fig. 2). The important zones in UCG are indicated in figure 2.

Another reason for establishing the reaction at the bottom of the seam is to prevent the flame front from moving to the top of the seam. Liquids (water and pyrolysis products) would tend to force the reaction upward if the permeable path were established in a higher position in the seam. Once a channel is allowed to form across the top of the seam, the slagged coal ash, which solidifies upon cooling, tends to seal the bottom of the channel preventing further combustion of the coal. This sealing can result in very poor resource utilization. Because of the liquid movement and collection, gasification in the updip direction is preferred over that in the downdip direction.

The Soviets used a linear well pattern where two rows of wells are simultaneously linked prior to the gasification process. They also sequenced

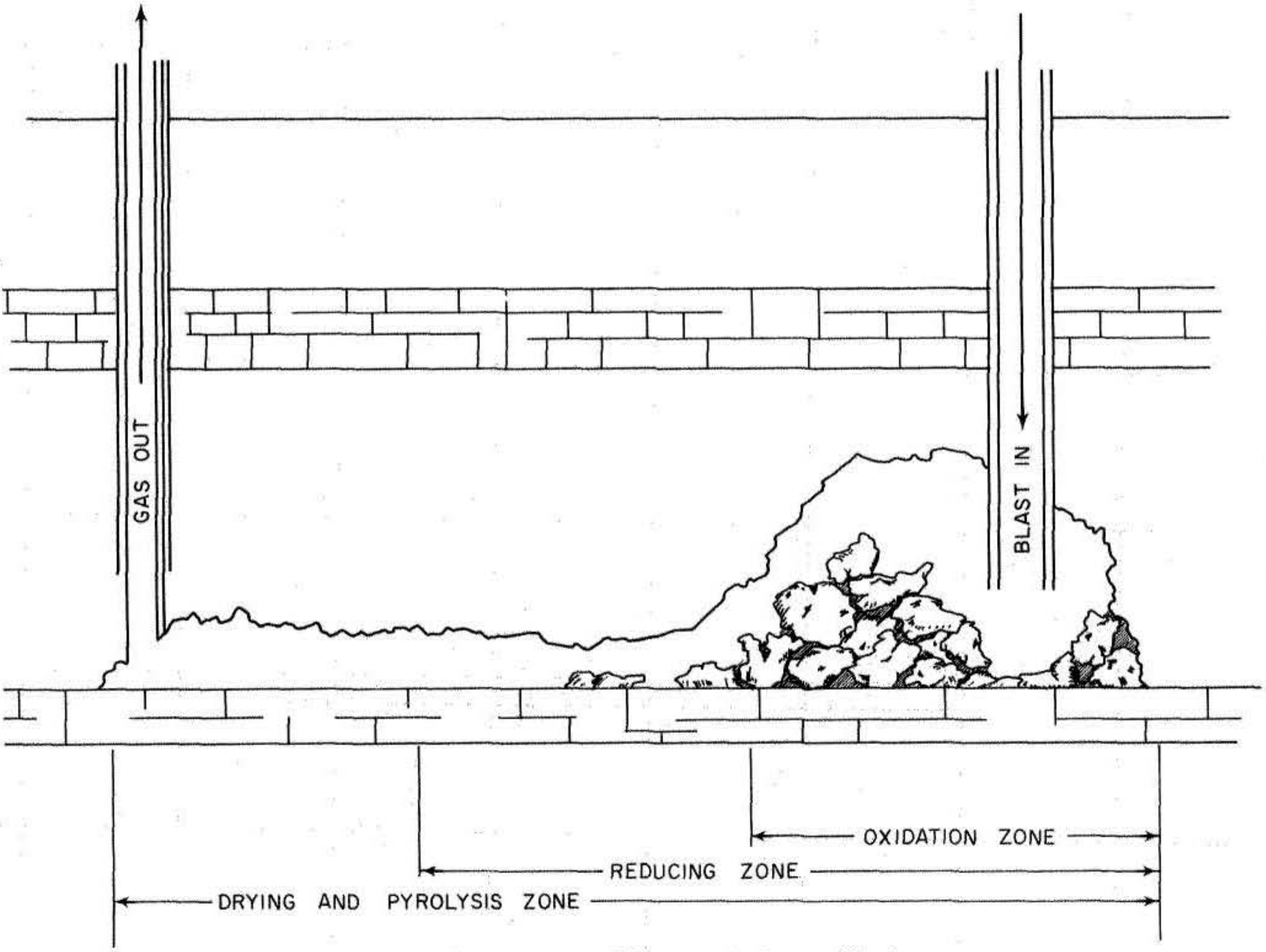

Figure 2. Formation of rubble zone during gasification.

the operations so that a consistent heating value was produced. Once the product gas reaches a low heating value, as it inevitably will at some point in the operation, that production hole is capped off, and the product gas is then forced to pass through the seam to the next production borehole, approximately 75 ft away. This new path has already been prepared by previous drying and backward-burning operations. Schematics of this approach have been presented by Elder (1963).

At the present time, three gasification power stations (Podmoskovnaya, Yuzhno-Abinsk, and Angren) of commercial size are operational, although not necessarily on a continuous basis. Variations in coal properties (rank, heating value, percent ash, moisture, volatiles), seam thickness, and geological setting (horizontal as opposed to steeply dipping seams) exist among the three sites (Skafa, 1960; Kreinin and Revva, 1966).

Since 1971, there has been new incentive to review the economic and technical feasibility, and evidence of the new interest is given by several ongoing field tests and laboratory programs. Recent major field tests have been sponsored by the Energy Research and Development Administration (ERDA) (Laramie Energy Research Center, Lawrence Livermore Laboratory, and Morgantown Energy Research Center) on both western and eastern coal, and by private companies (Gulf, Texas Utilities Fuel Company). Major laboratory experimental programs are in progress at Livermore, Morgantown, The University of Texas at Austin, and the University of Alabama.

Gulf Research and Development conducted a field test near a strip mine in Kentucky (Raimondi and others, 1975). The coal was a 9 ft seam at a depth of 107 ft and was fractured by use of air pressure about 30 percent above overburden pressure. The coal was gasified by forward combustion without any prior thermal permeability enhancement, and gas with an average heating value of 270 Btu/ft^3 was withdrawn from sample wells. No attempt was made to sustain a reasonable level of gas production; the high heating value indicated a high percentage of coal carbonized as opposed to gasified. It was estimated that the temperature in the combustion zone reached 2,500° to 3,000°F. After gasification, cement was pumped down the borehole so that the pattern of gasification could be observed when the coal was uncovered by the strip-mine operation. Some samples recovered indicated that the reaction followed both small and large crack patterns in the coal. Other samples were composed of fused rock, clay, and coke.

The most advanced field test in the United States is being operated by the Laramie Energy Research Center of ERDA at Hanna, Wyoming, on subbituminous coal. As early as 1972, gas was produced with heating values ranging from 30 to 465 Btu/scf. Over a 4-month period in 1974, an average yield of 130 Btu/scf was produced from a two-hole (inlet/outlet) system. The linked vertical borehole method was used, and forward burning was found unworkable without prior backward burning because of tars plugging up the flow paths in the coal. Estimates of coal-recovery efficiency ranged from 30 to 50 percent for the 30 ft seam.

A second Hanna experiment was performed in 1975, and for 38 days the heating value averaged 152 Btu/scf (higher heating value). The Russian percolation design for UCG was essentially used in this test. The UCG system was operated at relatively high flow, and production rates compared to previous tests, which aided in the high yields (Fischer and Schrider, 1975). The test was terminated before the combustion front reached the production well. A typical composition for the product gas is shown in table 1.

Calculating the thermal efficiency of this UCG test facility and comparing that with results from a Lurgi gasifier is also of interest. The thermal efficiency, defined as the total heating value of the gas recovered divided by the heating value of the coal reacted, is over 90 percent for the UCG test, whereas typical Lurgi gasifier efficiencies are 70 to 75 percent. One reason for this difference is that the Lurgi gasifier often uses excessive steam/air ratios to prevent slagging of the ash. Other advantages of the UCG system include the natural insulation provided by the overburden, which

Table 1. Typical Hanna UCG yield (water free).

Component	UCG
Hydrogen	18.66
Methane	3.60
Nitrogen and argon	47.71
Carbon monoxide	16.63
Hydrogen Sulfide	0.05
Ethane +	0.10
Higher heating value, Btu/scf	152.0

yields lower sensible heat losses than for the cooling system used in a conventional gasifier. The process heat from a Lurgi gasifier can be reused above ground, however. The fact that only a two-hole test system was used enhanced the reported efficiency for the Hanna test since no significant gas leakage was experienced. Leakage problems will become more severe for a commercial-scale field operation. Typical efficiency data for the Russian commercial system are given in table 2, showing a cold gas efficiency (item 1) more comparable to conventional gasifiers. Note that approximately 10-percent gas losses occur because of leakage.

Future tests at Hanna will be aimed at multiple well tests and developing gasification methods which uniformly sweep a field. One concept which has been tested is called "linedrive" and seeks to operate normal to the direction of maximum permeability. This technique has been discussed by Fischer and Schrider (1975). Recent testing of the "linedrive" method was not successful. Sandia Corporation is using elaborate instrumentation techniques for monitoring the burn zone development (Stoller, 1975).

The Lawrence Livermore Laboratory project, also sponsored by ERDA, consists of placing an array of chemical explosives within a thick coal seam (greater than 15 m). Using explosive fracturing a vertical rubble zone would be formed, yielding in effect a packed bed reactor. Steam and oxygen would be pumped into the bed at high pressure to produce a product with a high percentage of methane. The intermediate-Btu gas would then be collected through vertical wells and upgraded on the surface to synthetic natural gas. Site selection has been completed in Wyoming, and the first test burn was scheduled for 1976.

The Morgantown Energy Research Center of ERDA is concentrating on UCG of eastern bituminous coal, which is a swelling coal as opposed to the western shrinking coals. This experiment is using an approach called the "longwall generator," in which two parallel horizontal holes are directionally drilled (up to 600 ft) and then linked; the intent of this method is to provide gasification over a wide area. The economic trade-off in this case is between few directional holes and a large number of vertical holes.

Other field tests presently in the design stage include those of Texas Utilities Fuel Company, which will be performed on Texas lignite near Fairfield, Texas, and the Alberta Research Council along with an industrial consortium. The former test is based on a license of the Russian technology, and will use the percolation method.

Table 2. Thermal balance of the gasification process in generator 5a-b in seam IV interior (9m thickness) at Yuzhno-Abinsk from January 12, 1961 to January 31, 1961 (from Kreinin, 1964).

[Calorific value of the gas Q = 1,300 to 1,196 kcal/m^3 (146 to 134 Btu/ft^3); lower heating value. Gas leakage = 10%. Gas-water content = 290g/m^3. Relative blast intensity = 17 m^3/hr/m^2].

Item	Energy Balance Component	Energy Balance %
1	Heat of combustion of the dry gas	69.9
2	Heat of combustion of leakage gas	7.8
3	Heat content of the gas	4.2
4	Heat content of leakage gas	0.5
5	Heat content of water in the gas	9.2
6	Heat content of the humidity in gas leakage	1
7	Heat content of the ash residue	0.1
8	Losses to the surrounding medium	7.3
9	Heat content of the dry coal	
10	Heat content of water in the coal	0.1
11	Heat content of dry air blast	
12	Heat content of water introduced	0.5

TEXAS DEEP-BASIN LIGNITE

Underground coal gasification is currently of great interest as an extraction method for Texas lignite, mainly for those deposits which lie below strip-mining depth. Texas lignite resources, located mainly in eastern Texas, are very large and moderately low in sulfur (1.0 to 1.5 percent dry basis). Recent mapping of lignite lands by Kaiser (1974) of the Bureau of Economic Geology has indicated roughly 10 billion tons at stripping depth. More impressive, the deep-basin lignites (those lying between depths of 200 to 5,000 ft beneath the surface) have been estimated to be in excess of 100 billion short tons, which is the Btu equivalent of 10 times the proven reserves of oil and gas of Texas. Obviously all of this lignite cannot be recovered, but the order of magnitude is still significant.

The principal deposits of Texas lignite occur north of the Colorado River. Near-surface deposits, those found at 0 to 200 ft below the surface, occur within the outcrop of the main lignite-bearing geologic units. Deep-basin deposits, those found at greater than 200 ft below the surface, occur downdip and coastward from the near-surface lignite (fig. 3), with a dip of approximately 1°. The major deep-basin deposits occur in a broad arc which widens gradually from Gonzales County northeast to Cherokee County, where it splits and warps around the north and south flanks of the Sabine uplift (Panola and adjacent counties).

Primary commercial lignite deposits are found in lower Eocene rocks (Wilcox Group); deposits of secondary importance, in terms of resources and grade, are found in upper Eocene rocks (Yegua Formation and Jackson Group). Lignite of prime importance occurs as a component facies of ancient fluvial and deltaic rocks. Fluvial lignites occur in the Wilcox and Yegua north of the Colorado River. Deltaic lignites occur in the Wilcox, Yegua, and Jackson between the Trinity and southwest flank of the Sabine uplift in the deep basin.

TECHNICAL FEASIBILITY OF UCG IN TEXAS

It appears that Texas lignite may be especially suited for this process for the following technical reasons:

1. The overburden (usually clay or mud) tends not to form extensive fissures and cracks and is relatively impermeable to gas flow. The lignite also has an extremely high natural field permeability (1 darcy) and thus should require pneumatic fracturing only; the overburden would resist and cushion the propagation of artificial fractures to the land surface. A tight seal around the gasification region would allow relatively high-pressure operation and higher flow rates, minimizing leakage and improving yields.

2. The reasonably thick lignite seams (5 to 20 ft thick) would yield good utilization of the heat evolved during in situ gasification. Russian data (Gregg and others, 1976) indicate that seam thicknesses over 6 ft are feasible for UCG, whereas thinner seams (less than 3 ft thick) are not feasible, because of relatively high heat losses.

3. The mud roof and floor for Texas lignite would tend to settle down gradually during gasification, minimizing surface subsidence and maximizing recovery. This phenomenon would also help prevent excessive production of CO_2 (formed by oxygen bypassing) due to increased void space and thus would improve the yield of product gas.

ECONOMIC FEASIBILITY OF UCG IN TEXAS

Texas lignite appears to be technically amenable to underground gasification, and the economics of in situ production also appear to be favorable compared to that for coal deposits elsewhere in the United States. A high thermal efficiency would certainly increase the net value of the low-Btu gas. Other factors can be cited:

1. The high permeability would yield significant cost savings in two areas. Fracturing is obviated, and the well density can be much lower, thus lowering the drilling costs tremendously.

2. The thickness of the seams and the existence of multiple seams would yield a high energy content per well drilled, thus saving drilling costs and making the necessary operating field much smaller in size.

3. Above-ground coal-processing equipment and gasifiers, which contribute one-fourth of the total costs of the produced gas in the Lurgi process, would be eliminated.

4. Deposits of Texas lignite are located within 100 miles of the major demand centers of Texas, including Houston, Dallas, Austin, and San Antonio (fig. 3).

The depths at which in situ gasification can be applied depend on drilling costs and technology. Current drilling and completion costs probably limit its application to less than 2,000 ft. For a 1,000 MW plant, a 6 ft lignite seam, and a 60-percent recovery of coal as low-Btu gas, an areal extent of 1.50 square miles per year would need to be gasified.

There appear to be several modes of utilization for low-Btu gas produced from Texas lignite:

1. Direct combustion to produce electricity:

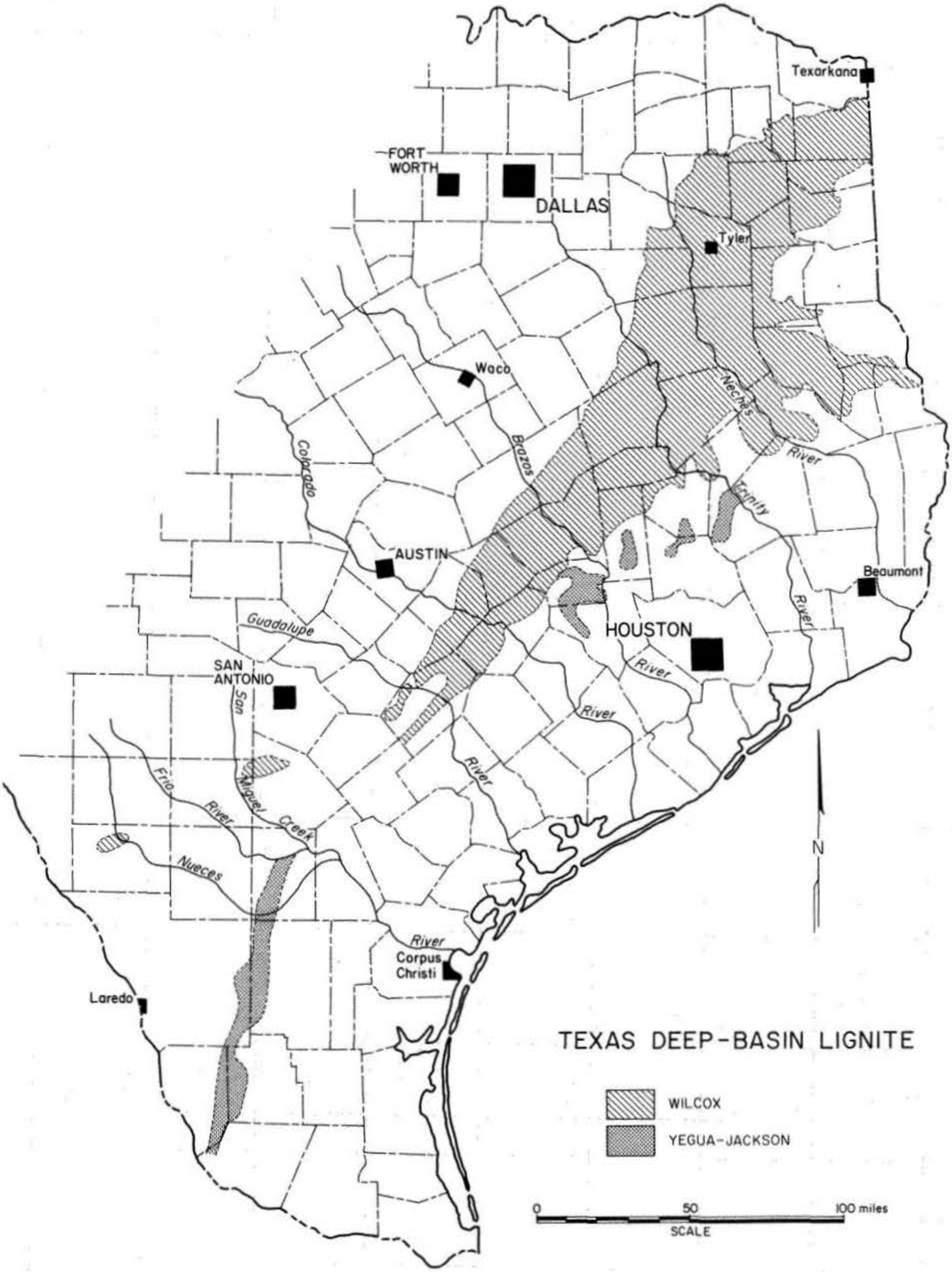

Figure 3. Distribution of Texas deep-basin lignite.

Projected improvements in gas turbine generators (combined cycle) could yield efficiencies approaching 50 percent (compared with 37 percent in conventional powerplants) with low-Btu gas from UCG.

2. Direct heating in industrial processes: Low-Btu gas could replace natural gas for direct firing of industrial processes. With the heavy concentration of energy-intensive industry in Texas, such a fuel would be very useful.

3. Chemical feedstocks: Much of the petrochemical industry now requires liquid petroleum or natural gas as a starting point for the manufacture of chemicals. The low-Btu gas could serve as a basic building block for the production of organics. Gasification with pure oxygen is a necessity in this application.

A recent study (Ozturegen, 1975) at The University of Texas at Austin has evaluated the economics for in situ gasification of Texas lignite. Figure 4 shows the projected cost in cents per million Btu of a clean low-Btu gas (hydrogen sulfide removed) as a function of seam thickness and depth beneath the surface of the Earth. The utility-financing method was used. As can be seen from the figures, the cost of the gas produced appears to level off at approximately a 6 ft seam thickness. It is apparent from the figure that for underground coal gasification, a low-Btu gas can be produced competitively for overburden to seam thickness ratios approaching 150 to 1 and possibly even higher. The equivalent strip-mining ratio will probably approach 15 to 1 in the future. Thus, a tenfold enhancement in economic recovery potential is offered by in situ gasification. Some of the assumptions used in developing these curves included a drilling cost proportional to the depth and a borehole spacing of 75 ft by 75 ft, which was the spacing usually used in the Russian operations. At this time the optimum well spacing for economic underground coal gasification is not known. It is obviously desirable to maximize the borehole spacing, since the amount of energy recovered per hole drilled is the most significant economic factor in underground coal gasification.

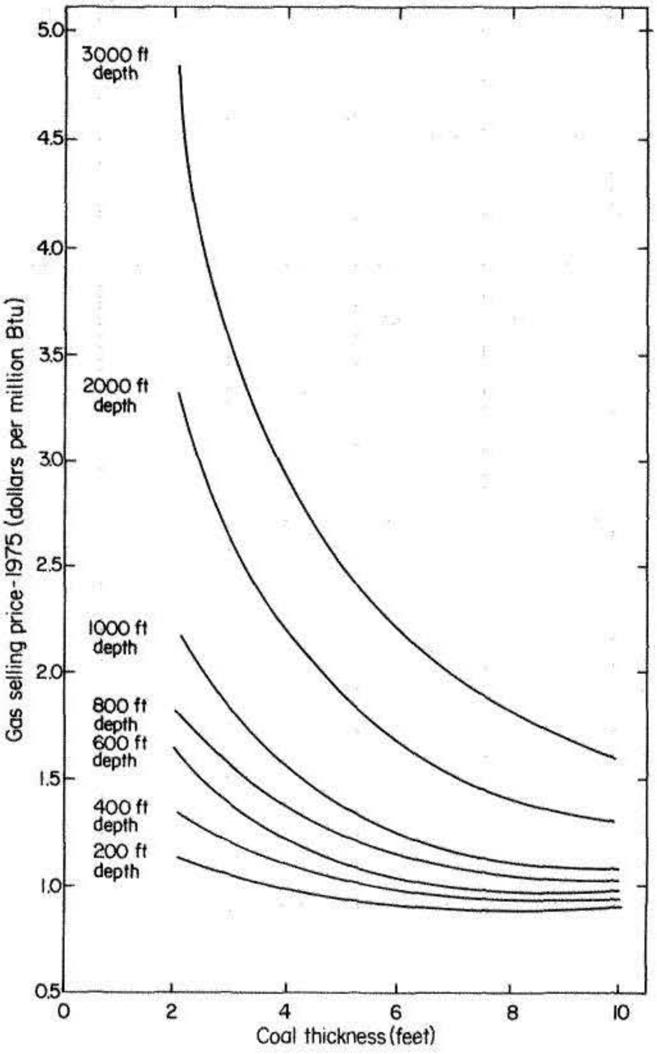

Figure 4. Gas selling prices with height of overburden a parameter.

Other assumptions made in the economic analysis include a gasification efficiency of 80 percent and a contact efficiency of 75 percent, thus giving an overall resource recovery of 60 percent. In other words, 60 percent of the latent energy available in the coal underground is recovered in the form of a low-Btu gas. These data are comparable to those obtained in the Russian commercial operations. The heating value of the gas produced during underground coal gasification is related to the thermal efficiency of the process and varies with the moisture and heating value of the coal gasified as well as the amount of water influx.

ENVIRONMENTAL ASPECTS OF UCG

In situ gasification overcomes many of the objectionable environmental features of strip and deep mining. The sulfur in the lignite is principally converted to hydrogen sulfide, which is easily removed from the product gas stream. Pollution by solid waste is reduced, since inert ash material is left underground, and massive excavation of the overburden is avoided. Surface-water-pollution problems common to conventional mining are also not encountered. However, UCG does present potential water-pollution problems in the subsurface environment.

Possible pollutants freed during gasification include phenols, tars, ammonia, and sulfur compounds. However, because of the high temperatures experienced in UCG, many of these objectionable compounds are thermally cracked to gaseous compounds, which are then removed from the gasification area through the product stream. Russian field data have indicated the presence of these compounds in produced water from the gasification area, but water samples from the ERDA field test at Hanna, Wyoming, indicated no effects on the ground water there. Hence, very few conclusions can be drawn at this time about the potential accumulation of pollutants underground.

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LIGNITE AND THE KOPPERS-TOTZEK PROCESS

G. V. McGurl[1] and J. F. Farnsworth[1]

ABSTRACT

The Koppers-Totzek coal-gasification process is described. Process conditions, including raw material and utility usages, overall material and energy balances, and efficiency are given for a Koppers-Totzek plan producing intermediate-Btu gas from Texas lignite. The environmental concerns and economics of the process are discussed.

INTRODUCTION

Solid fossil fuels represent about 85 percent of the indigenous supply of fossil fuels in the United States, but solid fossil fuels currently represent only about 17 percent of energy consumption in the United States. Physical security and financial stability will require greater utilization of our solid fossil fuels in the future. This will have to be achieved despite the higher costs of coal extraction and lignite over gas and oil and despite the greater ecological effects of mining and utilization of solid fossil fuels.

Coal and lignite can be utilized by direct burning, liquefaction, and gasification. There is no doubt that when the conditions are appropriate, direct burning represents the most efficient use of coal and lignite. There are a number of restrictions on direct burning: (1) the equipment must be designed to handle coal; (2) steam is the energy carrier; and (3) pollution regulations must be satisfied.

These restrictions are substantial hindrances to the increased use of direct coal firing. In general, it is very difficult to retrofit a boiler to burn coal. Large segments of industry, including ceramic and metallurgical industries, make substantial use of direct firing of fuel which is generally not practical with coal. Any coal- or lignite-fired boiler will require particulate-removal devices. The sulfur content of most coal and lignite is sufficiently high that SO_2 removal from the flue gas is required to meet national environmental standards. At the present time SO_2 scrubbing is only economically practical on large-scale boilers. Most Gulf Coast lignite is sufficiently high in sulfur content to require SO_2 removal when it is used to fire boilers.

The full utilization of our coal and lignite reserves will require conversion of the solid fuel to clean liquid or gaseous fuels, or both. The choice of the correct conversion process for coal and lignite will depend on user requirements, location of fuel source compared with that of the user, and the type of solid fuel used.

CONVERSION OPTIONS FOR COAL AND LIGNITE

Table 1 gives the advantages and disadvantages of coal liquefaction. Liquefaction is potentially the most energy-efficient conversion method. The complexity of the process causes high capital costs and substantial difficulties with solids separation, mechanical equipment, and pollution control. These difficulties have hindered the commercial application of this technology.

Table 1 gives the advantages and disadvantages of low-Btu gasification processes. Low-Btu gasification has applications for small gas requirements. It is potentially the least expensive

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Table 1. Advantages and disadvantages of four conversion methods.

Liquefaction	Low-Btu Gasification	Intermediate-Btu Gasification	High-Btu Gasification
Advantages:	Advantages:	Advantages:	Advantages:
Product easily transportable Product easily stored Product may have chemical-feedstock value Potentially the most energy-efficient conversion	Least expensive conversion Potentially more energy efficient than medium-Btu or high-Btu gasification	Less capital intensive than high-Btu gas Excellent feed for NH_3, CH_3OH plants Can be transported moderate distances Retrofitting on oil and natural gas boilers is relatively easy, and no derating is required NO_x emission control is easier with natural gas because of the wide flammability limits More energy efficient than high-Btu gas Best developed technology	Product can be mixed with natural gas No retrofitting required Long-distance transportation is economical
Disadvantages:	Disadvantages:	Disadvantages:	Disadvantages:
Only a portion of the coal is converted to liquid (other products are gas and char) Processes have solid-separation difficulties Coal-based liquids contain carcinogens Processes are complex because of the wide range of products produced	Transportation of product is expensive Cannot be retrofitted to existing facilities without substantial derating Less efficient combustion Not suitable for chemical feedstock More stringent sulfur removal required because of large gas volume	More capital intensive than low-Btu gas Product cannot be economically transported for long distances Retrofitting required	Highest capital cost Lowest energy efficiency Must be reformed to be used as NH_3, CH_3OH feedstock

and most energy-efficient gasification scheme, but studies have shown that the economic advantages are marginal. The most significant disadvantage is that utilization in existing boilers requires substantial derating because of large flue-gas volume and inefficient combustion.

The advantages and disadvantages of intermediate-Btu gasification are also shown in table 1. It is more efficient thermally and provides more gas per dollar of capital investment than high-Btu gas, and it can be readily used in equipment designed for natural gas with minimal retrofitting. Although intermediate-Btu gasification requires more capital investment and is theoretically less energy efficient than low-Btu gas, a study by a major research laboratory has shown that these penalties are slight.

The relative advantages and disadvantages of high-Btu gas are indicated in table 1. The major advantage is the complete interchangeability with natural gas which allows direct utilization of existing facilities. The primary disadvantage is the high capital investment and low energy efficiency of the process. For any product there will be significant differences in specific characteristics with different processes.

The Koppers-Totzek (K-T) process is suitable for either medium- or high-Btu gas. The Koppers Company, Inc., however, believes that its best market is in medium-Btu fuel gas and synthesis gas for ammonia and methanol.

Edgar and Richardson (1974) concluded that utilization of Texas lignite to produce high-Btu gas was undesirable because the proximity of the lignite deposits to the large Gulf Coast industrial users did not justify the higher capital cost and lower energy efficiency entailed in synthesis gas (SNG) production.

Because of its high volatiles content, Texas lignite is more suited for carbonization or hydrogenation processes. However, these processes leave a large amount of char, which is as high in sulfur content as the original lignite and which must be utilized. Gasification of this type of char in a K-T gasifier is practical. Substantial amounts of char from the Char Oil Energy Development (COED) process were successfully gasified in a K-T plant. Lignite is successfully gasified in a number of K-T plants with a carbon conversion greater than 98 percent. The performance of lignite char in a K-T gasifier will be similar to that of the lignite itself. The gas produced will contain somewhat more CO and somewhat less H_2 than the gas from lignite. The overall thermal efficiency of the gasification will also be higher because the char does not require drying. With the above exceptions the operation of the K-T gasifier would be the same for a lignite or a lignite char.

PROCESS DESCRIPTION

The K-T gasification process consists of: (1) feed preparation, (2) gasification, (3) heat recovery and gas cleaning, and (4) H_2S removal and sulfur recovery.

PULVERIZATION

To ensure high carbon conversion, the lignite must be ground to 70 percent minus 200 mesh. To feed properly into the gasifier, the lignite must be dried to about 8-percent moisture. Both the pulverization and drying are achieved simultaneously in a windswept pulverizer. Either a ball mill or a roller mill may be used. Figure 1 is a picture of the ball mill in Puentes, Spain. The choice of ball mill or roller mill is made on an economic and technical basis.

The ball mill may be preferable to the roller mill for pulverizing Texas lignite because the longer residence time allows more drying. Drying of high-moisture lignites is common in K-T plants. In Puentes, Spain, for example, the as-received lignite contains 50-percent moisture. It is predried in a rotary kiln to 35-percent moisture and dried to 8-percent moisture in a ball-mill system.

A schematic of a typical coal-preparation unit is shown in figure 2. From the pulverizer the lignite and air pass to a classifier where the oversized particles are separated and returned to the mill. Heat for drying is normally provided by combusting a portion of the product gas. The combustion gas is tempered with dry-waste nitrogen from the air-separation plant and recycled gas. The pulverized lignite is separated from the carrier gas in a cyclone. Part of the gas is recycled to temper the fresh combustion gas. The remaining gas is vented to the atmosphere through a bag-type dust collector. Lignite collected in the cyclone and dust collector is fed to a product

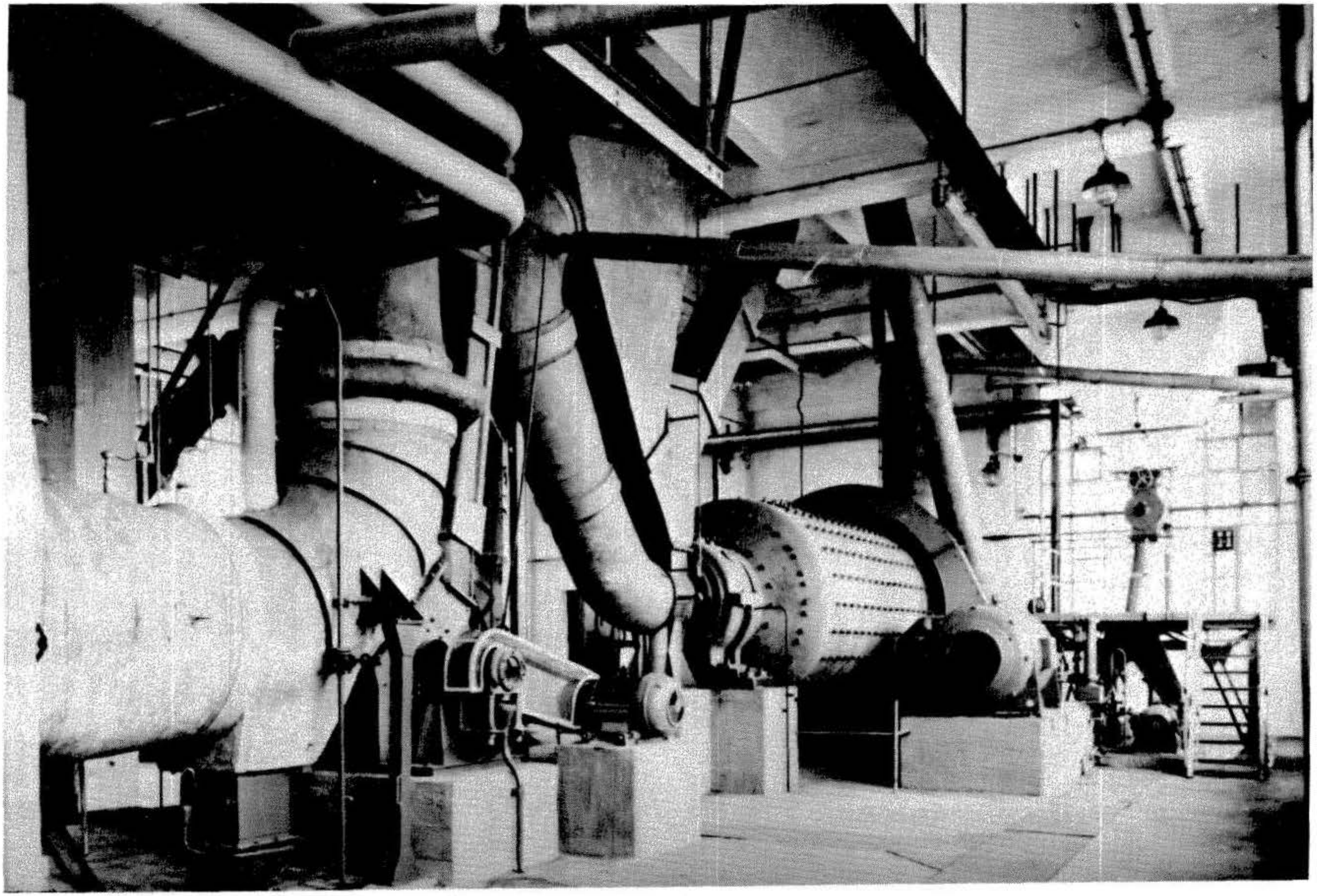

Figure 1. Ball mill, Puentes, Spain.

storage bin which normally holds about 4 hour's production. The pulverization system is designed to meet the entire needs of the plant by operating 20 hours per day.

The pulverized lignite is conveyed from the product storage bin to the gasifier service bins by a pneumatic conveying system using nitrogen as the conveying medium. Controls regulate the intermittent feeding of lignite from the service bins to the feed bins, which are connected to twin variable-speed screw feeders shown on figure 3. The pulverized lignite is continuously discharged from each screw into a mixing nozzle where it is entrained in oxygen and low-pressure steam. The mixture is then delivered through a transfer pipe to the burner head of the gasifier. Moderate temperature and high burner velocity prevent the reaction of the coal and the oxygen prior to entry into the gasification zone. A two-headed gasifier capable of gasifying over 400 tons of lignite per day is shown in figure 4. Figure 5 shows a schematic of the gasifier. The oxygen, steam, and coal react in the refractory lined steel shell gasifier at a slight positive pressure. Exothermic reactions produce a flame temperature of approximately 3,500°F. Lignite, oxygen, and steam are brought together in opposing burner heads spaced 180° apart. Four-headed gasifiers, capable of gasifying more than 800 tons of lignite per day, employ burner heads 90° apart. These larger units resemble intersecting ellipsoids having a major axis of approximately 25 ft and a minor axis of 13 ft. Gasification of the lignite is almost complete and instantaneous. Carbon conversion is a function of the reactivity of the coal, approaching 100 percent for lignites.

Endothermic reactions, occurring in the gasifier between carbon and steam, and radiation to the refractory walls, substantially reduce the flame temperature from 3,500°F to an equilibrium temperature of 2,700°F. Low-pressure process steam for the gasifier reaction is produced in the gasifier jacket from the heat passing through the refractory lining.

Ash in the lignite feed is liquefied at the high reaction temperature. Approximately 50 percent of the molten slag drops out of the gasifier in a slag quench tank and is recovered for disposal as a granular solid. The remainder of the slag and most of the unreacted carbon are entrained in the gas exiting the gasifier. Water sprays quench the gas to drop the temperature below the ash fusion temperature which prevents slag particles from adhering to the tubes of the waste-heat boiler. Ash fusion characteristics can be adjusted by the addition of flux to feed if required. This adjustment is not expected to be necessary with most Gulf Coast lignites.

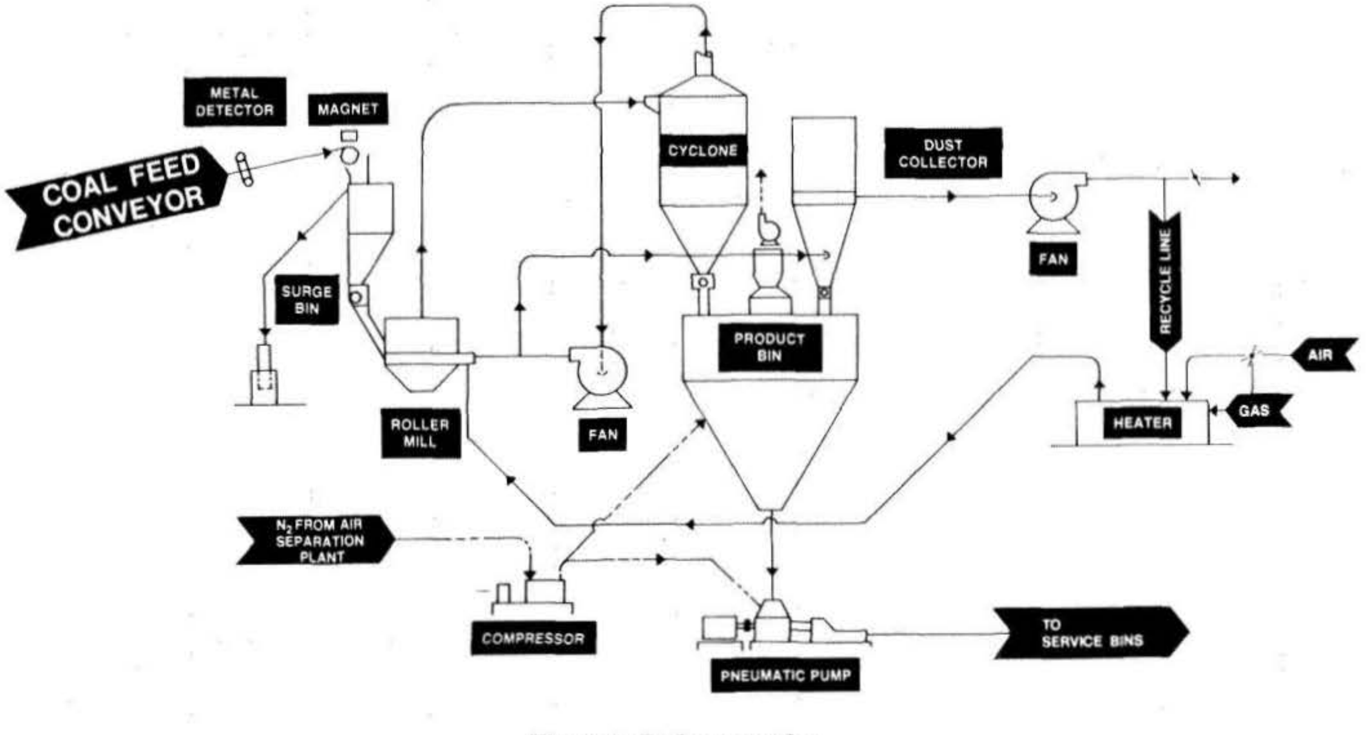

Figure 2. Coal preparation.

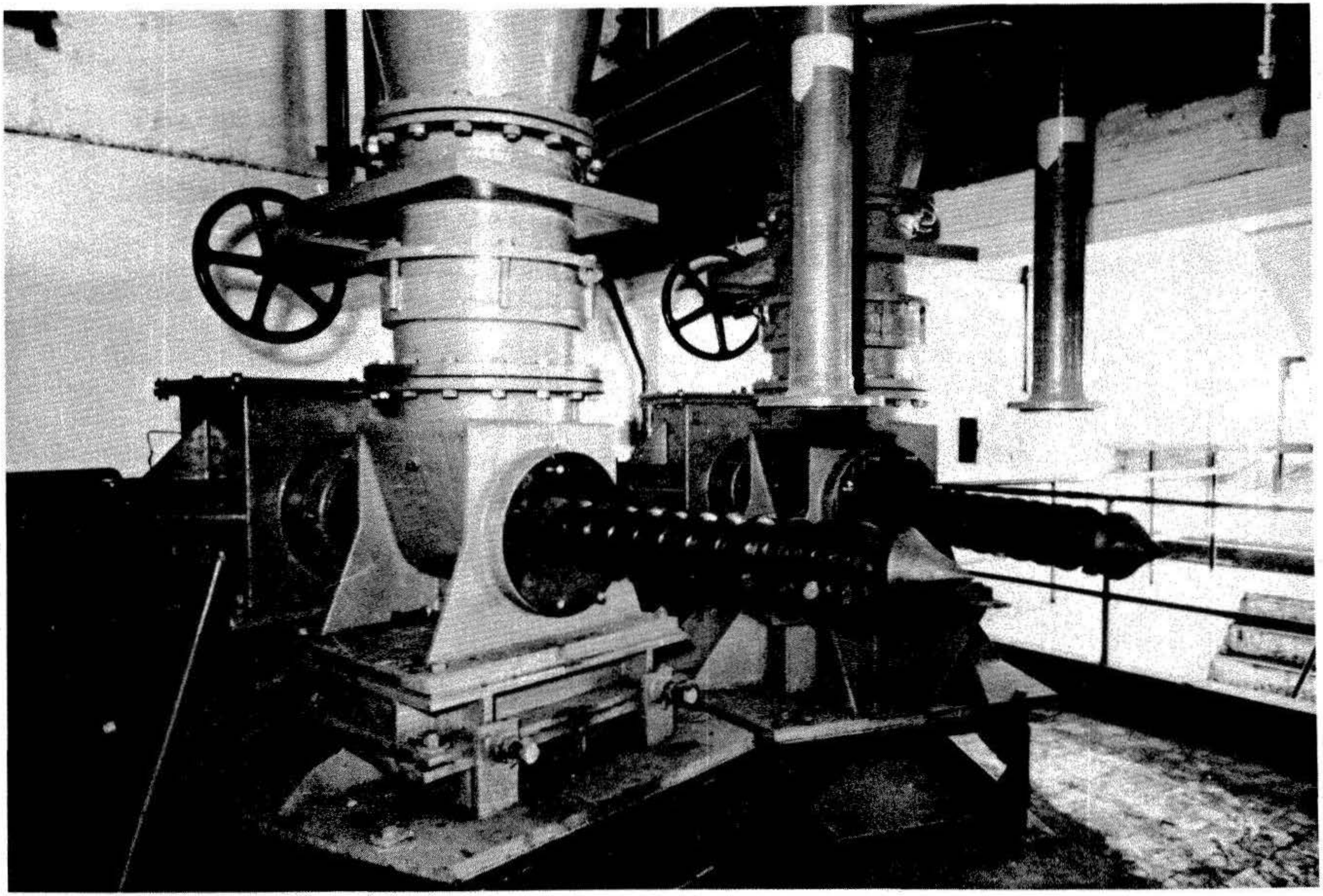

Figure 3. Screw feeders.

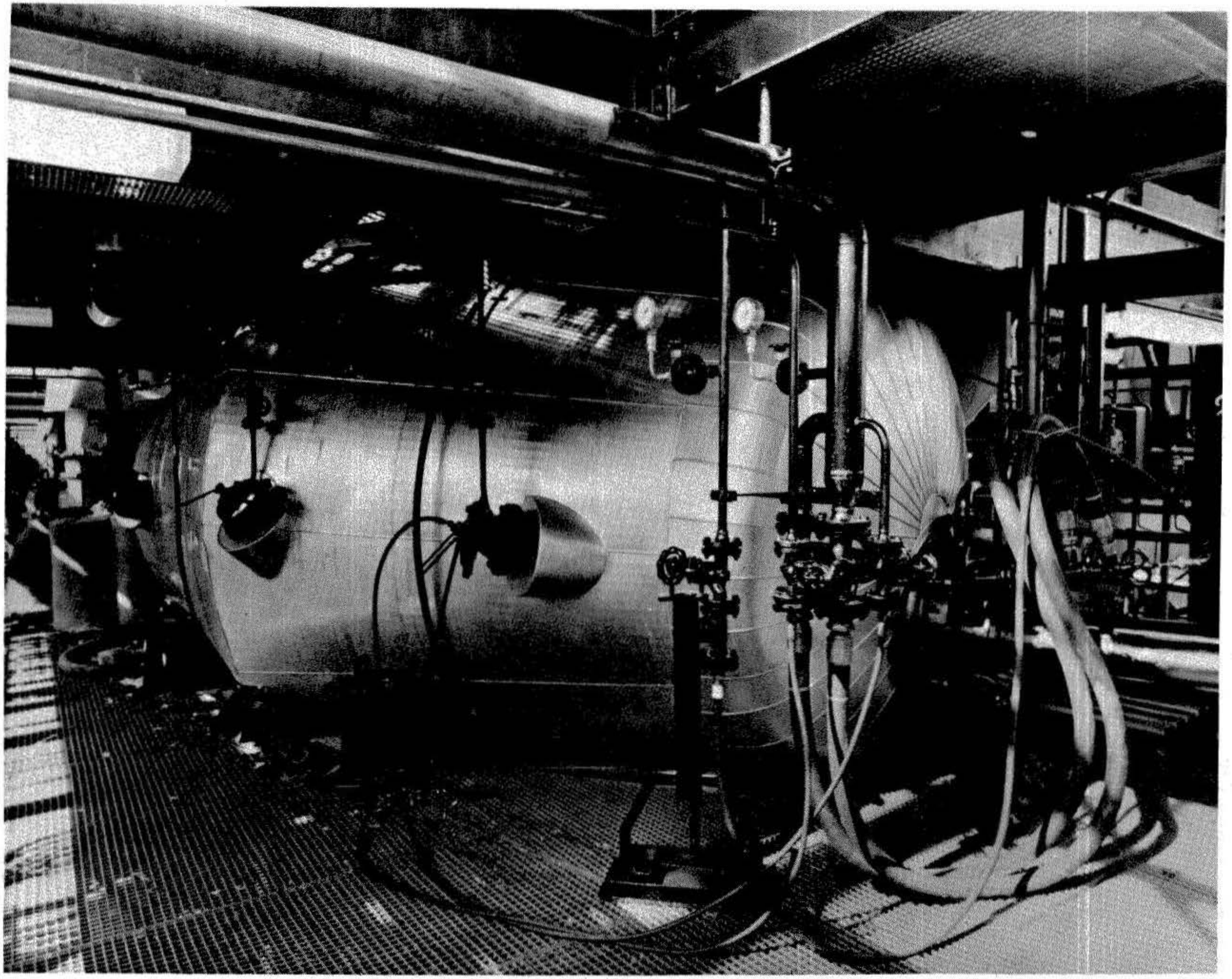

Figure 4. Two-headed K-T gasifier.

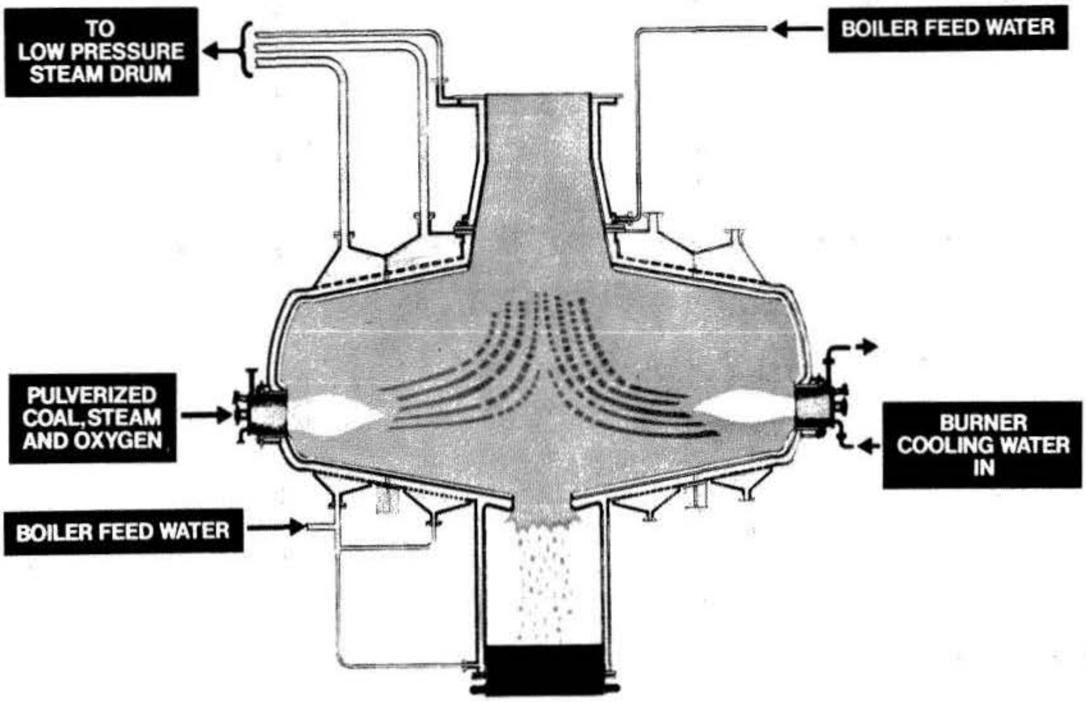

Figure 5. The K-T gasifier.

HEAT RECOVERY AND GAS CLEANING

An elevation drawing of the gasifier, heat recovery, and gas cleaning system is shown in figure 6. The raw gas from the gasifier passes through the waste boiler where high-pressure steam is produced. The conditions at which the steam is produced will depend on the specific requirements of the plant. All the existing plants produce saturated steam but there are no obvious problems in producing superheated steam at temperatures up to 700°F. The Koppers Company is currently proposing to build a plant in which varying types of superheaters would be tested. The primary problem that may be encountered is H_2S corrosion at tube wall temperatures above 750°F.

The gas is cooled to 350°F in the waste-heat boiler and then passes into a direct-spray-type washer cooler. The washer cooler is a ceramic lined tower with multiple sets of sprays and other internals. The gas is cooled to 100°F and 90 percent of the particulates are removed. After the washer coolers, the gas passes through two Theisen disintegrators in series. The disintegrators are high-speed squirrel-cage devices in which water is violently agitated and contacted with the gas. Each disintegrator removes 95 percent of the particulate matter in the gas stream fed to it. Water from the washer coolers, disintegrators, and slag quench tanks is sent to a clarifier where the particulate matter is removed and then is sent to a cooling tower from which it is recirculated through the system.

The cool, clean gas from the disintegrators passes to a blower which maintains positive pressure control on a gas holder and the inlet of the gas compressor. From the blower, a gas compressor is used which compresses the gas sufficiently above the desired delivery pressure to allow for pressure drops in the acid gas removal and flow-control systems.

ACID-GAS REMOVAL

The cool, clean gas leaving the gas-cleaning system contains sulfur compounds which must be removed to meet gas specifications. The type of acid-gas-removal process used depends on the product specifications for the gas and the original sulfur content of the fuel. For example, where the gas is used for chemical synthesis both high pressure and low sulfur content are required. This leads to the use of physical absorbent systems such as Selexol, Purisol, or Rectisol.

Gas used for fuel gas does not require high pressure or low sulfur content. This type of operation could justify the use of chemical-absorption systems or direct conversion systems. The sulfur in the fuel gas is in the form of H_2S and COS in a ratio of 90:10. High-sulfur fuels require the removal of a portion of the COS to meet applicable sulfur-emission standards. These fuels will require chemical-absorption systems such as carbonates or amines which remove some of the COS along with the H_2S and a major portion of the CO_2 as well. Choice of the proper chemical absorption system is controlled by the most economical means of removing enough sulfur while getting an acid-gas stream that is suitable for use in the sulfur-recovery process. Koppers has found that methyl diethanolamine (MDEA) system provides adequate removal, with good H_2S selectivity, at moderate energy usage. Figure 7 is a schematic of a typical MDEA system. This arrangement is typical of amine systems. The H_2S and a portion of the COS and CO_2 are removed from the gas by cool lean MDEA flowing countercurrent to the gas in the H_2S absorber. The foul solution from the bottom of the stripper is heated by interchange with hot lean solution from the stripper and sent to a reboiled stripper where the acid gases are regenerated. The acid gases are sent to a Claus unit or other sulfur-recovery system. The hot lean solution from the bottom of the stripper is cooled by interchange with foul solution and then further cooled with plant cooling water before being returned to the stripper. A small side stream from the hot lean solution stream is removed from regeneration.

Texas lignites do not have particularly high sulfur content, so it is not necessary to remove all of the H_2S and COS. Under these conditions a direct-absorption system such as Stretford or Takahax may be considered. These systems do not remove any COS. The advantages of these direct-conversion systems are relative simplicity and low energy usage. There are some problems, such as poor marketability of the product sulfur and disposal of spent solution, which must be carefully investigated before these processes are chosen.

MATERIAL AND ENERGY BALANCES

Three fuels have been chosen to indicate the range of performance using K-T gasifier. Inputs, outputs, and cold-gas efficiency are shown for each case.

Table 2 shows operating data for an Ohio coal, petroleum coke, and Texas lignite. The gas analysis varies only slightly with feedstock composition. Except for H_2S content, the only significant differences are higher CO_2 content for petroleum coke and somewhat higher hydrogen content in the fuels which contain more hydrogen initially. Higher rank coals require more oxygen for gasification and exhibit a lower gasification efficiency,

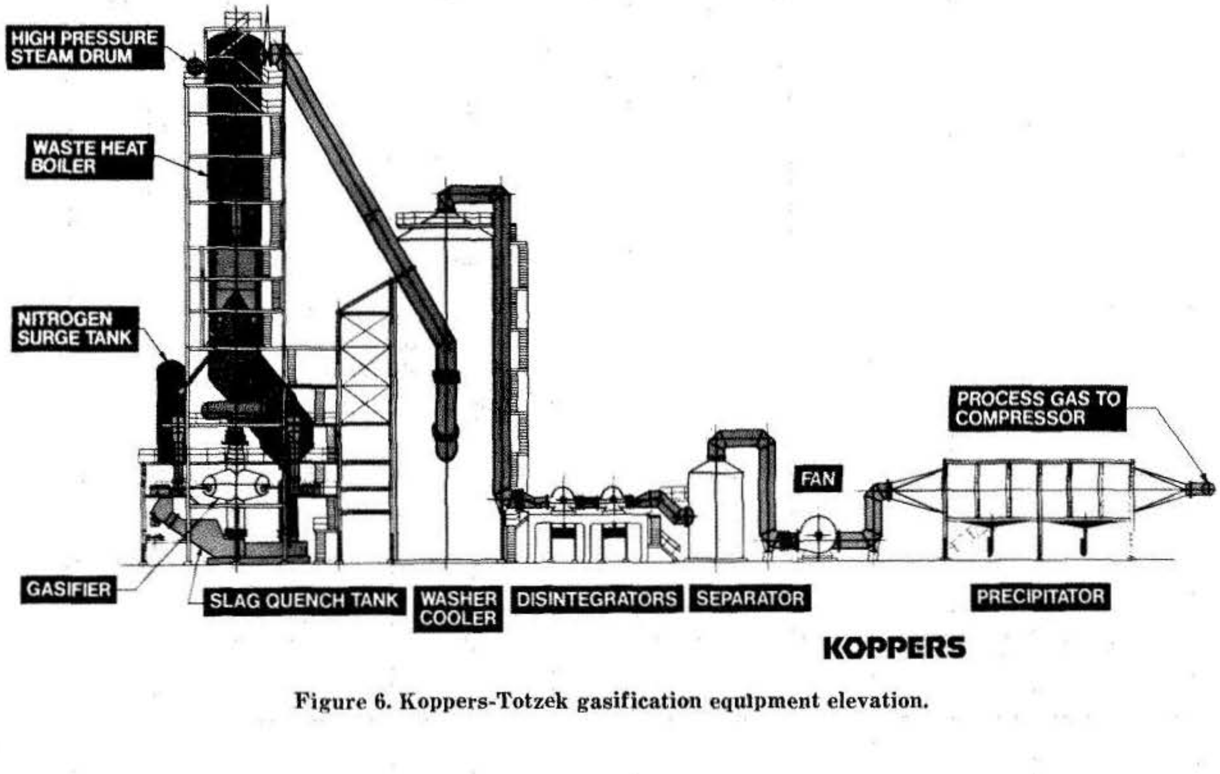

Figure 6. Koppers-Totzek gasification equipment elevation.

Table 2. K-T gasifier data.

Ohio Coal		Petroleum Coke		Texas Lignite	
Gasifier feed		Fresh coke		Gasifier feed	
Analysis—weight percent		Analysis—weight percent		Analysis—weight percent	
C	67.02	C	84.36	C	57.40
H	4.86	H	4.11	H	4.87
N	1.34	N	1.34	N	1.11
S	4.54	S	2.83	S	0.93
O	6.69	O	0.92	O	14.26
Ash	14.55	Ash	0.44	Ash	13.43
Moisture	1.00	Moisture	6.00	Moisture	8.00
	100.00		100.00		
					100.00
HHV, Btu/lb (1% H_2O)	12435	HHV, Btu/lb		HHV, Btu/lb (8% H_2O)	10302
Oxygen 98%,		as received	15574	Oxygen 98%,	
tons/ton of dried coal	0.842	Oxygen 98%,		tons/ton of dried lignite	0.748
Process steam,		tons/ton of fresh feed	1.171	Process steam,	
lbs/ton of dried coal	682	Process steam,		lbs/ton of dried lignite	197
		lbs/ton of fresh coke	1127		
Gasifier products		Gasifier products		Gasifier products	
Analysis—volume percent		Analysis—volume percent		Analysis—volume percent	
CO	53.22	CO	55.44	CO	55.90
CO_2	10.04	CO_2	13.00	CO_2	10.04
H_2	33.85	H_2	29.53	H_2	32.43
$N_2 + Ar$	1.20	$N_2 + Ar$	1.19	$N_2 + Ar$	1.22
H_2S	1.59	H_2S	0.75	H_2S	0.38
COS	.102	COS	0.09	COS	0.027
	100.00		100.00		100.00
Jacket steam,		Jacket steam,		Jacket steam,	
lbs/ton of dried feed	1028	lbs/ton of fresh coke	1237	lbs/ton of dried lignite	825
Steam 750 psig sat.,		Steam 750 psig sat.,		Steam 750 psig sat.,	
lb/ton of dried feed	3149	lbs/ton of fresh coke	5297	lbs/ton of dried lignite	2601
Dry gas make,		Dry gas make,		Dry gas make,	
SCF/ton of dried feed	63494	SCF/ton of fresh coke	76390	SCF/ton of dried lignite	53829
Gas HHV, Btu/SCF (dry)	280.8	Gas HHV, Btu/SCF (dry)	273.8	Gas HHV, Btu/SCF (dry)	284.8
HHV of gas/HHV of coal (%)	71.69	HHV of gas/HHV of coke (%)	67.15	HHV of gas/HHV of lignite (%)	74.4

which is to be expected since they have less volatile matter and are more difficult to gasify. There are a number of ways to calculate efficiency of gasification, each of which gives a different value. Table 3 shows several efficiencies for the K-T process using a typical Texas lignite. The main point of this is that when a gasification efficiency is stated, the specific basis for the calculation should be explained. To be acceptable for use, a coal-gasification system must be able to meet stringent environmental standards. The K-T process is capable of meeting any regulation so far proposed.

ENVIRONMENTAL EFFECTS

AIR EMISSIONS

Hydrocarbons, particulates, SO_2, CO, and NO_x are the pollutants that might be emitted from a gasification plant. Particulates are controlled by performing all lignite-processing steps in closed systems with vents through bag filters. The gas itself is scrubbed to a very low level of particulate content to protect the compressor. No hydrocarbons are produced in K-T gasification, and, therefore, hydrocarbon emissions present no problem. Only a few parts per million (ppm) of NO_x are present in the K-T gas, so there is no NO_x emission problem from the gasification plant. When the K-T gas is burned some NO_x will be formed. At the same flame temperature K-T gas forms about the same amount of NO_x as natural gas. The K-T gas however has a much wider range of flammability than natural gas and can be burned at a lower flame temperature to achieve better control of NO_x emissions. Carbon monoxide is a major component of K-T gas, but emission to the atmosphere would occur only if there were a leak in the system. Carbon monoxide detectors will be located throughout the plant to provide immediate warning of any leak. The K-T gas contains about 30 ppm SO_2. Essentially all of this SO_2 is removed during acid gas removal. The gas contains H_2S and COS which are converted to SO_2 when the gas is burned. Any desired degree of H_2S removal can be achieved. The limit of SO_2 emissions is that achievable in the tail gas unit of the Claus plant when a Claus plant is used. It is relatively easy to achieve SO_2 emission levels of 0.1 lb per million Btu based on the integrated gasification and utilization of the gas. Very small traces of H_2S are dissolved in the water used in the cooling system. When this water is passed over the cooling tower, a portion of this H_2S may be stripped out. It is not expected that the H_2S level in the plume at ground level would ever exceed the permissable Texas ambient standard of 0.08 ppm. In a similar manner, trace amounts of HCN and NH_3 are dissolved in the water, and some might be stripped out in the cooling tower. If any nuisance results, either indirect cooling or chemical addition can be used to solve the problem.

Two solid effluent streams are emitted from the plant. The liquid slag that falls into the slag quench tank is converted to a granulated sandy material that is useful for road construction. It is glossy and inert because of the high temperatures to which it has been exposed. The remaining ash and small amounts of unburned carbon are recovered from the clarifier bottoms as a fine-textured material. This should be disposed of in landfill in a similar manner to ash from lignite-fired boilers. In a grass-roots plant, there may also be some sludge from water-treatment operations which is mixed with this fine fly dust for disposal.

WATER POLLUTION

Water usage will be strongly dependent on the specified design of a given plant. Virtually all water consumption is for evaporation in cooling towers. Dry cooling can be substituted for a portion of this if necessary. There are two effluent water streams. One is from the plant cooling tower. This water is identical with the feed water except that the dissolved-solids content is higher. The other stream is from the gas-cleaning cooling tower and may contain ammonia and fixed cyanides in small amounts. These are treated using breakpoint chlorination which reduces the level of pollutant to the point at which the effluent is suitable for discharge into a trout stream. The breakpoint-chlorination method has been used successfully by Koppers to treat the effluent water from coke plants. This water initially contains much greater amounts of cyanide and ammonia as well as other pollutants than does the gas-cleaning cooling-tower water. After treatment for 72 hours, fish mortality tests in undiluted effluent show no mortality.

Table 3. Typical gasification efficiencies for Texas lignite.

	%
Gasification efficiency: (HV of cold gas + enthalpy of recovered steam)/total heating value of lignite	92.7
Cold gas efficiency: Total HV of cold product gas/total HV of lignite	74.4
Net cold gas efficiency: (Total HV of cold product gas-product gas used to dry lignite)/total HV of lignite	67.1
Overall efficiency (1): (Total HV of cold product gas-product gas used to dry lignite-product gas used to generate electricity)/total HV of lignite	60.0
Overall efficiency (2): Same as (1) except low S coal or lignite used to dry coal and generate electricity	65.7

The K-T process produces no tars, no phenols, and no condensable hydrocarbons because of the high temperatures used in the process. This simplifies the process and also reduces the requirement for extensive treatment of contaminated waters. Heavy coal-tar fractions, especially from coal hydrogenation have been cited as a cause of skin cancer. In one large pilot plant, the skin cancer rate was 16 to 34 times the national average despite a comprehensive hygiene program and regular medical checkups. The carcinogenic substances are polycyclic aromatic hydrocarbons (PAH). No PAH is present in the K-T products.

COSTS

The operating and capital costs of a K-T gasification plant depend greatly on the site as well as the end use of the gas. At the present time, no gasification process can project realistic prices which are competitive with oil prices except under exceptional circumstances. The cost of mining Texas lignite is reportedly quite low. Because of its relative proximity to industrial users and the

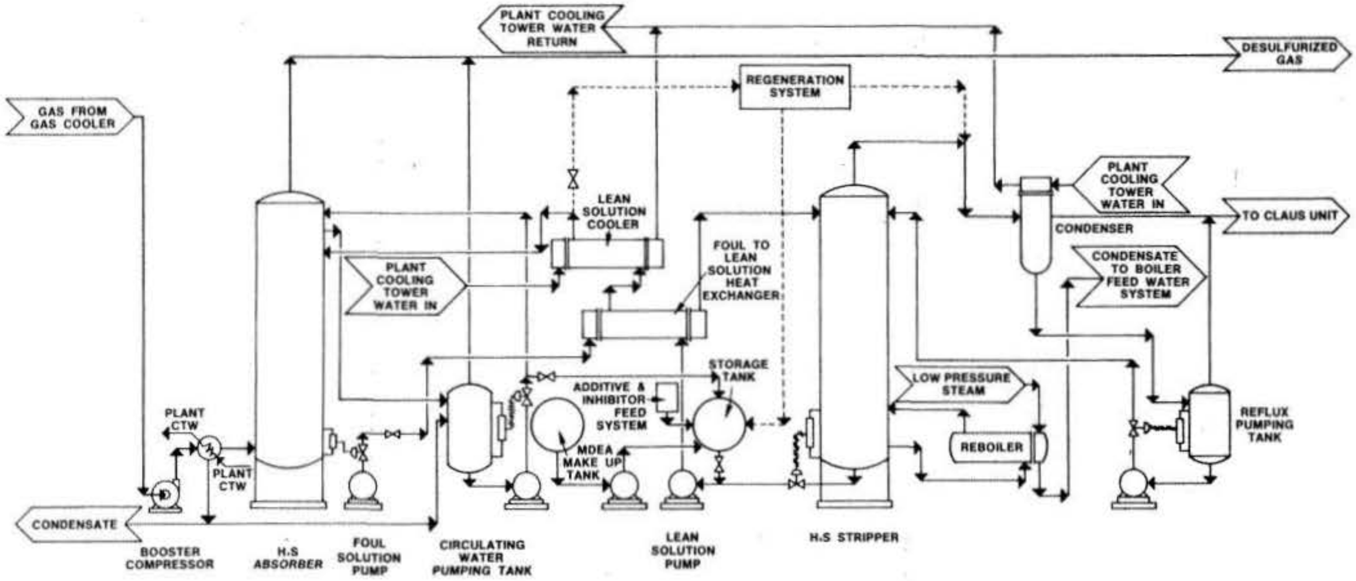

Figure 7. Low-pressure MDEA acid-gas removal system.

low production cost, a large K-T plant (125×10^9 Btu per day) could probably provide low sulfur, intermediate-Btu fuel gas at a price competitive with low-sulfur oil.

An example of the comparative capital costs of high-Btu and intermediate-Btu gasification is as follows. The January 1975 investment of 221×10^9 Btu per day grass-roots SNG plant was $\$1.05 \times 10^9$. A reasonable escalation to January 1976 would be 1.15×10^9, an investment of \$15.75 per million Btu per year. The January 1976 investment for grass-roots K-T plant producing intermediate-Btu gas rate of 125×10^9 Btu per day was $\$355 \times 10^6$. This is an investment of \$8.60 per million Btu per year. The K-T plant was designed for high-sulfur, agglomerating eastern coal in an area where very stringent pollution regulations must be met.

CONCLUSIONS

The following are typical characteristics of the K-T process.

1. Simple construction.
2. Accepts a wide variety of feedstocks.
3. Economically competitive with other commercially available processes.
4. Environmentally clean.
5. Provides easy retrofitting on gas- and oil-fired systems.
6. High unit capacity.
7. Safe.

The K-T process produces a readily usable intermediate-Btu fuel gas in an environmentally acceptable manner. The costs are competitive with other existing conversion processes.

LIGNITE GASIFICATION USING THE CO_2 ACCEPTOR PROCESS[1]

G. Curran[2]

ABSTRACT

The CO_2 acceptor process is in the final stage of development in a pilot plant in Rapid City, South Dakota. The gasifier product gas, without methanation, can serve the needs of the Gulf Coast area for clean fuel gas and for chemical feedstock using Texas lignite.

INTRODUCTION

The CO_2 acceptor process has been under development for several years sponsored by the Energy Research and Development Administration (ERDA) and the American Gas Association (AGA). The pilot plant has a feed rate of dry lignite of 32 tons per day and is in Rapid City, South Dakota. Having substantially solved the mechanical problems and having demonstrated the technical feasibility of the process, we are now in the final stage of development at the pilot plant. The work will be completed 1 year from now. If all continues to go well, the next step will be to build a large demonstration plant.

Until recently both Conoco and ERDA had oriented the process toward the production of synthetic natural gas (SNG). This paper emphasizes the application of the process to the needs of the Gulf Coast area, with its enormous needs for clean fuel gas for in-plant steam and power generation and for process heaters, as well as for chemical feedstocks. Tables 1 and 2 are a detailed heat-and-material balance for the gasification section in which the raw synthesis gas is produced. The design is based on pilot plant data obtained during operations with North Dakota lignite for a total of 130 days at full process conditions of pressure and temperature. In the context of our orientation toward SNG, the heat-and-material balance represents a gasification plant which produces synthesis gas equivalent to 250 million ft^3 per day of SNG. The dry lignite feed rate is 16,000 tons per day. The process concept requires multiple parallel train operation so that smaller plants can be built without seriously affecting the process economics. Figure 1 is a flow diagram of the heart of the process. It is a fluidized-bed system which operates at 150 pounds per square inch, gage (psig). The lignite is fed at the bottom of the gasifier where the rapid devolatilization reactions occur; then fixed carbon is gasified by steam in the upper portion of the fluidized bed. All the heat required for gasification is supplied by a continuously recirculating stream of acceptor. Most of the heat is supplied by reaction of CO_2 with lime. The lime enters the top of the char bed and showers down through the fluidized bed and collects in the bottom of the gasifier in a bootlike configuration. The CO_2 acceptor reaction is reversed in the regenerator at about 1850°F where the heat is supplied by burning the residual char from the gasifier with air. The acceptor, leaving the gasifier, passes through a standleg and then is conveyed through a pneumatic lift line to the regenerator by the combustion air. In the pilot plant, that pneumatic lift line has a vertical rise of 100 ft. The residual char also passes through a standleg and, again, is pneumatically conveyed to the regenerator by a stream of regenerator-recycle flue gas. The acceptor, after regeneration, then flows through a standleg to the gasifier, thereby completing the loop. Ash is removed from the system by elutriation from the regenerator and is collected in external cyclones. Seals between the two reactors are provided by the three standlegs, all of which are purged with recycle gas. As the acceptor continues to circulate, it loses activity

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[1] Paper edited from a transcript of oral presentation.

[2] Conoco Coal Development Company; Library, Pennsylvania 15129.

Table 1. Mass, elemental, and heat balance for gasifier.

Basis: 1 hr
Datum: 60°F, H_2O (l)

	Lb	Mols	Mol%	H	C	N
				Elemental Balance, lb		
INPUT						
Preheated Lignite						
Mineral ash-free Coal	1,201,700.	—	—	53,820.	852,200.	15,000.
Oxygen Released from Ash	600.	—	—	x	x	x
Ash	100,900.	—	—	x	x	x
Subtotal	1,303,200.	—	—	53,820.	852,200.	15,000.
Steam	1,265,500.	70,243.	—	141,600.	x	x
Acceptor from Regenerator						
$MgO \cdot CaO$	4,821,100.	50,011.	—	x	x	x
Inert	850,800.	—	—	x	x	x
Subtotal	5,671,900.	—	—	x	x	x
Heat of Reaction						
$MgO \cdot CaO$ to $MgO \cdot CaCO_3$ (17,504 mols at 76,200 Btu/mol).						
Total Input	8,240,600.	—	—	195,420.	852,200	15,000.
OUTPUT						
Fuel Char to Regenerator						
Mineral ash-free Char	249,100.	—	—	2,100.	246,600.	x
Sulfur in CaS in Ash	1,200.	—	—	x	x	x
Ash	100,900.	—	—	x	x	x
Subtotal	351,200.	—	—	2,100.	246,600.	x
Acceptor to Regenerator						
$MgO \cdot CaCO_3$	2,408,600.	17,154.	35.00	x	206,000.	x
$MgO \cdot CaS$	24,300.	215.	0.44	x	x	x
$MgO \cdot CaO$	3,050,200.	31,641.	64.56	x	x	x
Inert	833,800.	—	—	x	x	x
Subtotal	6,316,900.	49,010.	100.0	x	206,000.	x
Reject Acceptor						
$MgO \cdot CaCO_3$	49,150.	350.1	35.00	x	4,200.	x
$MgO \cdot CaS$	500.	4.4	0.44	x	x	x
$MgO \cdot CaO$	62,250.	645.7	64.56	x	x	x
Inert	17,000.	—	—	x	x	x
Subtotal	128,900.	1,000.2	100.0	x	4,200.	x
Gasifier Gas						
CH_4	173,850.	10,838.	10.12	43,700.	130,150.	x
CO	428,000.	15,280.	14.26	x	183,500.	x
CO_2	299,400.	6,804.	6.35	x	81,700.	x
H_2	100,550.	49,868.	46.54	100,550.	x	x
N_2	7,550.	269.	0.251	x	x	7,550.
NH_3	9,050.	531.	0.496	1,600.	x	7,450.
N_2S	1,750.	51.3	0.048	100.	x	x
H_2O(v)	423,500.	23,506.	21.94	47,400.	x	x
Subtotal	1,443,650.	107,147.3	100.005	193,350.	395,350.	15,000.
Heat of Reaction						
Heat of Combustion (Reactants—Products ex Acceptor and CaS)						
Coal Sulfur to CaS (257.8 mols at 196,540 Btu/mol)						
Heat Loss						
Total Output	8,240,600.	—	—	195,400.	852,200	15,000.

Table 1. Mass, elemental and heat balance for gasifier, **Continued.**

O	S	Ash + Inert	MgO · Ca	Temp. °F	△h or Cp	△H, MM Btu	Heat Comb. HHV MM Btu
				INPUT			
270,400.	10,300.	x	x	500			
600.	x	x	x	500			
x	x	100,900.	x	500			
271,000.	10,300.	100,900.	x		145.0 Btu/lb	189.0	14,302.6
1,123,900.	x	x	x	1200	1,607 Btu/lb	2,034.4	x
800,200.	x	x	4,020,900.	1856	23,17 Btu/mol°F	2,081.3	—
x	x	850,800.	x	1856	0.254 Btu/lb°F	388.3	—
800,200.	x	850,800.	4,020,900.			2,469.6	—
						1,333.8	
2,195,100.	10,300.	951,700.	4,020,900.			6,026.8	14,302.6
				OUTPUT			
x	390.	x	x	1520			
x	1,190.	x	x	1520			
x	x	100,900.	x	1520			
x	1,580.	100,900.	x		508.6 Btu/lb	178.6	3,672.4
823,400.	x	x	1,379,200.	1520	37.88 Btu/mol°F	948.8	—
x	6,930.	x	17,400.	1520	23.38 Btu/mol°F	7.4	—
506,300.	x	x	2,543,900.	1520	22.79 Btu/mol°F	1,052.9	—
x	x	833,800.	x	1520	0.247 Btu/lb°F	301.1	—
1,329,700.	6,930.	833,800.	3,940,500.			2,310.2	—
16,800.	x	x	28,150.	1520	37.88 Btu/mol°F	19.4	—
x	140.	x	350.	1520	23.38 Btu/mol°F	0.2	—
10,350.	x	x	51,900.	1520	22.79 Btu/mol°F	21.5	—
x	x	17,000.	x	1520	0.247 Btu/lb°F	6.1	—
27,150.	140.	17,000.	80,400.			47.2	—
x	x	x	x	1520	19,860 Btu/mol	215.2	4,151.2
244,500.	x	x	x	1520	11,010 Btu/mol	168.3	1,860.5
217,700.	x	x	x	1520	16,840 Btu/mol	114.6	x
x	x	x	x	1520	10,050 Btu/mol	501.3	6,142.8
x	x	x	x	1520	10,620 Btu/mol	2.9	x
x	x	x	x	1520	16,700 Btu/mol	8.9	87.4
x	1,650.	x	x	1520	14,170 Btu/mol	0.7	12.4
376,100.	x	x	x	1520	1,782.8 Btu/mol	755.0	x
838,300.	1,650.					1,766.9	12,254.3
						1,624.1	
						50.6	
						49.2	
2,195,150.	10,300.	951,700.	4,020,900.			6,026.8	15,926.7

Table 2. Mass, elemental, and heat balance for regenerator.

Basis: 1 hr
Datum: 60°F, H_2O (l)

Elemental Balance

	Lb	Mols	Mol%	H	C	N
		INPUT				
Fuel Char						
Mineral ash-free Char	249,100.	—	—	2,100.	246,600.	x
Oxygen released from ash	2,350.	—	—	x	x	x
Ash	99,750.	—	—	x	x	x
Subtotal	351,200.	—	—	2,100.	246,600.	x
Acceptor from Gasifier						
$MgO \cdot CaCO_3$	2,408,600.	17,151.	35.00	x	206,000.	x
$MgO \cdot CaS$	24,300.	216.	0.44	x	x	x
$MgO \cdot CaO$	3,050,200.	31,641.	64.56	x	x	x
Inert	833,800.	—	—	x	x	x
Subtotal	6,316,900.	49,008.	100.0	x	206,000.	x
Makeup Acceptor						
$MgCO_3 \cdot CaCO_3$	184,500.	1,000.2	—	x	24,000.	x
Inert	17,000.	—	—	x	x	x
Subtotal	201,500.	1,000.2	—	x	24,000.	x
Lift Gas						
CO_2	83,650.	1,903.	32.36	x	22,850.	x
CO	4,100.	146.	2.48	x	1,750.	x
H_2	40.	3.	0.06	10.	x	x
N_2	106,300.	3,793.	64.51	x	x	106,300.
$H_2O(v)$	600.	35.	0.59	70.	x	x
Subtotal	194,690.	5,880.	100.0	80.	24,600.	106,300.
Air						
O_2	617,650.	19,302.	20.88	x	x	x
N_2	2,034,600.	72,613.	78.53	x	x	2,034,600.
H_2O	9,750.	543.	0.59	1,090.	x	x
Subtotal	2,662,000.	92,458.	100.0	x	x	2,034,600.
Heat of Reaction						
$MgO \cdot CaS$ to $MgO \cdot CaO$ (67.56 mols at 196,540 Btu/mol)						
Heat of Combustion (Reactions—Products ex Acceptor and all CaS)						
Total Input	9,726,290.	—	—	3,270.	501,200.	2,140,900.
		OUTPUT				
Spent Char	109,400.	—	—	x	4,900.	x
Acceptor to Gasifier						
$MgO \cdot CaO$	4,821,100.	50,011.	—	x	x	x
Inert	850,800.	—	—	x	x	x
Subtotal	5,671,900.	—	—	x	x	x
Regenerator Gas						
CO	82,550.	2,947.	2.47	x	35,400.	x
CO_2	1,688,550.	38,368.	32.13	x	460,800.	x
N_2	2,140,900.	76,406.	63.98	x	x	2,140,900.
H_2	130.	66.7	0.06	130.	x	x
SO_2	4,270.	66.6	0.06	x	x	x
S_2	70.	1.0		x	x	x
H_2S	150.	4.5	0.01	10.	x	x
COS	390.	6.5		x	80.	x
H_2O (v)	27,950.	1,552.	1.30	3,130.	x	x
Subtotal	3,944,960.	119,418.3	100.01	3,270.	496,280.	2,140,900.
Heat of Reaction						
$MgO \cdot CaCO_3$ to $MgO \cdot CaO$ (17,154 mols at 76,200 Btu/mol)						
$MgCO_3 \cdot CaCO_3$ to $MgO \cdot CaO$ (1000.2 mols at 121,010 Btu/mol)						
Heat Loss						
Total Output	9,726,260.	—	—	3,270.	501,180.	2,140,900.

Table 2. Mass, elemental, and heat balance for regenerator, **Continued.**

O	S	Ash + Inert	MgO · Ca	Temp, °F	Δh or Cp	ΔH, MM Btu	Heat Comb. HHV MM Btu
				INPUT			
x	390.	x	x	1520			
2,350.	x	x	x	1520			
x	1,190.	98,550.		1520			
2,350.	1,580.	98,550.	x		508.6	178.6	3,672.4
823,400.	x	x	1,379,200.	1520	37.88 Btu/mol°F	948.8	—
x	6,930.	x	17,400.	1520	23.38 Btu/mol°F	7.4	—
506,300.	x	x	2,543,900.	1520	22.79 Btu/mol°F	1,052.9	—
x	x	833,800.	x	1520	0.247 Btu/lb°F	301.1	—
1,329,700.	6,930.	833,800.	3,940,500.			2,310.2	—
80,100.	x	x	80,400.	60	—	x	—
x	x	17,000.	x	60	—	x	—
80,100.	x	17,000.	80,400.			x	—
60,800.	x	x	x	290			x
2,350.	x	x	x	290	1,735 Btu/mol	10.3	17.8
x	x	x	x	290			0.4
x	x	x	x	290			x
500.	x	x	x	290	1,159.6 Btu/lb	0.7	x
63,650.	x	x	x			11.0	18.2
617,650.	x	x	x	290	1,608 Btu/mol	147.8	x
x	x	x	x	290			x
8,700.	x	x	x	290	1,159.6 Btu/lb	11.3	x
626,350.	x	x	x			159.1	x
						13.3	
						3,250.4	
2,102,150.	8,510.	949,350.	4,020,900.			5,902.6	3,690.6
				OUTPUT			
x	5,960.	98,500.	x	1856	454.6 Btu/lb	49.7	70.3
800,200.	x	x	4,020,900.	1846	23.17 Btu/mol°F	2,081.3	—
x	x	850,800.	x	1856	0.254 Btu/lb°F	388.3	—
800,200.	x	850,800.	4,020,900.			2,469.6	—
47,150.	x	x	x	1856	13,820 Btu/mol	40.7	358.8
1,227,750.	x	x	x	1856	21,360 Btu/mol	819.7	x
x	x	x	x	1856	13,400 Btu/mol	1,024.2	x
x	x	x	x	1856	12,380 Btu/mol	0.8	8.2
2,150.	2,130.	x	x	1856	21,800 Btu/mol	1.05	x
x	70.	x	x	1856	15,480 Btu/mol	—	0.3
x	140.	x	x	1856	18,370 Btu/mol	0.2	1.1
100.	210.	x	x	1856	22,830 Btu/mol	—	1.5
24,800.	x	x	x	1856	1,977.7 Btu/lb	55.3	x
1,301,950.	2,550.	x	x			1,942.4	369.9
						1,307.1	
						121.0	
						32.8	
2,102,150.	8,510.	949,350.	4,020,900.			5,922.6	440.2

toward the CO_2 acceptor reaction; some of it is purposefully removed and replaced with fresh makeup stone, either limestone or dolomite. The pilot plant has been operating since September 1975 on limestone, although the flow diagram does show dolomite being used. They are substantially equivalent, pound for pound. The makeup rate is 2 moles of calcium for each 100 moles of calcium which is transferred from the regenerator to the gasifier. The heat content of the exit gases from both reactors is sufficient to generate and superheat all the gasifier steam and to compress the regenerator air. Therefore, the process is totally self-sufficient with respect to external fuel requirements.

Operation of the pilot plant has demonstrated the key features of the process which are: synthesis gas is produced without an oxygen plant; there are no tars, oils, or phenols; and there are not any detectable amounts of relatively stable substances such as benezene or naphthalene. More than 99 percent of the feed carbon is consumed within the process; the synthesis gas is hydrogen rich compared with all other gasification processes. The raw synthesis gas contains low concentrations of CO_2 and H_2S which reduce the cleanup requirements. The tendency of a fluidized-bed system is to be sensitive to feedstocks, such as lignite, which have low ash-melting temperatures. The entire history of the pilot plant operation in Rapid City has shown that no slag was ever formed.

ECONOMICS

There are no reliable cost figures. The C. F. Braun Company has completed a comparative economic study for all of the so-called new gasification processes, including the CO_2 acceptor. The study was sponsored by ERDA and AGA and will be published probably in 1976. We have begun our own economic study on a much more detailed basis than C. F. Braun was able to do in their limited study. This study should be completed by February 1977.

ENVIRONMENT

Table 2 shows a summarized sulfur balance taken from the heat- and material-balance tables. The dry lignite in this case contains 0.8 percent sulfur. On the basis of 100 parts of sulfur entering the gasifier, only 16 percent of the sulfur appears in the raw synthesis gas. A small amount leaves with the reject acceptor, and the sulfur is in the form of unreactive calcium sulfide. Most of the sulfur is transferred to the regenerator, and about 25 percent of the total feed sulfur leaves as SO_2 in the regenerator offgas. The rest of the sulfur is rejected as calcium sulfide in the coal ash which leaves the regenerator. This calcium sulfide is highly reactive, and the ash cannot be dumped. We have worked out a process in which the ash is slurried with water and reacted with CO_2 at ambient conditions. Calcium carbonate is formed, and H_2S is evolved. This H_2S-rich stream is combined with the H_2S recovered from the raw synthesis gas and is processed in a conventional Claus plant, giving a total yield of about 75 percent of the sulfur as elemental sulfur. The water requirement for the large plant is relatively small. It is 4,800 acre-ft per year, which corresponds to 4.3 million gallons per day. There is no aqueous discharge to the ground. All water consumption is that used chemically to react with the lignite to form the synthesis gas plus evaporation loss from cooling towers and from the ash-slurry pond. The chemical consumption is about one-half the total. As to the fate of cyanides, trace elements, and so forth, we will hire an expert outside contractor to characterize thoroughly all the effluvia from the pilot plant. This work will also be completed within 1 year.

CLEAN FUEL GAS

Table 3 shows the composition of the synthesis gas. The right-hand column shows the content of NH_3 and H_2S at the top of the gasifier bed. When that gas is cooled to 100°F to condense the unreacted steam, about 90 percent of the ammonia is removed. Very little H_2S, less than 10 percent, is removed during cooling. The higher heating value of this gas is 386 Btu/ft^3. The clean gas shown in the left column is produced with a thermal efficiency of 85 percent based on the higher heating values of the gas and of the dry lignite fed to the gasifier. If the cooled gas is used as fuel without sulfur removal, the sulfur content is equivalent to burning 0.25 percent fuel oil.

Through the use of established technology, the sulfur content can be reduced to any desired level. This gas properly can be called a low-Btu gas, although I would rather call it a medium-Btu gas to distinguish it from the truly low-Btu gas which can be produced by the various air-blown gasification processes. These gases typically contain 45 or 50 percent nitrogen and have a higher heating value of about 130 Btu/ft³. They would be expensive to transport by pipeline and probably would have to be consumed on site. The distinction is important because our medium-Btu gas, with its high hydrogen content, leads to considerably lower pressure drops across a pipeline. As an illustration, for a given cost of compression, a pipeline using our gas will deliver about 50 percent as much energy as a natural gas pipeline would, compared with about 9 percent with the low-Btu gas.

Table 3. Gas composition, dry basis.

Compound or Element	Mol, percent Clean Gas	Top of Gasifier Bed
CH_4	13.1	13.0
CO	18.4	18.3
CO_2	8.2	8.1
H_2	60.0	59.6
N_2	0.3	0.3
NH_3	—	0.64
H_2S	—	0.061
	100.0	100.001

CHEMICAL FEEDSTOCK

The composition of our gas is quite similar to the dry gas composition of the exit gas from a primary reformer operating at about 450 psig in an ammonia plant where natural gas is used as the feedstock. Our calculations show that the energy consumption per ton of ammonia in terms of total heating value of both the process gas and fuel gas is substantially the same when our gas is substituted for natural gas. In the context of conversion of an existing ammonia plant, to use our gas the primary reformer would be used as a preheater. The performance of the water-gas-shift reactors and the CO_2 absorber would not be affected appreciably. A 1,000-ton-per-day ammonia plant would require about 11 percent of the flows that are shown in the heat-and-material balance.

With regard to the use of our synthesis gas as a methanol feedstock, the methane content of the gas is such that the maximum amount of methanol that can be produced from it is about 40 percent based on the heating value of the methanol and of the synthesis gas. The purge stream from the synthesis loop could be converted to SNG. With the great need for fuel gas in this area, conversion of the purge gas to SNG would be an unnecessary expense. The purge gas is at 800 to 1,000 psig leaving the methanation loop and could be distributed over a fairly wide area as a clean fuel gas. In some circumstances it may be more economical to convert a smaller amount of the synthesis gas to methanol by reducing the recycled gas to the converter to the minimum value consistent with good control of temperature, thereby making more clean fuel gas available.

TEXAS LIGNITE

All of our development work on lignite has been based on North Dakota lignite. We will start soon on our laboratory study to find out whether Texas lignite is suitable for the CO_2 acceptor process from the standpoint of particle-size degradation and of reactivity. If this is so, we have authorization already from ERDA and AGA to perform a 2,000-ton test on Texas lignite in the pilot plant.

NEW LIQUID FUELS FROM COAL: PROGRESS IN THE ERDA PROGRAM

G. A Mills[1]

ABSTRACT

A comprehensive research, development, and demonstration program for production of clean liquid fuels from coal and lignite is progressing rapidly. This program, with present annual funding of more than $100 million, is being carried out in academic, governmental, and industrial facilities under sponsorship of the Federal Energy Research and Development Administration. The coal-liquefaction program has entered a new phase with the operation of several large pilot plants and plans for construction of a demonstration plant. This program is designed to test technical advances in each type of liquefaction process.

Cost estimates for coal-derived liquids from these processes are high and require great capital investment. Consequently, an active research program has been initiated seeking more efficient and less costly processes which can be the basis of third-generation plants.

One novel coal-liquefaction process is flash hydropyrolysis. When coal or lignite is heated rapidly (in seconds) in the presence of hydrogen and subsequently quenched, high yields of aromatic liquids are produced. An important feature is the concept that the coal structure is not really intransigent, and if "overcooking" can be avoided, large amounts of volatile products can be obtained with minimum coke production.

A second special opportunity, one for which much of the technology has been established, involves the reaction sequence: coal or lignite $CO + H_2 \rightarrow CH_3OH \rightarrow$ high-octane gasoline. The technology for manufacture of methanol from coal is available today. Methanol is an exceptional fuel which offers unusual opportunities for clean combustion for generation of electricity and for automotive use. Furthermore, using a remarkable new catalytic process, Mobil Research and Development has found that methanol can be converted to high-octane gasoline in high yields. The aromatic character of this gasoline distinguishes it from the Fischer-Tropsch product and illustrates the effectiveness of the concept of using catalysts to achieve molecular-engineering advances.

Other promising new processes include the very active zinc chloride catalyst system, hydrogenation using carbon monoxide and water, and others suggested by basic research leading to an understanding of coal structure as it relates to liquefaction reactions.

INTRODUCTION

In the United States, the needs for energy fuels are actually needs for fuels in suitable form that are economically or politically beneficial to manufacture. We have an ample supply of fossil fuels to meet our energy requirements for the next critical 50 to 100 years. However, these potential fuels are mostly in the form of coal and lignite. What is the problem? They are *hard-to-handle* solids rather than gases or liquids, and they contain unwanted impurities, particularly sulfur and ash. Furthermore, although it is possible to convert coal to high-quality gas and liquids, present processes are too costly and either unreliable or at least not of demonstrated operability.

Liquids are especially desired because of their convenience in storage, shipping, and use, which makes them suitable for application in each of four sectors—transportation, generation of electricity, industrial use, and commercial and home heating. But recent cost estimates for manufacture of refined heating oil and gasoline from coal are high, as much as $25 per barrel. Furthermore, an examination of this high cost shows that *a disproportionate fraction* is due to high capital charges. A plant that produces 50,000 barrels per day can cost $1 billion. Coal, especially lignite, represents a relatively small fraction of the charges for manufacture of liquids since 2 to 3 barrels (bbls) of oil can be produced from 1 ton of coal.

The problem of high capital costs arises because of the many processing steps, low production rate, high pressure, great hydrogen consumption, and inefficiency in certain steps, especially

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[1] Division of Fossil Energy Research, U.S. Energy Research and Development Administration; Washington, D.C. 20545.

solid-liquid separation. Thus, certain specific problem areas have been identified. Research and development is being directed at these on a priority basis.

As will be summarized later, under the Energy Research and Development Administration (ERDA) sponsored coal-liquefaction program, several processes are now being tested in large pilot plants that are believed to be significant improvements over those employed in Germany during World War II. However, even for these processes, the high costs for liquid products mentioned above makes them also presently uneconomical. Therefore, there is a great need and opportunity to develop new or greatly improved processes which can be regarded as third-generation plants.

TIMING

The uncertainty of when and at what rate synthetic liquid fuels will be installed is illustrated in figure 1, taken from the Project Independence report (Federal Energy Administration, 1974). "Business as usual" is very much slower compared to what is possible under an "accelerated" or "unrestricted" type of action. Technical advances can speed the time when synthetic fuels plants are installed.

COAL LIQUEFACTION—ERDA RESEARCH PROJECTS

The conversion of coal and lignite to petroleum-type products consists essentially of two kinds of chemical transformations, adding hydrogen and removing heteroatoms (sulfur, nitrogen, and oxygen). Of the heteroatoms, oxygen is most likely to be present in the largest amount. An interesting illustration of the carbon-hydrogen-oxygen compositional relationship of a number of fossil fuels has been assembled by Allred (personal communication) and is shown in figure 2. Lignite, with an oxygen content of about 30 percent, is intermediate between wood and petroleum.

Lignites with a sulfur content of about 1 percent are referred to as having moderate or even low sulfur contents. The specification for lignite for new electric generation facilities is 1.2 lbs of SO_2 per million Btu of input, which for lignites corresponds to 0.5 percent or lower sulfur. Therefore, a 1-percent sulfur lignite is too high and thus unacceptable. Therefore, because of sulfur regulations, either a low-sulfur synthetic fuel must be made or means must be found for sulfur removal during combustion, such as stack-gas scrubbing or fluid-bed combustion using limestone.

There are basically four types of coal-liquefaction processes: pyrolysis, solvent extraction, direct hydroliquefaction, and indirect (from $H_2 + CO$). Research on each of these types of processes is in progress at ERDA. Current coal-liquefaction research projects sponsored by ERDA are summarized in table 1. To illustrate the status of this program, more detailed comments follow on two projects, flash hydropyrolysis and methanol.

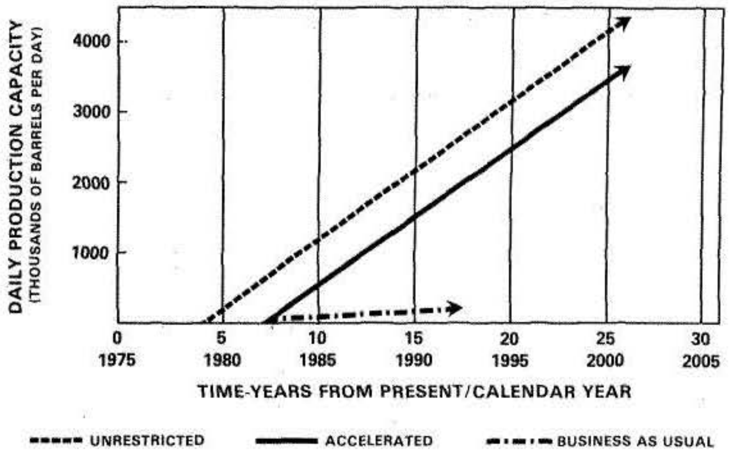

Figure 1. Growth of synthetic liquid fuel production capacity.

FLASH HYDROPYROLYSIS

A number of coal researchers believe that the structure of coal is not as intractable for conversion to liquids and gases as it appears. Specifically, in present coal-conversion processes, the long periods of heating at high temperatures actually degrade or chemically change part of the coal into a more intractable, condensed polynuclear form than was present in the original coal structure. To avoid this change, a number of suggestions have been made involving the application of new catalysts capable of operating at a lower temperature. These have been reviewed previously (Quader and others, 1969), and a recent evaluation has been presented (Schroeder, 1976).

One concept under investigation is flash hydropyrolysis. Coal or lignite is converted to liquid and gaseous hydrocarbons directly by rapid heating (in seconds) with preheated hydrogen followed by rapid cooling. For example, lignite was converted to 25-percent liquids (15-percent aromatics, mostly benzene, and 10-percent volatile oil), 35-percent light gases ($CH_4 + C_2H_6$), and the remaining 40 percent as char (Steinberg and Fallon, 1975). Conditions are 1,500 pounds per square inch (psi), 700°C, and 20 sec residence time. It is estimated that 6 lbs H_2 are required per 100 lbs lignite. The product distribution for various residence times is shown in figure 3.

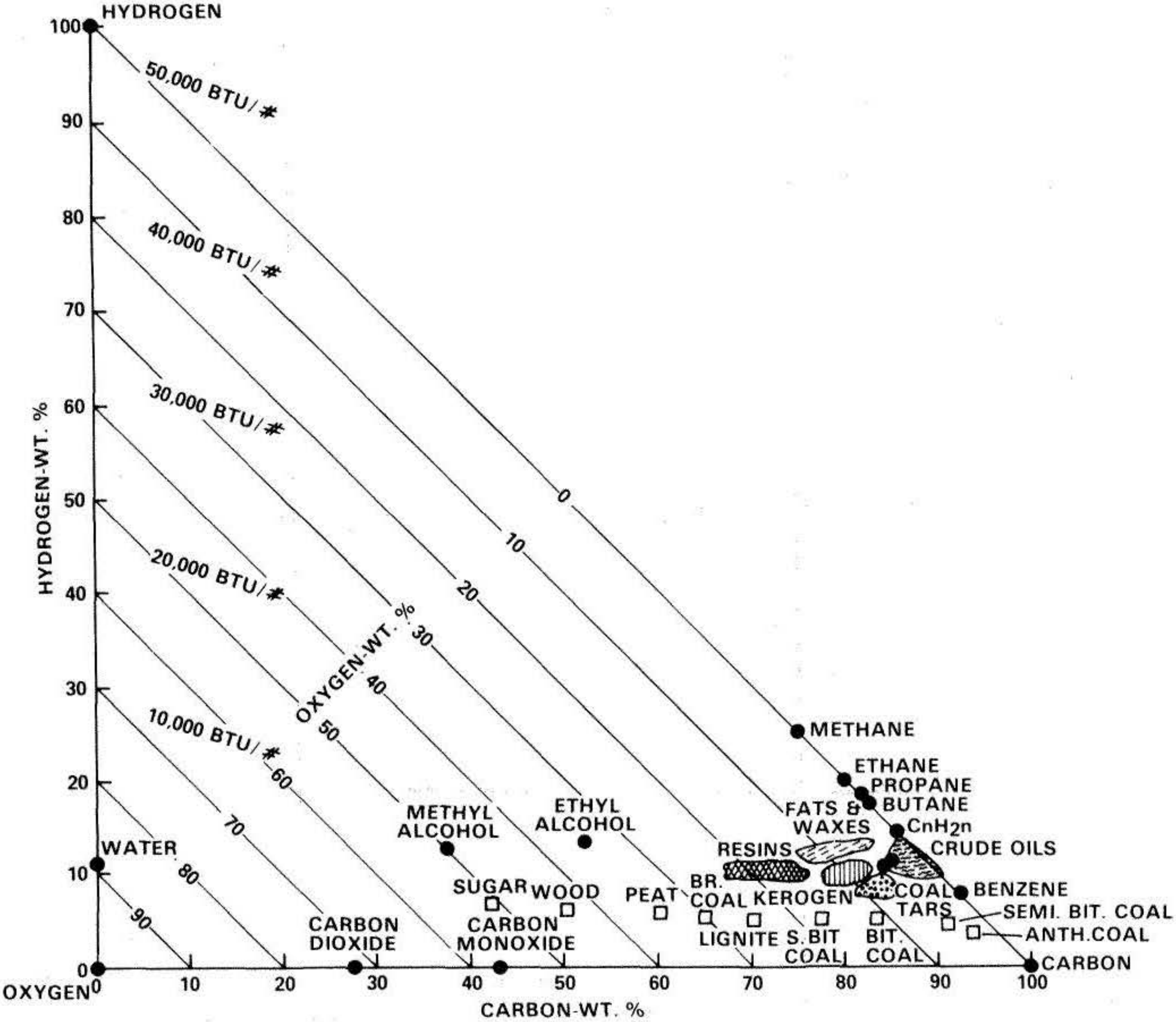

Figure 2. C-H-O content of fossil fuels.

Conversions to liquids and gases can be increased by the use of catalysts. Quader and others (1969) reported work on hydrogenation in a dilute-phase free-fall reactor at temperatures of about 515°C and pressures as much as 2,000 psi. Using stannous chloride equal to 15-percent weight of coal, up to 75-percent conversion was reported with a product distribution of 43-percent liquids, 32-percent gas, and 25-percent char.

The basic mechanism appears to involve a thermally induced cracking of bonds in the coal structure, followed by hydrogenation of the reactive fragment, and then rapid removal of product molecules so that further reaction and excessive hydrogenation is avoided.

The concept of flash hydropyrolysis has been vigorously advocated by Schroeder (1976). Using coal impregnated with 1-percent ammonium molybdate solution, he reports that in a reaction time of less than 1 min at 2,000 psi and 932°F, one can produce as much as 30-percent distillable liquid and 40-percent tar, with most of the balance gas (minimum or no char). The concept is to have a simple, direct process and to minimize capital costs.

Under ERDA sponsorship, laboratory work is being carried out at Brookhaven National Laboratory and the City University of New York (Squires and others, 1975), and continuous bench scale work on scale-up has begun at the Institute of Gas Technology. Flash hydropyrolysis is regarded as having potential for dramatic improvement of conversion of coal and lignites to clean gaseous and liquid fuels.

Table 1. Coal liquefaction: ERDA research projects.

METHOD	CONTRACTOR
Pyrolysis	
Flash Hydroprolysis	Brookhaven National Laboratory; Institute of Gas Technology; City University of New York;
Extractive (delayed) coker	A.D. Little/Foster Wheeler; Gulf Oil
Extractive	
Project Lignite	University of North Dakota
Solvent Extraction	Auburn University
Hydroliquefaction	
Zinc Chloride	Conoco/Shell; University of Utah
Petrocoal	Morgantown Energy Research Center
Disposable Catalyst	Sun Oil
Indirect	
$CO + H$	Mobil Oil
Refining	Air Products; Universal Oil Products
Catalysts	Battelle/Harshaw; Engelhardd

METHANOL AND IMPROVED FISCHER-TROPSCH

The so-called indirect conversion of coal to liquids consists of the steps of converting coal to a gaseous mixture of $CO + H_2$ and then converting this gas to liquid. This is the basis of the Fischer-Tropsch process, the only current commercial process for converting coal to gasoline. A plant with an equivalent capacity of 5,000 to 7,000 bbls per day is in operation in South Africa (SASOL). Construction of a second plant about 10 times larger is underway at a cost of over $1.5 billion. In the Fischer-Tropsch process, a mixture of CO and H_2 is combined over a catalyst to form hydrocarbons, most of which are in the gasoline boiling range. The advantage of this process is that it is well engineered and reliable. Disadvantages are the high cost and low thermal efficiency, and the hydrocarbon is characteristically a straight chain and therefore of a low octane rating. (They can be upgraded at a further cost.)

An interesting alternative has been proposed: to process the $CO + H_2$ over a different type of catalyst to form methanol for fuel use (Mills and Harney, 1974). Methanol synthesis from $CO + H_2$ is well established commercially for chemical purposes and has been improved in recent years.

Methanol also has potential for use as a motor fuel either blended with gasoline (about 15-percent methanol) or used alone. Extensive automotive test programs have been carried out that define the possible advantages of methanol. It has a high octane rating (106 research clear) and somewhat lowered pollution characteristics in combustion. However, there are difficulties in establishing a new fuel distribution system for general use by the public. Perhaps fleet use represents the best practical initial transportation application. A high-compression-ratio engine operating on methanol can offer high efficiency, with reported potential for 40-percent improvement in fuel efficiency (Vantine and others, 1975). An advantageous combination manufacture of methanol and pipeline gas from coal as coproducers has been proposed (Mills and Harney, 1974).

METHANOL TO HIGH-OCTANE GASOLINE

Recently, a new opportunity was created with the discovery by Meisel and others (1976) that methanol could be converted almost quantitatively to hydrocarbons and water (equation 1):

$$x\mathrm{CH_3OH} \rightarrow (\mathrm{CH_2})x + \mathrm{H_2O}. \qquad (1)$$

The hydrocarbons are predominantly in the gasoline-boiling range (C_4 to C_{10}), and the gasoline has unleaded research octane numbers from 90 to 100. The key to the process is the catalyst, which is of the crystalline "molecular sieve" type having channels and cavities of such a size that the molecules leaving the catalyst are of a controlled size. Durene (tetramethyl benzene) is scarcely able to leave and thus to be produced. Since changes in the catalyst can be made to change the products formed, the concept has been termed "molecular engineering" in catalyst design.

In the process, methanol is converted to 99+ percent in a single pass at 600° to 800°F and about 300 psi to a mixture of hydrocarbons whose composition is shown in figure 4. Essentially, no hydrocarbons above C_{11} are produced. This uniquely narrow range of product molecular weights is consistent with the constrained structure of the zeolite. The gasoline yield is 75 to 80 percent of the hydrocarbons, a yield which can be raised to about 90 percent by alkylation of the gaseous products.

A very important feature of the process is the aromatic character of the hydrocarbons which contribute to the high octane and distinguish the process from the conventional Fischer-Tropsch. A typical distribution of aromatics is on a percentage basis: C_6, 1; C_7, 8; C_8, 34; C_9, 35; C_{10}, 19; C_{11}, 3.

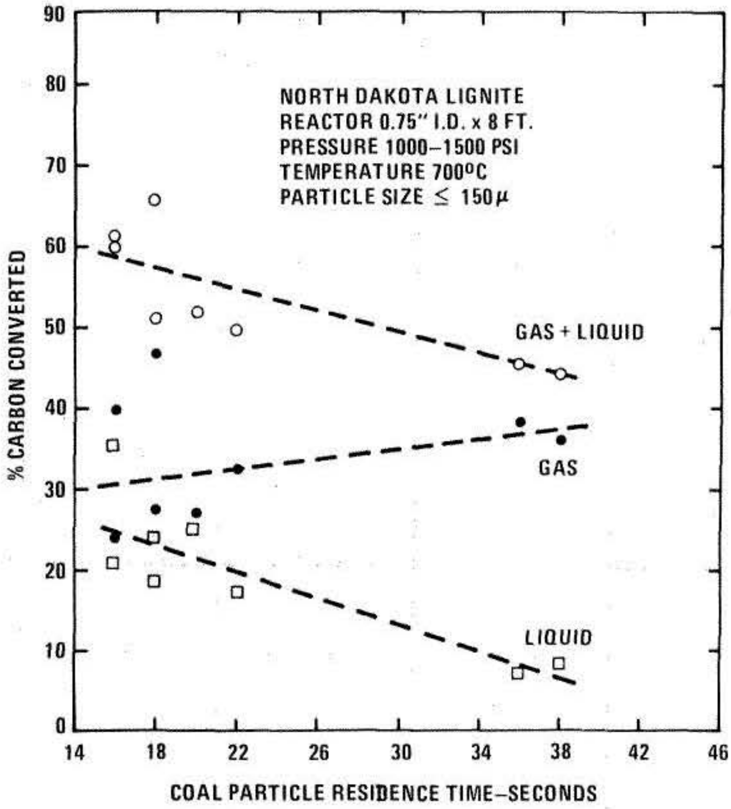

Figure 3. Gas phase coal hydrogenation versus coal residence time.

ECONOMICS OF THE PROCESS

It is estimated that it will cost about 5 cents to produce 1 gal of gasoline from methanol. It takes about 2.4 volumes of methanol to produce 1 gal of gasoline, thus the total cost is 2.4× + 5 cents per gallon, where x is the cost of crude methanol in cents per gallon.

This catalytic invention opens up a whole new area for "improved Fischer-Tropsch" processes. The next step is to learn how to bypass methanol manufacture and go directly from CO + H_2 to high-octane gasoline.

Aromatics production is desirable for gas use and chemicals manufacture, and their production is also advantageous in requiring less hydrogen compared to paraffins production (equations 2 and 3).

$$6\,CO + 9\,H_2 \rightarrow C_6H_6 + 6\,H_2O \qquad (2)$$

$$6\,CO + 12\,H_2 \rightarrow C_6H_{12} + 6\,H_2O \qquad (3)$$

The hydrogen requirement for the production of aromatics can be reduced 25 percent relative to the formation of the corresponding paraffins.

Considering thermodynamic equilibrium, one can convert synthesis gas to benzene 90 percent at 842°F and 600 psi.

Each of the three systems, coal to methanol for fuel use, methanol to gasoline, and CO + H_2 to gasoline are research projects regarded as offering new promising technologies and are being actively developed in cooperation with industry and ERDA laboratories.

OTHER NEW LIQUEFACTION PROCESSES SPONSORED BY ERDA

Several additional novel catalytic systems for adding hydrogen to coal offer promise for further plants. In the CO steam process, a combination of CO and steam hydrogenate ignite more rapidly and to a greater degree than does hydrogen itself under the same conditions of temperature and pressure. This promising process has been described previously and is also part of the research on Project Lignite (Souby, this volume). It is also expected that this process will soon be tried in a larger scale in pilot plant operation.

Other significant new processes under active research are: hydrocracking with molten zinc chloride, delayed coking combinations, hydroextraction and improvements in catalysts, and process variations suggested by basic research. In an advanced developmental scale are the H-coal and synthoil processes, both of which are direct catalytic hydroliquefaction processes.

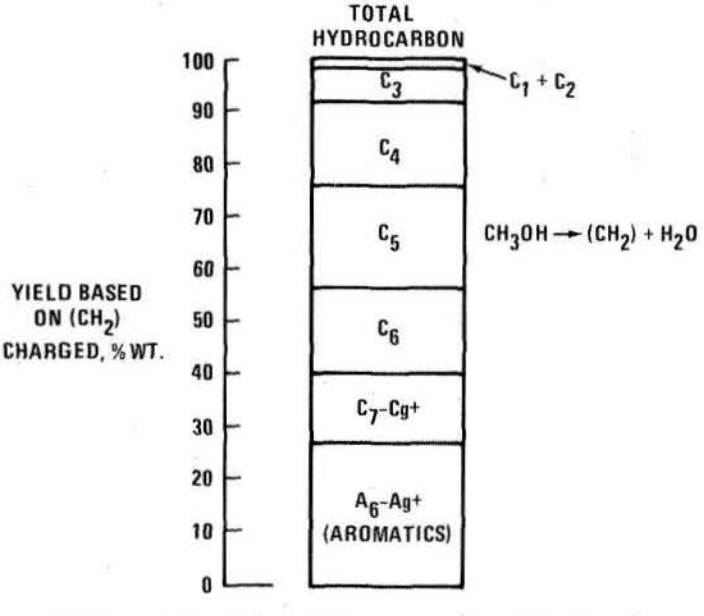

Figure 4. Product yield from conversion of methanol.

COAL LIQUEFACTION— PILOT AND COMMERCIAL PROGRAM

The primary objective of the ERDA coal liquefaction program is to provide technology which is economically feasible and environmentally satisfactory to convert coal to a clean liquid fuel for electric power generation, transportation, and heating homes and industry. The short-term strategy is to develop, on an industrial scale, the conversion of coal to a low-sulfur, low-ash oil suitable for electric power generation. This capability will release petroleum and natural gas for other uses. The longer term objectives are to develop technology for production of gasoline, diesel and other fuels, and chemical feedstocks.

Table 2 shows the major projects and status, and figure 5 shows the overall program illustrated in the form of alternate and sequential process steps.

A number of significant events have occurred recently. The design of a $237 million coal-liquefaction demonstration plant is underway, and an evaluation of its potential is expected in the fall of 1976.

The PAMCo (Pittsburgh and Midway Co.) solvent-refined coal pilot plant at Tacoma, Washington, has been in operation for and is completing the manufacture of 3,000 tons of products for large-scale combustion tests. Operation has been generally satisfactory, although difficulties in solids-liquids separation have been experienced.

Plans for construction of a 300/600 ton-per-day H-coal pilot plant have moved forward. Engineering and laboratory work have now provided further basis for construction of the plant which is expected to be installed in Kentucky.

Other significant events are the initiation of construction of a 10-tons-per-day unit using the synthoil process and the construction and testing by U. S. Steel of a unit for coproduction of low-sulfur coke and aromatic liquids.

Table 2. Coal liquefaction: Major ERDA installations.

	$ MILLIONS	CONTRACTOR	STATUS
PYROLYSIS			
Coalcon	237	Coalcon	Design
COED[a]	21	FMC	Complete
Clean Coke	9	U.S. Steel	PDU Operation
DIRECT CATALYTIC			
H-Coal	11	HRI[b]	Design
Synthoil	8	Foster Wheeler	Construction
SOLVENT-REFINED COAL			
SRC	42	PAMCo	In Operation

[a] Char Oil Energy Development.
[b] Hydrocarbon Research, Inc.

OVERALL ERDA/FOSSIL ENERGY PROGRAM/BUDGET

The overall budget for fossil energy appears in table 3. The amount and distribution of funding indicate the emphasis being given to fossil energy research. Funding of coal liquefaction in fiscal year 1977 is expected to be over $100 million; included in this category are budget items of liquefaction, large fractions for demonstration plants, and advanced research and supporting technology.

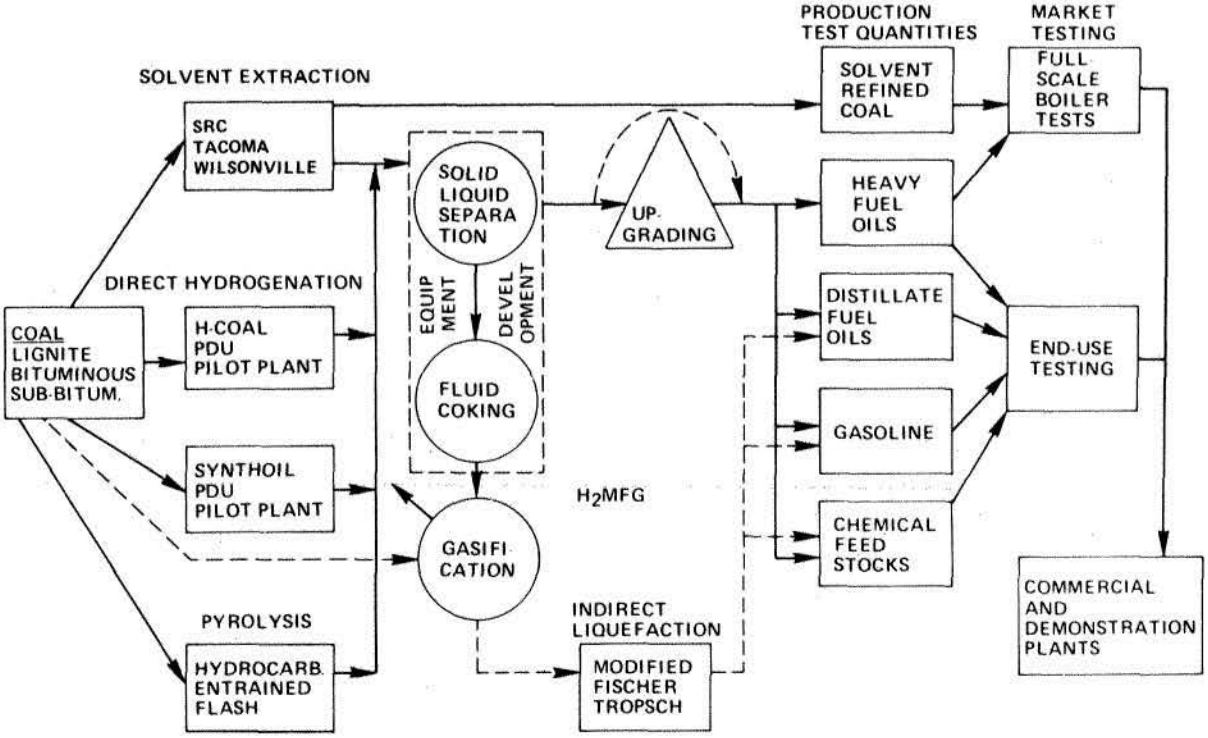

Figure 5. Liquefaction development strategy.

Table 3. Fossil Energy: U.S. Energy Research and Development Administration.

FY 1977 Budget Estimates
(Dollars in Thousands)

SUMMARY TABLE BY SUBPROGRAM

FOSSIL-ENERGY DEVELOPMENT OPERATING EXPENSES	Fiscal Year 1976 Estimate B/A[a]	OBS.	B/O[b]	Transition Quarter Estimate B/A & OBS.	B/O	Fiscal Year 1977 Estimate B/A & OBS.	B/O
COAL							
1. Liquefaction	$ 89,912	$129,465	$ 92,937	$ 26,443	$ 15,693	$ 73,946	$ 79,546
2. High-BTU Gasification	53,364	57,320	37,338	9,250	7,450	45,054	59,234
3. Low-BTU Gasification	24,552	49,215	36,026	6,720	4,113	33,052	39,952
4. Advanced Power Systems	10,001	10,423	7,461	3,500	1,700	22,500	12,800
5. Direct Combustion	38,096	65,302	32,645	13,500	5,100	52,416	52,116
6. Advanced Research and Supporting Technology	35,393	40,087	32,061	8,850	4,600	37,085	36,585
7. Demonstration Plants	31,900	32,650	14,250	7,750	3,700	53,000	50,600
8. Magnetohydrodyamics	29,544	32,593	18,400	7,800	4,200	37,411	27,341
Total coal program	312,762	417,055	271,118	83,813	46,556	354,494	358,194
PETROLEUM AND NATURAL GAS							
1. Gas and Oil Extraction	41,423	43,546	32,859	8,426	9,000	35,074	30,374
2. Supporting Research	1,797	1,797	1,582	450	500	1,831	1,831
Total petroleum and natural gas program	43,220	45,343	34,441	8,876	9,500	36,905	32,205
IN SITU TECHNOLOGY							
1. Oil Shale	13,720	13,721	9,834	1,950	2,000	21,085	12,085
2. In Situ Coal Gasification	6,137	7,510	7,560	1,680	1,787	8,236	6,736
3. Supporting Research	1,265	1,265	1,113	300	300	1,310	1,310
Total in situ technology program	21,122	22,496	18,507	3,930	4,087	30,631	20,131
TOTAL OPERATING EXPENSES	$377,104	$484,894	$324,066	$ 96,619	$ 60,143	$422,030	$410,530

[a] Budget authorization.
[b] Budget outlay.

UNIVERSITY PROGRAMS

A vigorous and expanding program of fossil energy research is being sponsored by ERDA/Fossil Energy on campus at universities. Table 4 lists interesting areas of research for coal programs, and figure 6 illustrates the distribution of activities and yearly levels of funding. At present, almost 100 contracts are active in coal research involving an estimated 400 students and faculty members. We look forward to the important technical contributions from the universities in partnership with ERDA as well as valuable training and communications benefits.

There are many additional ERDA research areas which have not been discussed. These are being covered to a great extent by other papers in this volume (in situ gasification by Edgar, combustion of lignite by Sondreal, as well as Project Lignite by Souby).

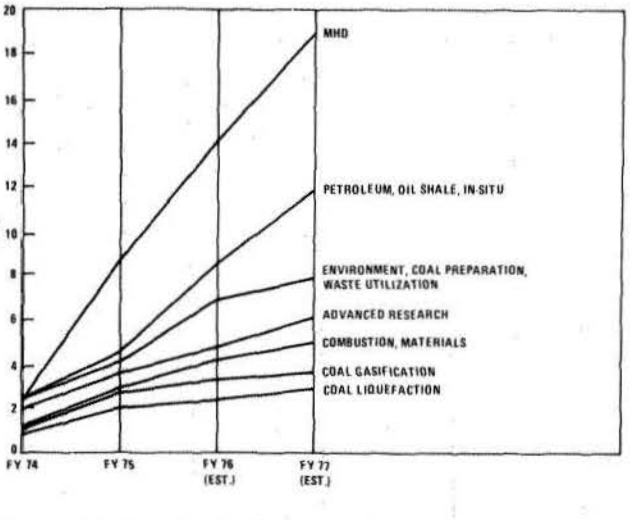

Figure 6. Level of effort in ERDA—Fossil Energy university research program

Table 4. Fossil energy research, university programs.

- I. Objectives.
    - A. Locate and use talents of university personnel to carry out fossil energy research.
    - B. Provide communications channel between ERDA-FE and universities.
        - Research needs.
        - Information dissemination.
    - C. Assure adequate manpower base in fossil energy science and technology.
- II. Research topics.
    - A. Processes.
        - Coal structure and composition.
    - B. Thermophysical and thermodynamic data.
        - Phenomenological studies.
    - C. New concepts (Catalysts, Analysis, Conversion Process).
        - Reaction mechanisms.
    - D. Modeling and systems studies.
    - E. Direct utilization.
        - Basic data for engineering systems.
        - Exploratory research on gas cleaning.
        - Chemistry of selected alkaline materials.
        - Combustion mechanisms.
    - F. Materials and combustion.
        - Basic studies on materials.
        - Modification of analytical tools.
        - Development of novel measurement devices.
        - New concepts (Materials, Reactors, Separators).

FUTURE

Certainly lignite coal will play a key role in satisfying our energy needs in both the near and the long term. How this can be done and especially how new science and technology can contribute to the use of lignite was the subject of the conference. Political considerations and economic events, particularly the availability and the price of foreign crude, will be major factors in determining the timing to increasing use of lignite. In addition, advances made in new and improved technology can make a major contribution in hastening an expanded use of lignite and, also of great importance, in minimizing investment in plants that will cost billions of dollars.

Many areas of research on lignite offer opportunities for new and improved technology, including improved environmental factors. Your attention is drawn to two comprehensive series of symposia on lignite held in North Dakota (U.S. Bureau of Mines, 1973) and Montana (Fort Union Coal Field Symposium, 1975). No doubt the obvious growing use of lignite for generation of electricity offers an important expanding use for the near future. In addition, there are exciting research, development, and demonstration programs for broadening the scope and improving the efficiency for lignite utilization. The overall ERDA/fossil energy programs have been described by White (1976a and 1976b). In this paper, liquefaction processes-have been discussed to illustrate the rhythm and pace of this ERDA program and to provide the basis for discussion and possible actions.

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POTENTIAL FOR LIGNITE LIQUEFACTION

A. M. Souby[1]

ABSTRACT

After 85 years of research on lignite, the University of North Dakota entered into a contract with the Office of Coal Research for "Project Lignite," a research program aimed at upgrading Northern Great Plains province coals to premium fuels. The ultimate goal is the design of a pilot plant for an integrated lignite refinery producing liquid, solid, and gaseous fuels and chemical feed stocks, utilizing novel techniques developed by the project coupled with current technology for coal and hydrocarbon processing.

Major emphasis at present is being given to the operation of a process development unit (PDU) for solution hydrogenation of lignite to produce solvent-refined lignite (SRL). The PDU incorporates a solid-liquid separation (SLS) system based on the enhanced solubility of coal liquids in a light solvent at elevated pressure and near the critical temperature of the solvent. In the liquefaction section of the PDU, 88-percent conversion and 63-percent yields of SRL and lighter oils based on mineral-ash-free coal have been achieved. The SLS section has not yet been run in conjunction with the liquefaction section of the PDU. Shakedown operation of the system with undeashed solvent refined coal (SRC) from Tacoma resulted in poor overall recovery, since some of the charge settled out in other parts of the system other than being withdrawn from the precipitation tower. The SRC recovered had less than 0.05-percent ash and was 100-percent soluble in pyridine. The SLS section has been modified to provide much better mixing ahead of the precipitation tower.

A unit is under construction for the hydrogenation of SRL, since it appears that the best approach to the production of light fuel products or of synthetic crude oil would be a two-stage process. The SRL free of ash and low in sulfur would be produced in the first stage in a noncatalytic reaction with minimum hydrogen consumption, and this SRL would then be catalytically hydrogenated in the second stage. In small-scale-batch autoclave experiments, SRL has been converted to the extent of 90 percent to lighter liquid products with about 40 percent of the products being in the gasoline boiling range.

Economic studies have indicated that SRL can be produced to sell for about $1.70 per million Btu and that shipping the SRL for use in electric generating plants in urban areas is competitive with producing electricity in lignite-fired plants and transmitting electricity to the urban areas if the distance involved approaches 600 miles.

A number of processes for coal liquefaction have been studied and publicized. These include H-Coal, Synthoil, COSTEAM, PAMCo SRC, Southern Services SRC, and CRESAP liquefaction. In addition, proprietary processes about which less is generally known are under development by Exxon, Garrett Research, Gulf, Kerr-McGee, Lummus, and perhaps others. Large pilot or demonstration plants proposed or planned include H-Coal, Synthoil, Clean Fuels West, and Coalcon, though the latter is a hydrocarbonization process rather than liquefaction.

A large portion of the Nation's coal resource is lignite, and though there are extensive plans for utilizing lignite directly in electrical generating plants and in substitute natural gas (SNG) gasification plants, there will remain much more than enough to support a synthetic or substitute liquid fuel industry. This industry would initially produce a clean boiler fuel meeting environmental requirements and then expand to produce a synthetic crude oil suitable for refining into conventional liquid fuels for transportation use.

SOLVENT-REFINED LIGNITE

Research on lignite has been conducted at the University of North Dakota since 1891. The University's Fuel Analysis Laboratory has served mining and power companies and state agencies and institutions for almost 40 years. The U. S. Bureau of Mines, in 1950, established on the University of North Dakota campus the Grand Forks Lignite Research Laboratory, now the Grand Forks Energy Research Center of the Energy Research and Development Administration (ERDA).

In 1959, the Great Northern Railroad, now the Burlington Northern Railroad, began sponsoring research on lignite gasification at the university. Upon completion of this project, Burlington Northern continued sponsoring research at the university on the production of solvent-refined lignite (SRL) based on the process developed by Pittsburgh and Midway Coal Mining Company for bituminous coal. This program was continued under sponsorship of the Office of Coal Research (OCR) of the U. S. Department of the

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[1] Project Lignite; University of North Dakota, Grand Forks, North Dakota 58202.

Interior through a subcontract with Pittsburgh and Midway.

In late 1971, the commitment to lignite research increased dramatically. The department of chemical engineering and the engineering experiment station negotiated a 5-year contract, signed in March of 1972, with the OCR on "Project Lignite" in the amount of $3,356,600. This broad program has as its objective the upgrading of Northern Great Plains province coals to premium fuels and chemical products. The ultimate goal is the design of a pilot plant for an integrated lignite refinery producing liquid, solid, and gaseous products using novel techniques developed during the course of the project integrated with currently available technologies for coal and hydrocarbon processing.

Major emphasis at present is being given to the operation of a process development unit (PDU) for the solvent refining of lignite. A simplified block flowsheet of the process is presented in figure 1. Pulverized lignite of full moisture content is slurried with solvent. The slurry is pressurized, preheated, and reacted at selected temperature and pressure in a reducing gas atmosphere. The products are then separated as gases, liquids, and SRL from the unreacted coal and mineral matter. A pictorial representation of the liquefaction section of the PDU is shown in figure 2. The details of the design and proposed operation of the PDU have been presented by OCR Research and Development (Project Lignite, 1976). The results of a recent run in the PDU are shown in table 1.

Table 1. Solvent-refined lignite PDU.
Run M-5C, 4/1/76
2500 psig, 750-825°F

MATERIAL	CHARGE	PRODUCTS	NET YIELDS[a]
Gas	27.1	42.9	36.5
Solvent	6.7	6.7[b]	0
MAF coal	43.4	4.1	9.4[c]
Water	18.9	13.9	−11.3
Ash	3.9	3.3	−1.6
Light oil	—	3.8	8.7
SRL	—	25.3	58.3
Total	100.0	100.0	100.0

[a] As weight percent of mineral ash free (MAF) coal.
[b] Not recovered for recycle.
[c] Unconverted coal.

The PDU incorporates a solid-liquid separation (SLS) system based on the enhanced solubility of coal liquids in a light solvent at elevated pressure and near the critical temperature of the solvent and the concomitant agglomeration of the mineral-matter/unconverted-coal phase, thus permitting separation by countercurrent decantation. A flow diagram of the SLS system is shown in figure 3.

Solid-liquid separation has been a problem in all coal-solubilization processes. The usual approach of filtration has serious operational problems plus very high costs, and there is a problem of availability of sufficient filter aid for a commercial plant. The approach taken is innovative and shows promise as a possible solution. The system has been completed and has undergone preliminary testing. Indications are that it will be capable of successfully handling the necessary separations for the PDU.

The SRL product is a solid material suitable for boiler firing under proper conditions. A far more substantial contribution of lignite towards meeting the Nation's energy needs would be its adoption as a feedstock to provide liquids for heating and transportation fuels. The Project Lignite investigators believe strongly that the best way to achieve liquid products from lignite is by using a two-stage process incorporating solvent refining to SRL as the first step, followed by upgrading to liquids by catalytic hydrogenation.

The chemistry department at the University of North Dakota has conducted studies directed toward the determination of hydrogenation conditions for the economically feasible conversion of SRL to light liquid hydrocarbon fuels. A number of commercial catalysts and methods of pretreatment have been investigated, and SRL has been converted to light liquids in greater than 90-percent conversion with about 40 percent of the products in the gasoline boiling range. An example of the product distribution obtained in one of the hydrogenation experiments is shown in table 2. An SRL hydrogenation unit has been designed and partially constructed. A schematic flow diagram of the unit is shown in figure 4.

Faculty members of the economics department have conducted studies of various coal-conversion processes. A recent study compares the cost of solvent refining of lignite with that of solvent refining of bituminous coal based on an

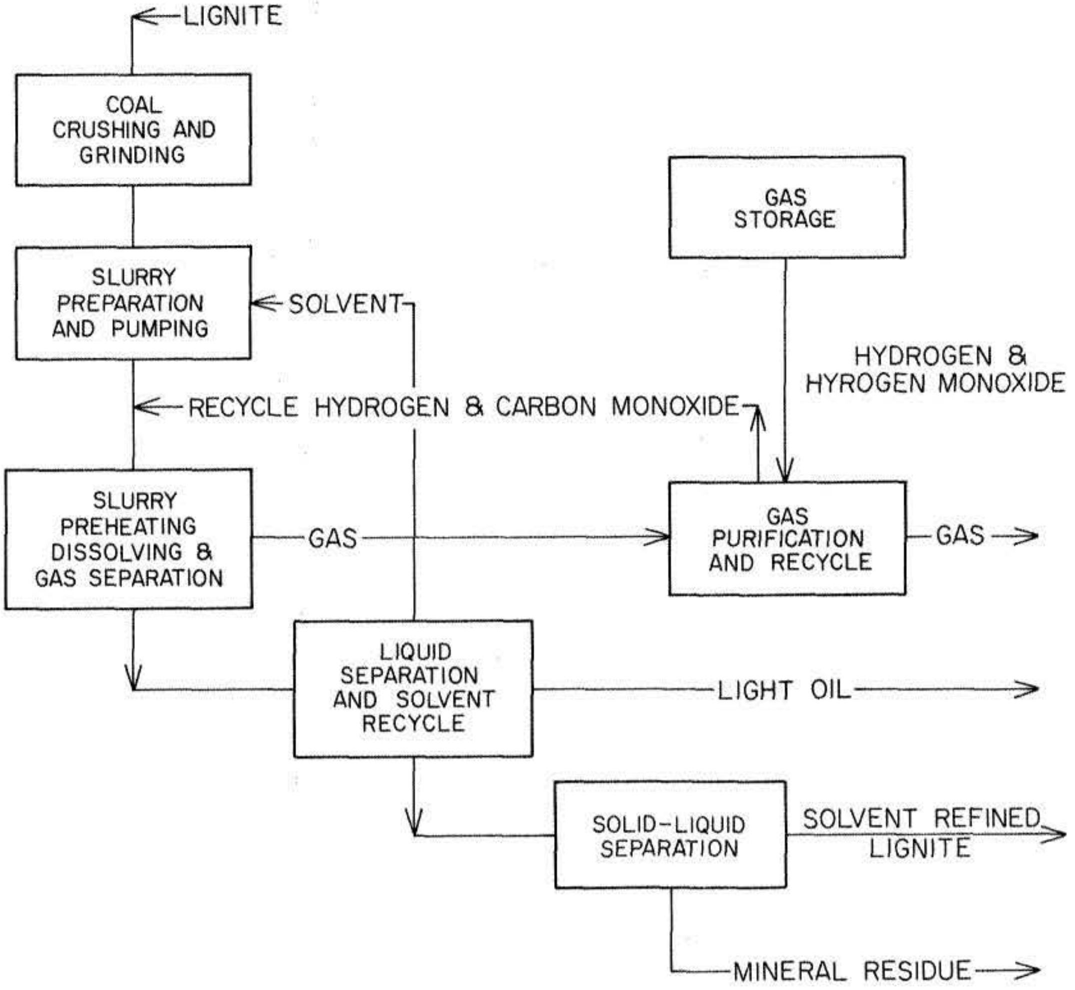

Figure 1. Block flowsheet for PDU.

OCR Research and Development report (Project Lignite, 1974). The major clean fuel products from an SRL plant would sell for $1.70 per million Btu and from an SRC plant for $2.18 per million Btu. An ERDA report (1976) indicates the price of synthetic crude would be $2.23 per million Btu. An economic comparison of these three plants, an SRL plant producing a high-melting boiler fuel, an SRC plant producing fuel oils, and a synthoil plant producing synthetic crude oil, is shown in table 3. Another study compares the generation of electricity at a mine-mouth lignite-fired boiler plant in North Dakota and transmission to a major urban market with the mine-mouth conversion of lignite to SRL and shipment of the SRL to the urban area as fuel for an electric generating plant. The results of this study are shown in table 4, where it is indicated that for the 420-mile distance, lignite is the more economical fuel. However, transmission costs increase much more rapidly than rail costs, and at a distance of 600 miles, the two cases supply power at the same cost.

Table 2. Product distribution from a no-solvent hydrogenation experiment.[a]

GAS		DISTILLATION FRACTIONS
Methane	6g (8-10%)	IBP[b] 200°C/atm (35%)
Ethane		IBP 89°C/1 mm Hg (10%)
Propane		89°-139°C/1 mm Hg (10%) 139°-200°C/1 mm Hg (20%)
NH_3	0.7g	200°-250° C/1 mm Hg (2%)
H_2O	3g	Vacuum bottom (10%)
H_2 uptake	4-5g	(87%)

[a] Overall conversion 90 percent.
[b] Initial boiling point.

A recent report of Catalytic, Incorporated (1976) compares the production of light liquid fuels from western coal with the production of

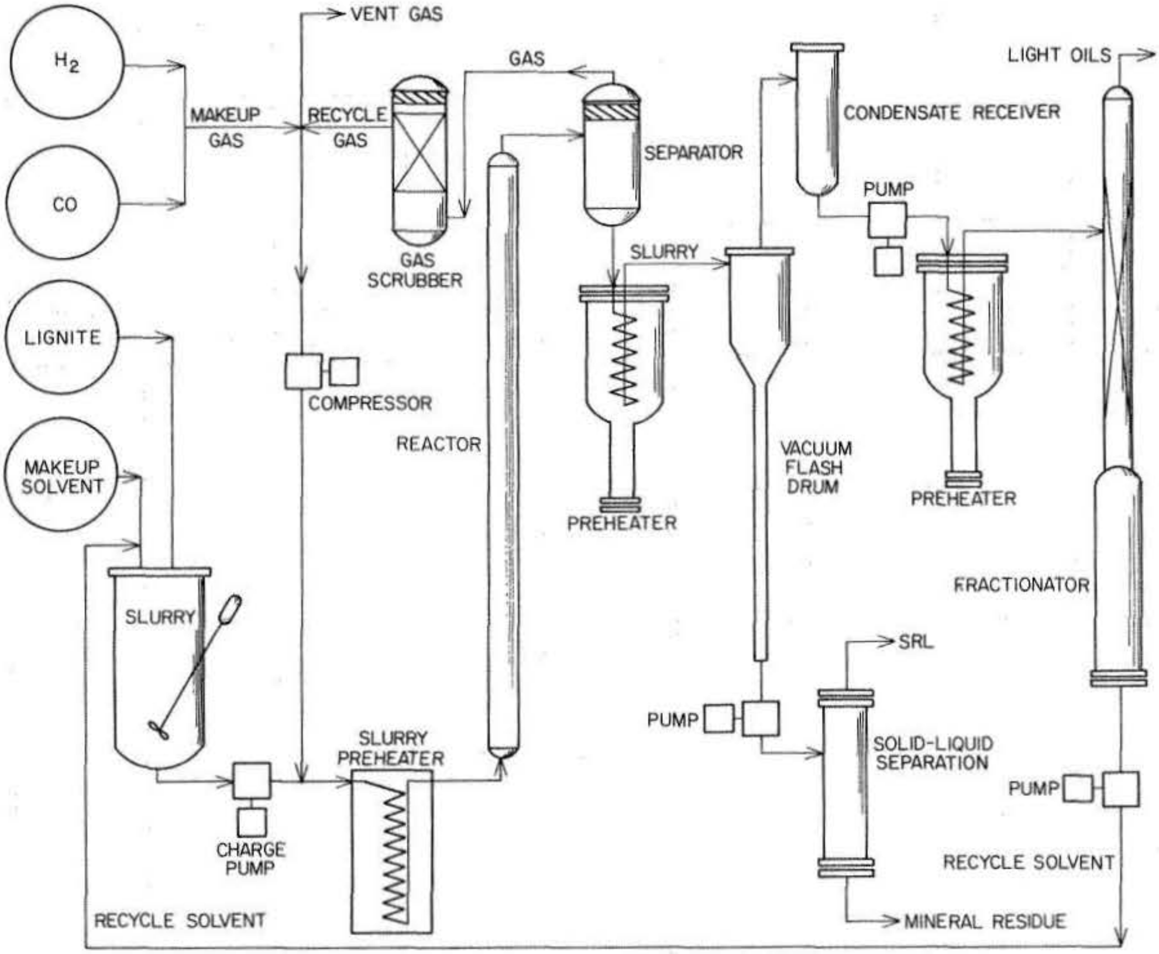

Figure 2. Flow diagram of process development unit.

Table 3. Comparison of coal liquefaction plants
11,050 tons per stream day fuel products output.

TYPE OF PLANT	SRL	SRC + HYDRO	SYNTHOIL
Coal feed	Lignite	Illinois no. 6	Wyodak
Primary product	SRL	Fuel Oil	Syncrude
Energy output, MM Btu/SD[a]	367,000	382,000	391,000
Coal feed, T/SD	36,000	24,000	38,000
Total investment, MM $	551	581	730
Operating cost, MM $/Year	109	172	160
Coal cost, MM $/Year	42	103	63
Product selling price[b], ¢/MM Btu	170	218	223
$/Bbl FOE[c]	10.20	13.10	13.40

[a] Stream day (SD).

[b] Discounted cash flow return, 12 percent.

[c] Fuel oil equivalent.

synthetic pipeline gas. This report indicates the price of liquid fuels to be \$2.62 per million Btu and the price of SNG to be \$2.78 per million Btu. The results of this study are summarized in table 5.

A number of processes for liquefaction of coals are either planned or operating. Friedman and others (1976) presented an overview of these at the 1975 Lignite Symposium at Grand Forks, North Dakota. The processes they discussed are summarized below, excluding those based on pyrolysis or carbonization.

DIRECT CATALYTIC HYPDROGENATION PROJECTS

The processes in this category differ in the mechanics of the reactor or the kind of catalysis used, or both. Otherwise, they are similar in catalytically adding hydrogen to coal to liquefy it to fuel oil and to remove the sulfur as hydrogen sulfide.

H-Coal Process

This process is being developed by Hydrocarbon Research, Incorporated with support from ERDA and various oil companies. The current process development unit (PDU) has a 22-ft-high by 8-inch inside diameter ebullated bed (catalyst beads) reactor into which is fed a slurry of fine coal in a recycle oil distillate fraction. Catalyst is added and withdrawn, as needed, with the slurry stream. Reactant hydrogen also flows upward in the reactor, assisting the suspension of solids (ebullation). High yields have been obtained from bituminous and subbituminous coals with good desulfurization; oil having 0.5 percent or less sulfur was produced from coal having 3.4 percent sulfur. About 75 percent of the product oil is like crude petroleum.

Synthoil Process

This process is being developed at the Pittsburgh Energy Research Center of ERDA. In this one-step hydrodesulfurization process, coal, conveyed in recycled carrier oil, is propelled by turbulent flow of hydrogen through a fixed bed of cobalt and molybdenum catalyst pellets, accomplishing over 94-percent conversion to oil in about 2 minutes of reaction time. Unused hydrogen is recycled to provide the necessary turbulence. Product oil is liquid at room temperature like number 2 to number 6 fuel oil.

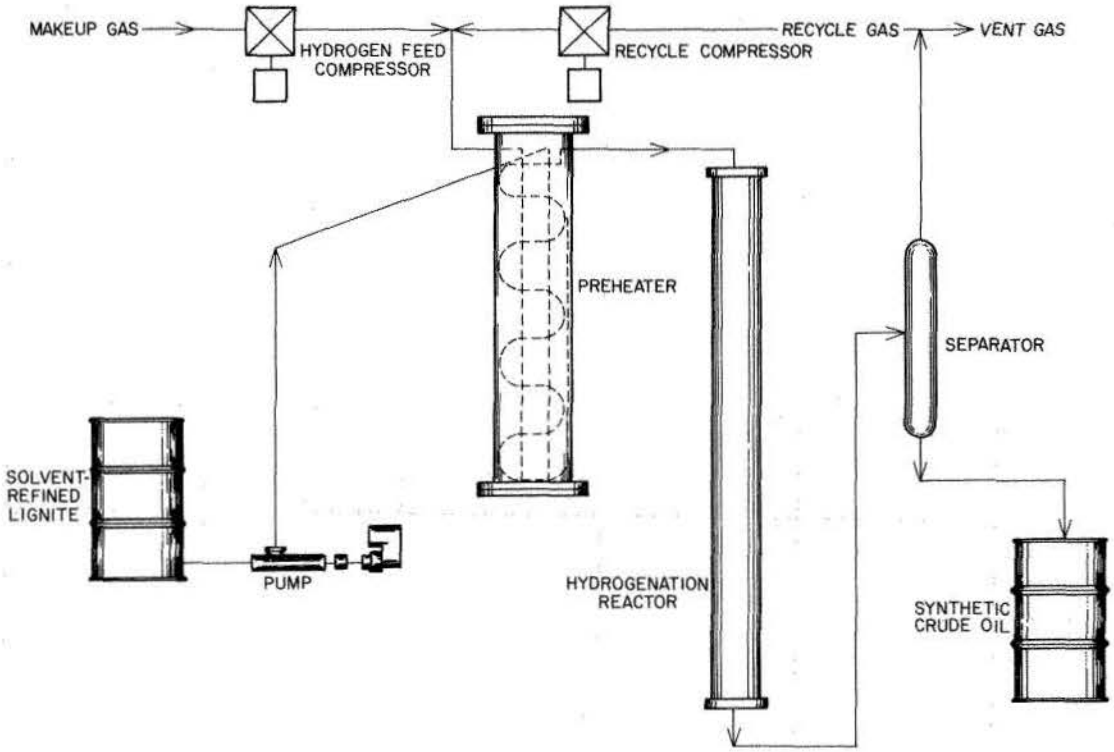

Figure 3. Diagram of the solid-liquid separation.

Zinc Chloride Catalysis

This process is being developed at the Conoco Coal Development Company, supported by an ERDA contract, with Shell Oil as a supporting participant. The reactor contains a molten pool of zinc chloride salt through which the coal feed slurry and hydrogen are passed. This molten salt is a very powerful catalyst, and it was previously shown that coal extract could be almost completely converted to gasoline. The project is now redirected to produce fuel oil rather than gasoline from coal rather than extract.

Disposable Catalyst Hydrogenation

Studies of this process have been initiated at the Pittsburgh Energy Research Center of ERDA. It is an advanced followup of the Bergius process as used in the first-stage liquid-phase industrial coal hydroliquefaction of Germany in World War II. The obvious attraction is the low cost of disposable catalysts for producing fuel oil. The catalyst is fed with the coal through the reactor.

COSTEAM Process

This process is currently undergoing development at the Pittsburgh Energy Research Center and at the Grand Forks Energy Research Center of ERDA and is specifically directed at liquefaction of lignites that are low in sulfur so that the fuel oil product is also low in sulfur. No catalyst is added, and synthesis gas (carbon monoxide and hydrogen) is used instead of hydrogen. The process utilizes the natural alkalinity of lignite to catalyze the water-gas-shift reaction to produce active hydrogen. The water is naturally present in the lignite.

SOLVENT-EXTRACTION-BASED PROJECTS

These processes all involve a solvent to extract a liquefied product from coal, and the solvent acts as the agent that transfers hydrogen to the coal to extend the degree of liquefaction. The transfer agent may or may not be rehydrogenated catalytically before recycling.

PAMCo Solvent-Refined Coal Project

A 50 ton/day pilot plant is currently in operation for this process developed by the Pittsburgh and Midway Coal Company with support by OCR (now ERDA). The product is normally solid, having less sulfur than the coal, deashed, and meltable. Coal is mixed with a recycled fractionated solvent and heated with hydrogen in a reactor at about 1,200 to 1,600 pounds per square inch (psi) to dissolve the coal. Hydrogen transfer from solvent to coal occurs, assisting and stabilizing dissolution. Hot solution is filtered to remove the ash and pyrite. Because no added catalyst is used, the amount of organic sulfur removed as H_2S is not as extensive as for catalytic desulfurization processes; however, products from 3-percent sulfur coal have only about 0.8-percent sulfur. Ash content as low as 0.1 percent has been obtained by filtering through a rotary precoat filter.

Table 4. Mine-mouth versus urban power generation.
440 Megawatt Generating Plant
Minneapolis-Saint Paul (420 miles from mine)

Plant location	Mine mouth	Minneapolis-Saint Paul
Plant fuel	Lignite	SRL
Total capital investment, MM $	338	150
Operating cost, MM $/Year	29	82
Fuel cost, MM %/Year	12	73
Selling price, ¢/kWh	2.8	3.2
For 600 miles, ¢kWh	3.3	3.3

Table 5. Mine-mouth plant in Powder River Basin to produce 480,000 MM Btu/SD fuel products.

Type of plant	Liquefaction	Gasification
Coal feed, T/SD	39,000	42,300
Total investment, MM $	1,331	1,434
Cost of product, ¢/MM Btu		
Coal	55.8	60.1
Operating and maintenance	57.4	58.3
Capital cost	152.6	164.3
Byproduct credit	(3.6)	(4.3)
Total	262.2	278.4
Cost, $/Bbl (FOE)	15.70	16.70

Southern Services SRC Project

This industry-supported process is much like PAMCo's SRC process, although the pilot plant is a smaller one of 6 tons/day. Other differences are that a multilayer leaf filter is used instead of a rotary drum filter and that a recoverable diluent is used to reduce product solution viscosity to aid filtration. Extended operations have been successful, and a product similar to that from PAMCo has been produced.

This project is a cooperative effort involving the A. D. Little Company, Foster Wheeler Corporation, and the Pittsburgh Energy Research Center (integrated by an ERDA contract). Laboratory batch studies are underway to determine the feasibility and economic potential of conversion of coal to distillate fuels by deep extraction followed by thermal cracking (delayed coking) in the same vessel. The novel feature of this process is the use of delayed coking to separate volatile liquid products from unconverted residue and ash instead of removing such solids from the liquid by filtration as in the above two SRC processes. If successful, this process could replace filtration and be incorporated in modified form into the PAMCo pilot plant.

Solvent-Refined Lignite

This process, developed at the University of North Dakota, has been discussed previously.

Cresap Liquefaction Facility

In 1965–69, Consol Coal Company had constructed and operated a 20 ton/day pilot plant at Cresap, West Virginia. The process then used was based on solvent extraction of coal followed by residual solids separation prior to secondary fluidized-bed catalytic hydrogenation of extract to provide distillate fuels. Extraction and solids removal to 1-percent ash by hydroclones was successful. Some hydrogenation of the cleaned extract was achieved. However, fully integrated operations were not realized because of mechanical problems. Currently, the Fluor Corporation has a contract from ERDA for these facilities and is developing, for reliable operations, liquefaction processing components, such as extractors, valves, pumps, reactors, and seals. As reliable components are developed, a liquefaction process will be integrated at the site. The evolved integrated process may be (but not necessarily) a modified

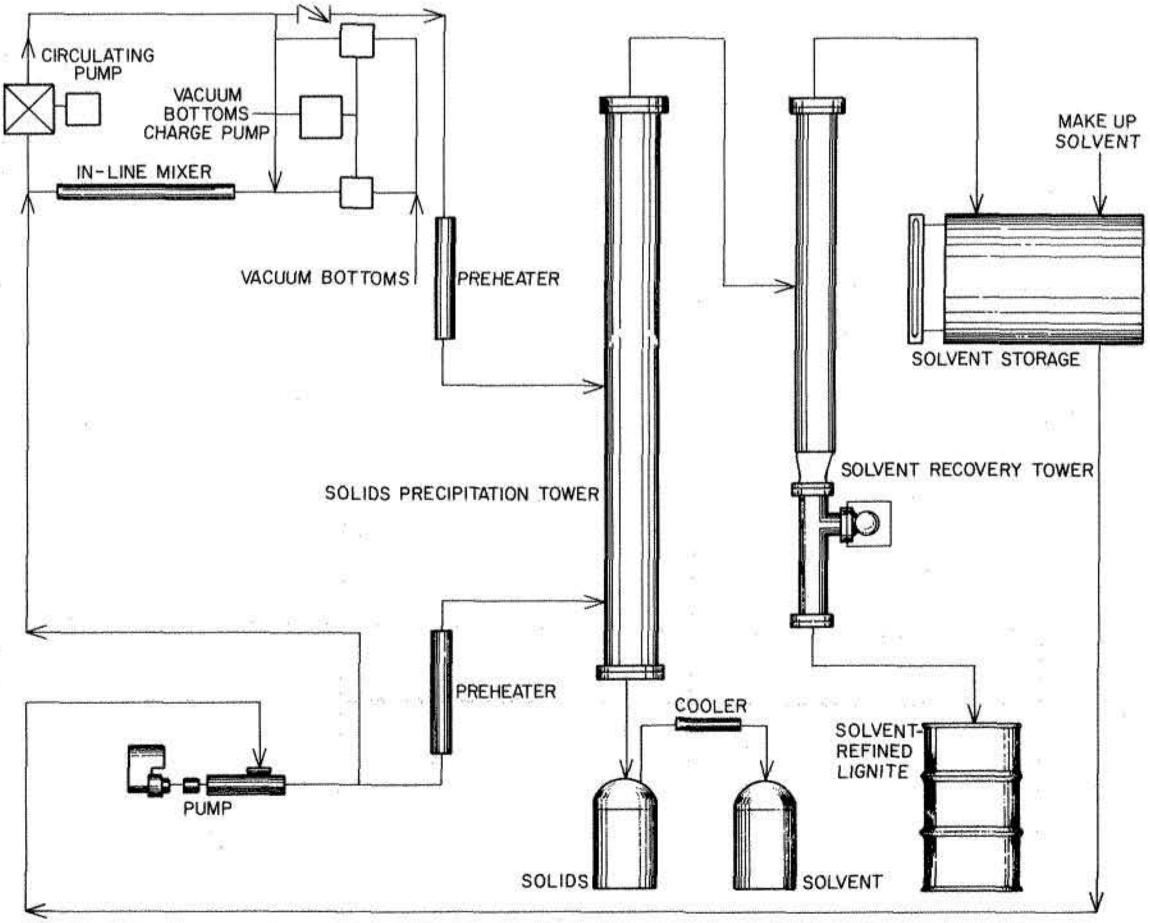

Figure 4. The SRL hydrogenation unit.

Consol process using different extractors, different (or no) interstage solids separators, and different hydrogenation reactor styles.

In addition to the aforementioned projects, which are wholly or partly sponsored by ERDA or Electric Power Research Institute (EPRI) and have received public notice, there are a number of proprietary processes being developed through private funds. Little has been published about these, but companies active in this area include Exxon, Garrett Research, Gulf, Kerr-McGee, Lummus, and perhaps others.

Several large pilot plants or demonstration plants have been proposed or planned including H-Coal, Synthoil, and Clean Fuels West. Coalcon might be added to this list, although their process is basically hydrocarbonization rather than liquefaction.

ROLE OF LIGNITE

A large portion of the Nation's coal resource is lignite, with approximately 350 billion tons in North Dakota. Of this, over 20 billion tons is estimated recoverable by surface mining with overburden of less than 100 ft and with beds of 5 ft or more. If the nation is to meet its goal of energy independence, a significant contribution can be and must be made by the low-rank coals. Chemical and physical properties of lignite make this low-rank coal suitable for conversion to upgraded solid, liquid, or gaseous fuels or to electric power by several methods.

Utilization of lignite at present is primarily for the production of electric power, though limited use is made of lignite for commercial and domestic heating. Two gasification projects for the production of substitute natural gas from lignite are underway for North Dakota, although all the necessary permits have not yet been obtained. There are excess reserves available, beyond those necessary to support proposed electrical generation and gasification needs, which could be used to produce upgraded solid and liquid fuels.

Lignite as mined has a high inherent moisture content and a low calorific value per unit weight, which preclude long-distance movement except in special circumstances usually dictated by environmental regulations. The moist lignite can be hydrogenated in an atmosphere of synthesis gas in the presence of an organic solvent. Hydrogenation does not need to be extensive to produce a product which is liquid at 350° to 450°F. The initial solubilization reaction is rapid and can be accomplished at lower temperatures and pressures than those required for direct hydrogenation using hydrogen. Sulfur content is reduced during the solubilization, and the mineral matter can be removed from the hot, liquefied coal to yield SRL. The SRL is environmentally acceptable and has over twice the heating value of lignite per unit weight. Such a product can be reasonably transported to population centers for utilization without the requirement of extensive pollution-control equipment at the point of use. However, the product is limited to the applications where a solid or a high-melting liquid can be used.

The SRL is fairly low in components known to inhibit effective hydrogenation catalysts. Consequently, it is a superior feedstock for a second hydrogenation step in which sufficient hydrogen is added to produce a liquid product in the gasoline boiling ranges. Laboratory data show that this step can be accomplished with a high extent of conversion.

The two-stage hydrogenation process is most effective because the initial hydrogenation can be done under relatively mild conditions without use of expensive hydrogen. The upgraded product, SRL, can be used as a solid fuel in environmentally distressed areas. The second-stage hydrogenation step can be accomplished with a specific hydrogenation catalyst designed to give high liquid yields under optimum conditions. Production of a petroleum-type liquid would allow existing refineries to continue to produce liquid fuels should normal crude petroleum supplies be curtailed.

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LIGNITE AS A SOURCE OF CHEMICAL FEEDSTOCKS

W. P. Scarrah[1] and W. H. Calkins[2]

ABSTRACT

Natural gas, natural gas liquids, and crude petroleum are the predominate raw materials for the United States petrochemicals industry. However, only a small percentage of the total production of these materials is used for chemical feedstocks. Most of it is consumed as fuel to produce energy. As coal comprises 87 percent of our fuel reserves compared to only 4 percent for petroleum and natural gas, it seems inevitable that coal must be utilized more extensively for both energy and chemicals production. Due to its accessibility and favorable chemical reactivity, lignite is feasible for conversion to more convenient fuels and chemicals. Three lignite-based sources of chemical feedstocks are lignite, improved fuels, and byproducts from improved fuels. Some feedstocks can be directly separated from the sources, but most will be obtained via additional chemical processing. Because of its structure, coal is primarily attractive as a source of aromatic compounds. However, by converting it into synthesis gas (carbon monoxide and hydrogen) it can be used to synthesize paraffins and olefins. Experience has shown that successful coal-based chemical industries are dependent on completely integrated coal-processing facilities including mining, preparation, and conversion to power and more serviceable fuels as well as conversion to chemicals. This provides the opportunity to produce chemical feedstocks from all three lignite-based sources. Most existing coal technology is oriented toward breaking coal into smaller components and adding hydrogen to produce improved fuels. More emphasis on the utilization of lignite as a source of chemical feedstocks might result in less complex processes than used to produce fuels.

INTRODUCTION

Since World War II, three basic raw materials have accounted for 70 percent or more of the feedstock needs of the United States petrochemicals industry: natural gas, natural gas liquids (condensate), and petroleum.

A tremendous tree of products has been developed from these three raw materials serving every segment of the national economy, including fertilizer, plastics, insecticides, synthetic fibers, medicines, and finishes and coatings.

NATURAL GAS

Natural gas or methane is the raw material for several important products (synthesis gas, hydrogen cyanide, and acetylene) and processes. Methane is reformed with steam to synthesis gas, a mixture of carbon monoxide (CO) and hydrogen (H) (table 1). The synthesis gas, with addition of carbon dioxide (CO_2) to correct the carbon-hydrogen balance, is used to produce methanol by reaction at elevated temperatures and pressures over appropriate solid-phase catalysts. Synthesis gas is also used for a number of syntheses by oxo processes to form various aldehydes, alcohols, or carboxylic acids. Acetic acid is an example of one of these. In the water-gas-shift reaction (table 1), carbon monoxide is converted into hydrogen and carbon dioxide. The carbon dioxide can be removed by scrubbing the mixed gases, and the resulting hydrogen can be used for ammonia synthesis or various hydrogenation reactions, such as hydrogenation of vegetable oils.

Hydrogen cyanide, now produced directly from methane by the Andrussow process, is used to make sodium cyanide for metal plating and many other uses. Hydrogen cyanide is used, among other things, in the synthesis of adiponitrile, an important intermediate to nylon plastics and fibers (table 1).

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Most acetylene is now produced from methane in place of the old calcium carbide method. Acetylene is no longer important as a chemical intermediate, but is still an important gas for welding (table 1).

NATURAL GAS LIQUIDS

The lower boiling fractions of natural gas condensate are major sources of ethylene and propylene in the United States. These fractions are mostly ethane and propane and steam which crack in high yield to ethylene and propylene (table 1).

PETROLEUM

Petroleum, too, is a major source for a number of important petrochemicals such as benezene, toluene, xylene, and butadiene. Benzene, toluene, and the various isomers of xylene are formed in petroleum naphtha reforming and also in catalytic cracking of petroleum gas oil fractions. They are generally removed from these process streams by solvent extraction or selective adsorption. There is a fairly highly developed technology for interconverting between these aromatic compounds to achieve an appropriate balance to match market demands (Mager,1972). Benzene, of course, is used to synthesize styrene and phenol, important for rubbers and plastics. Cyclohexane, made by hydrogenation of benzene, is an important intermediate to adipic acid and caprolactam, both of which go into nylon plastics and fibers.

Butadiene is produced by cracking refinery gases (butane) or the higher boiling fractions of natural gas condensate. Butadiene, of course, is a major ingredient for synthetic rubber and acrylonitrile-butadiene-styrene (ABS) plastics as well as nylon plastics and fibers. A greatly simplified chart of major petrochemical sources is shown in figure 1.

Natural gas and petroleum are, however, not only the major raw material sources for the petrochemical industry, but they are also the principal fuels of the country, supplying over 75 percent of the energy we now use in the United States. In fact, the proportions of these materials used for petrochemicals are relatively small compared to fuel usage. In the United States, only about 10 percent of the natural gas, including natural gas liquids, goes into chemical use. With petroleum, only about 6 percent goes into chemicals. Coal, the original source of organic chemicals, is a very minor source today, with less than 1 percent of the coal mined going into chemicals and that mostly as side products of coke production for steel manufacture.

Although petrochemicals manufacturing consumes only 6 to 10 percent of natural gas and petroleum currently, it is clear that petrochemicals production and consumption are growing much faster in this country than are fuels use. Chem Systems, Incorporated, has projected petrochemicals growth in the United States to the year 2000 and predicts it to require more than 43 percent of the domestic production of petroleum and natural gas forecast for that year, amounting to over 10 million barrels per day of petroleum equivalent for petrochemicals. A great deal of petroleum and some natural gas will be imported, but it is probably unreasonable to assume that that much oil and gas will be available for petrochemicals unless the government sets these materials aside for chemicals use. This situation appears to be unlikely.

Table 1. Conversion reactions.

$CH_4 + H_2O \rightarrow CO + 3H_2$ (synthesis gas)
$CO + 5H_2 + CO_2 \rightarrow 2CH_3OH + H_2O$ (methanol synthesis)
$CO + H_2O \rightarrow CO_2 + H_2$ (water-gas shift)
$3H_2 + N_2 \rightarrow 2NH_3$ (ammonia synthesis)
$CH_4 + NH_3 + O_2 \rightarrow HCN + 2H_2O + H_2$ (hydrogen cyanide synthesis)
$2CH_4 \rightarrow CH{:}CH + 3H_2$ (acetylene synthesis)
$CH_3 \cdot CH_3 \rightarrow CH_2{:}CH_2 + H_2$ (ethylene synthesis)
$CH_3 \cdot CH_2 \cdot CH_3 \rightarrow CH_2{:}CH_2 + CH_4$ (ethylene synthesis)
$CH_3 \cdot CH_2 \cdot CH_3 \rightarrow CH_3 \cdot CH{:}CH_2 + H_2$ (propylene synthesis)

In addition, of course, petroleum and natural gas represent currently 75 percent of our fuel consumption and only 4 percent of our fuel reserves. Natural gas shortages are already occurring, and about 40 percent of the petroleum we consume is now imported. A gradual transition must clearly be made to other more abundant fuels, such as coal (87 percent of our energy reserves) and shale oil (8 percent of our energy reserves), as well as nuclear energy. It seems inevitable that eventually *chemicals, too,* will have to be based on more plentiful raw materials. Although generally chemicals can tolerate higher prices for hydrocarbon feedstocks than most fuel applications, still the inevitable rise in natural gas and crude petroleum prices brought on by rising exploration costs and the Organization of Petroleum Exporting Countries (OPEC) will intensify the constant search for lower cost raw materials.

The need to develop fuel alternatives based on coal and shale is receiving a great deal of attention by the Energy Research and Development Administration, and over $400 million per year are being spent on development of processes for *coal gasification* and coal and shale liquefaction. These synthetic crude oils represent potential chemical feedstocks as well, although they are not being developed primarily for that purpose and are not being optimized for chemical use.

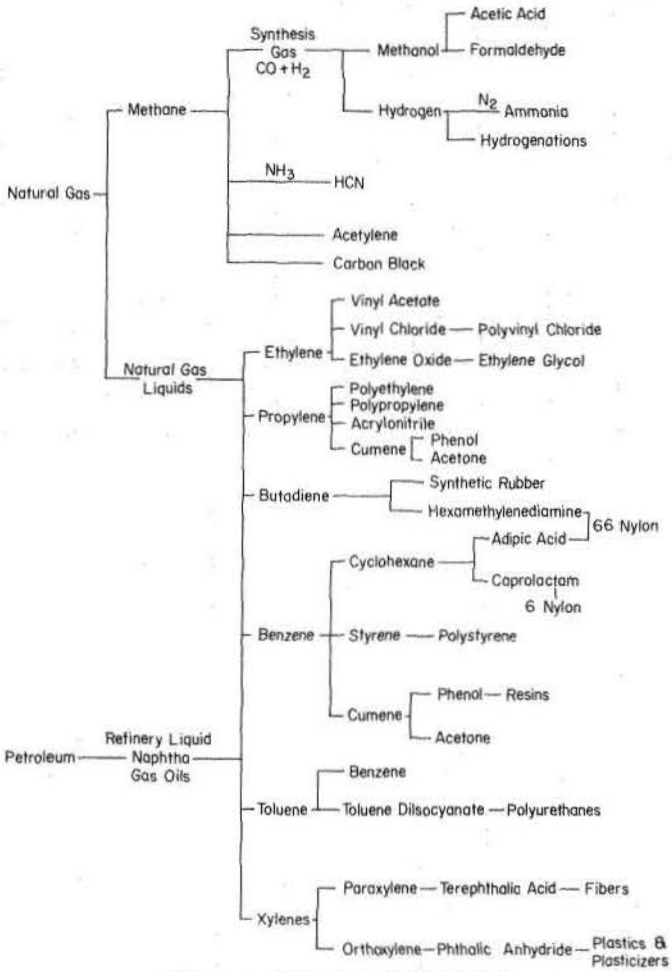

Figure 1. Petrochemical sources.

LIGNITE FOR CHEMICAL FEEDSTOCKS

Lignite is one of the more desirable types of coal for conversion into chemical feedstocks because (1) it is generally more reactive than other coals and (2) its *nonagglomerating* properties are essential for some of the conversion processes. As listed, there are three potential lignite-based sources of chemical feedstocks: (1) lignite, (2) improved fuels, and (3) byproducts from improved-fuels production.

Experience in the German brown-coal industry (Bureau of Mines, 1954) and in The Union of South Africa (Frohning and Cornils, 1974) has shown that a successful coal-based chemical industry depends on the integration of the numerous phases of coal processing and utilization: mining; preparation; and conversion to improved fuels, electrical power, and chemicals. The ability to obtain intermediate process streams and to dispose of undesirable coproducts usable for their energy content allows the production of chemical feedstocks that would prove uneconomical if manufactured independently. Therefore, it is likely that all three of the above sources will be used to provide chemical feedstocks.

CHEMICAL FEEDSTOCKS FROM LIGNITE

It is technically feasible to obtain chemical feedstocks directly from lignite. The principal processes are gasification and oxidation.

Gasification is the process whereby lignite is primarily converted into the simple components of *synthesis gas—carbon* monoxide and hydrogen. These components can then be used as building blocks to synthesize higher molecular weight products. The synthesis gas can be utilized for three groups of chemical reactions (Bureau of Mines, 1954):

1. Reactions between carbon monoxide and hydrogen with or without other reactants, for example, production of oxygenated compounds and hydrocarbons (Fisher-Tropsch process).
2. Reactions between hydrogen and other reactants, for example, production of ammonia.
3. Reactions between carbon monoxide and other reactants.

Although gasification can be used to produce both chemical feedstocks and fuels, the composition of the raw gas would depend on its final use. Chemical-feedstocks production would be best when using a raw gas containing mostly carbon monoxide and hydrogen; the Koppers-Totzek gasification process would be suitable for this objective. A high percentage of methane would be desirable for fuels production, and the Lurgi or CO_2 acceptor processes produce appreciable methane during gasification. The predominantly straight-chain hydrocarbons obtained through the Fischer-Tropsch synthesis provide an excellent substitute naphtha with a high proportion of olefins; this result is in contrast to the branched and naphthenic hydrocarbons obtained with coal hydrogenation (Frohning and Cornils, 1974). Process parameters can be varied to provide a wide range of hydrocarbons. At the South African Coal, Oil and Gas Corporation plant (Sasolburg, South Africa), two different Fischer-Tropsch processes are currently being used; this operation is successful because of low coal costs, restricted competition from lower cost petroleum, and the special economic and political situation in South Africa (Frohning and Cornils, 1974).

The oxidation of coals has been directed toward the production of aromatic polycarboxylic acids through the reaction of gaseous oxygen with slurries of coal in dilute caustic solutions (Montgomery and McMurtrie, 1964). The Henkel process has been successfully used to rearrange aromatic polycarboxylic acids to terephthalic acid (Bearse and others, 1975). Other oxidation products are humic acids; this heavier material has not been well characterized (Lavine, 1939). Weathered lignite that has been subjected to natural oxidation is called leonardite (Lavine, 1939); a comparison of compositions of a North Dakota lignite and leonardite is given in table 2. Significant quantities of humic acid have been found in leonardite and some work has been done on their recovery using caustic extraction (Youngs, 1963). Future work is planned at the University of North Dakota to investigate the use of humic acids as a source of chemical feedstocks. They appear attractive because they can be recovered at ambient temperatures and pressures in contrast to the rather severe processing conditions required to produce improved fuels and their byproducts.

Table 2. Analysis of a North Dakota lignite and leonardite.

	LIGNITE	LEONARDITE
Proximate Analysis (Wt-%)		
Moisture	32.96	36.72
Volatile Matter	29.13	39.43
Fixed Carbon	30.93	13.59
Ash	6.98	10.26
Ultimate Analysis (Wt-%)		
Carbon	66.11	51.33
Hydrogen	4.65	3.53
Oxygen[a]	17.06	25.48
Ash	10.41	16.21
Sulfur	0.84	2.09
Nitrogen	0.93	1.36

[a] Oxygen is calculated by difference.

CHEMICAL FEEDSTOCKS FROM IMPROVED FUELS

Because of the current energy situation it is probable that the production of improved fuels will provide initial lignite-derived chemical feedstocks. There are three principal processes used to convert lignite to improved fuels: pyrolysis, gasification, and hydrogenation (gaseous, liquid, solid products).

Pyrolysis consists of heating the coal in the absence of oxygen to recover the volatiles. A comparison of some tars obtained from laboratory low-temperature fluidized pyrolysis of Texas and North Dakota lignites is shown in table 3. The table illustrates the acidic nature of North Dakota tars and their higher content of unsaturated compounds relative to those of Texas tars. Also the Texas lignite had a higher tar yield which is associated with its relatively high content of waxy and resinous materials. However, the yield of liquids from lignite pyrolysis is so low compared to yields from highly volatile bituminous coals that the latter will be more suitable for pyrolysis. A recent report (Scotti and others, 1975) describing pilot-plant runs using the Char-Oil Energy

Table 3. Composition of primary tars obtained from low-temperature, fluidized pyrolysis of lignite.

LIGNITE SOURCE	SANDOW, TEXAS	GARRISON, N.D.
Distillate Yield[a] (Vol-% of dry tar)	51.7	42.0
Distillate Composition (Vol-%):		
Acids	29.8	66.8
Bases	3.4	3.2
Neutral Oil	66.8	30.0
Neutral Oil Composition (Vol-%):		
Olefins	31.1	43.3
Aromatics	32.4	35.4
Paraffins	36.5	21.3

[a] Distillation at 620 mm Hg.

Development (COED) pyrolysis process showed that the yields of liquids were 1.1 to 1.5 barrels per ton (bbl/ton) using high-volatile bituminous coals and 0.7 bbl/ton using North Dakota lignite. At present, Husky operates a pyrolysis process in North Dakota for the purpose of recovering char to manufacture barbecue briquettes.

Gasification has already been discussed in the previous section. It should be emphasized again that the gasification processes used for fuel production will probably have significant amounts of methane in addition to synthesis gas. However, the gas can still be used for chemical feedstocks production with the Fischer-Tropsch synthesis.

Many hydrogenation processes are being investigated to produce fuels. Those processes producing liquid and solid fuels dissolve the coal in a solvent followed by either catalytic or noncatalytic hydrogenation at elevated temperatures and pressures. These improved liquid and solid fuels can also be used to produce chemical feedstocks.

The predominant characteristic of coal-derived liquids is their high content of naphthenes and aromatics. They are also serviceable sources of chemical feedstocks because they are primarily hydrocarbons without most of the ash, water, and heteroatoms (sulfur, nitrogen, and oxygen) present in the original coal. The composition of the liquids can vary appreciably, however, depending on the characteristics of the coal and the process used to produce the improved fuel. The liquids are essentially synthetic crude oils (syncrudes) and are suitable for processing into chemical feedstocks using conventional petroleum-refining-separation and hydrogenation technology. The solids would require much more extensive hydrogenation and cracking. Probably only the lighter fractions of the improved fuels will be converted into chemical feedstocks. Dow Chemical has an ERDA contract "Chemicals from Coal" in which they are applying petroleum-refinery technology to liquids obtained from the COED pyrolysis process and to liquids obtained from two catalytic hydrogenation processes, the Hydrocarbon Research Inc. H-coal process and the ERDA synthoil process. Dow is also investigating the solid fuel produced using the Pittsburgh and Midway solvent-refined coal process.

CHEMICAL FEEDSTOCKS FROM BYPRODUCTS

The byproducts of potential interest for chemical feedstocks that can be recovered from improved fuel processes such as pyrolysis, gasification, and hydrogenation include inorganics, gases, tars, and tar acids.

The inorganics include hydrogen sulfide and ammonia; these components must be removed to reduce air and water pollution. Both components are removed through absorption from gas streams. Two product combinations are possible: anhydrous ammonia and elemental sulfur or ammonium sulfate and sulfuric acid. The combination selected is dependent on the sulfur content of the lignite and transportation cost to markets (Skeist Laboratories, Inc., 1968).

After ammonia, hydrogen sulfide, and carbon dioxide have been removed from the gas stream, the C_2-C_4 hydrocarbons can be cryogenically separated. This latter fraction can have significant quantities of ethylene and propylene if hydrogen was not used in the prior improved fuels process.

Tars would be subjected to separation and hydrogenation as previously covered in the discussion concerning the use of improved liquid fuels for chemical feedstocks.

Tar acids include phenol, cresols, and cresylic acids. They will be present in both wastewater and hydrocarbon streams and can be recovered through extraction. The potential yields of tar acids far exceed the current demands (Skeist Laboratories, Inc., 1968).

CONCLUSIONS

From the foregoing discussion, the following conclusions can be drawn:

1. It appears inevitable that coal will be used to supply chemical feedstocks because of the depletion of natural gas and petroleum reserves and the rapid increase in the consumption of hydrocarbons for chemicals relative to fuels.

2. Lignite is one of the more serviceable types of coal for conversion to chemical feedstocks because of its chemical reactivity and nonagglomerating characteristic.

3. Economics indicate that chemical feedstocks will probably be obtained from an integrated coal-processing facility where lignite, improved fuels, and byproducts can be utilized.

4. Straight-chain hydrocarbons can be obtained by gasification of lignite into synthesis gas (CO and H_2) followed by subsequent catalytic synthesis.

5. The fairly easy extraction of humic acids from leonardite might provide an economical raw material for conversion into chemical feedstocks.

6. Naphthenic and aromatic compounds can probably be recovered from lignitic sources by using petroleum refinery technology.

7. Sulfur and nitrogen will be recovered because of their potentially adverse impact on the environment.

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A LIGNITE-FIRED ROTARY KILN

J. R. Butler[1]

INTRODUCTION

The Elgin-Butler Brick Company plants are located approximately 30 miles east of Austin near Elgin, Texas. One plant specializes in manufacturing glazed structural clay products, and the other plant specializes in manufacturing face brick, fire brick, and refractory products. Combined, the plants produce about 75 million modular brick equivalents per year. We use approximately 2,500,000 ft^3 of natural gas per day supplied by the LoVaca Gathering Company.

This paper will review our experiences in trying to use lignite as a fuel in converting a natural-gas-fired rotary kiln to one fired with lignite.

DISCUSSION

About 1900, my grandfather located a superior clay when digging a post hole for a fence which was to surround the property from which he was getting oak for burning in the brick kilns in Austin. The clay was of such good quality that a plant was started in Elgin circa 1903. This plant has used everything from wood to natural gas to burn the brick.

In time, we started manufacturing glazed tile and found that the best clay was underneath a layer of "black trash" or lignite trash as it was called in those days. The lignite was and is a real problem in that, if it gets into the body that is being glazed, it leaves imperfections in the glazed surfaces. No one wanted to throw away the lignite because it might be useful someday. As a result, after decades of mining, we have several mountains of lignite—actually it is a mixture of lignite and clay—on the property.

For years we attempted to use lignite in the body of our brick and tile. The early attempts culminated in a test I ran about 1960 in which we put about 30-percent lignite into our clay body and loaded a periodic kiln with the material. The object of the test was to heat the kiln with natural gas until the coal would burn by itself, burning the material from the inside out rather than from the outside in, with the resulting product being a lightweight building block that had superior insulating qualities. The test started routinely; the temperature increased, and the lignite started to burn. Then the lignite started emitting black smoke evidenced by a plume extending 300 ft or more into the air and occasionally flashing. Nothing like this had ever occurred in our smaller production tests, and we did not know whether to smother the kiln or to open the fire boxes and doors. After considerable deliberation, we did nothing. The reducing conditions gave us a molten mess that could only be removed with an air hammer. Four months later we finished cleaning the kiln. Needless to say, our subsequent attempts to use lignite have been conducted somewhat more cautiously.

In another attempt to use lignite, this time in a rotary kiln, we mixed lignite with feed clay, and the results were, again, clay fired under reducing conditions—which we did not want. We had difficulty getting oxygen to the lignite. We do feel, however, that this is a feasible process if large-sized lignite particles are used.

We then took a new course of action in trying to use lignite. We wanted to gasify it and use 125 Btu/ft^3 producer gas. We called well-known com-

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bustion companies asking what gasifiers they marketed. We had preliminary estimates that started at $100 million and went higher. Our plants were only using $300,000 to $400,000 of natural gas per year, and for the start-up price of the gasifiers we could buy 10 or more brick plants! Obviously the cure was many times worse than the problem.

We did have a response from the McDowell-Wellman Company which indicated we could gasify lignite for our plants for about $1 million if we could pelletize the lignite. However, the tests involved in pelletizing cost $150,000, and we would still have no guarantee that it would work. When these estimates were received, gas was inexpensive, and we did not pursue the project. We do feel, however, that an approach along this line is economically feasible, but we were not and are not in a position to develop such a process just for our own use. We do hope that those in the gasification business will eventually realize the enormous economic potential of small lignite gasification systems and begin manufacturing them.

In looking for methods to use lignite, we consulted the National Coal Board in England, and they recommended that we test a unit they developed called an "octopus." The octopus was a small coal-grinding unit equipped with a blower which blew the ground coal with air out eight different hoses. The cost of the new unit was approximately $6,000. We borrowed a used unit, tested it on a tunnel kiln, and found that we could blow lignite into a tunnel-kiln hot zone, and it would sustain heat and maintain combustion. As anticipated, however, the lignite ash deposited on the brick rendered the process unsatisfactory. The important point, however, was that we had an indication that lignite could be fired directly on a small scale with very small burners and inexpensive equipment. We knew that powerplants were burning coal or lignite directly, but their process involved drying the lignite, and their equipment costs amounted to millions and millions of dollars.

We were firing a rotary kiln to get calcined clay and using about 330,000 ft^3 of natural gas per day. We thought we could fire the kiln with lignite, and the small amount of ash in the calcined clay would not matter. Calcined clay is a raw clay fired to a state of semi-vitrification and mixed with raw clay to obtain certain drying and shrinkage characteristics in various clay products.

While we were contemplating converting the rotary kiln to lignite, and considering the economics, the LoVaca gas cost began to rise. Gas supply to our company was even curtailed. With the incentives of rising gas costs, plus the thought that if we could show others how to fire lignite on a small scale, we could sell small quantities of lignite, we began seriously to try to convert the rotary kiln from gas firing to lignite firing. We subsequently found someone experienced in designing relatively small-scale coal-firing systems.

The lignite-fired kiln is a round tube about 75 ft long and 6 ft in diameter. The raw clay is fed into the kiln by means of a conveyor that comes from a hopper equipped with an apron feeder. The clay falls into the kiln tube, goes through the kiln, and falls onto the ground. Prior to the conversion, a single natural gas, air-inspirator burner was used to fire the kiln. The kiln produces approximately 120 tons of calcine per day (fig. 1).

We asked the consultant to see if he could design a system whereby we could use lignite that had been stockpiled from our clay-mining operations. We needed a feeder that could handle unprocessed lignite—lignite that was not ground and certainly not dried. We felt that a feeder could feed unprocessed lignite because our stockpiled lignite had broken down from chunks 2 to 3 ft in diameter to 4-inch chunks and smaller as it dried out in the stockpiles.

We asked the consultant whether he could devise a firing system that would fire wet lignite and lignite containing clay impurities and one that would allow us to control the flame temperatures in case ash fusion in the kiln became a problem. Finally, we needed an extremely economical system. He was given a typical lignite ultimate analysis and was shown the stockpiles. He felt he could design a firing system that would cost less than $45,000. We were somewhat skeptical, but he finally gave us enough hope to continue the project.

The one big question was, Would we have to use gas or some other fuel to ignite the lignite and/or sustain combustion? How much additional fuel we would need was unknown, but 10 percent of the Btu's in the system was estimated. The final design was one in which lignite was to be fed into a hopper with a 4-inch grid on top to screen out lignite chunks that did not break down (fig. 1).

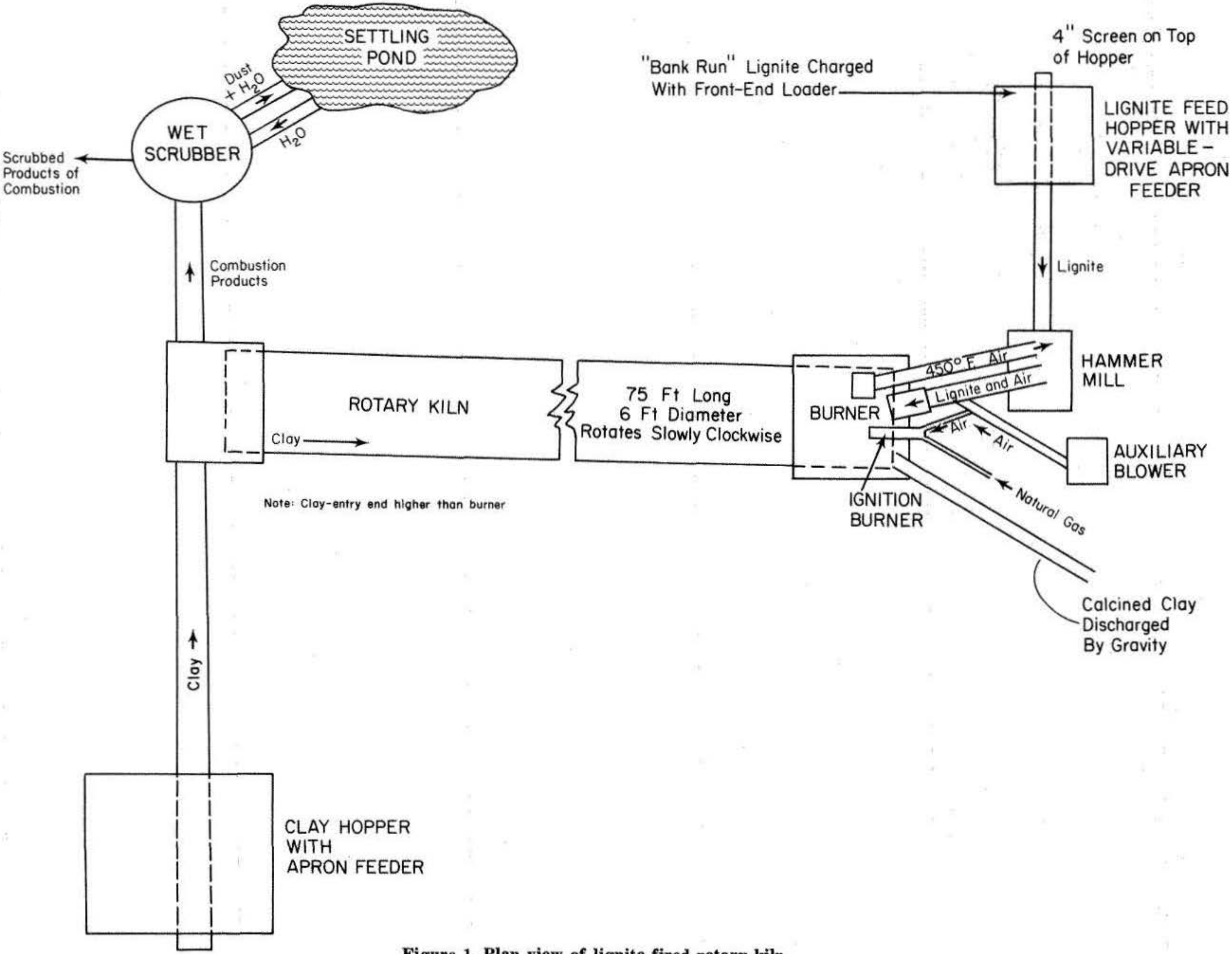

Figure 1. Plan view of lignite-fired rotary kiln.

The percent of large lignite chunks was very small, and the lignite would usually dry quickly enough to break down and feed without having someone break up the lignite chunks to get them through the grid. The hopper, which has an opening that can be regulated, was and is equipped with an apron feeder, which is a belt that passes under the hopper. The apron feeder was equipped with a variable-speed conveyor connected to a control unit that was coupled with an optical pyrometer. A high or low kiln temperature would speed up or slow down the conveyor to increase or decrease the lignite feed.

The lignite is fed into a hammer mill at about 1 ton per hour, ground, and then air-swept into the kiln burner. The air comes from the hood of the kiln at approximately 450°F. This is the key to handling the wet lignite and wet clay impurities as the high temperature dries both. The lignite particle size is controlled by the volume of air and a deflector between the pulling air fan and the hammer mill. Additional air can be added by an auxiliary blower if necessary to increase the velocity of the lignite particles. The lignite particles are blown onto the clay feed stream in the rotary kiln. We have a natural gas igniter burner with which we can regulate the flame velocity, the amount of gas, and the flame temperature. The igniter burner fires tangentially into the air-lignite fuel stream to ignite the lignite.

Fortunately, the firing system did everything it was supposed to do. We reduced ignition fuel to about 5 percent and have reduced the overall Btu consumption of the kiln by 20 percent while maintaining the same production and temperature of 1,900°F.

We can regulate the burning time of lignite by changing the particle size of the lignite, changing velocity of the lignite that is blown in, changing the temperature of the carrying air or the amount of excess air, or changing the draft of the kiln. We do not yet know what the optimum operating conditions are.

We do know that the velocity of the lignite and the way it is ignited are most critical. Apparently the lignite particles that are brought in through the burner are running parallel to the carrying air, and when ignition starts, it is important to create turbulence. As the lignite burns from the outside to the inside, a small layer of ash forms that must be knocked off the particle to achieve quick combustion. Obviously, turbulence and particle size affect this condition drastically. We installed adjustable deflectors at the end of the burner pipe. Incidentally, burning does not take place until after the lignite leaves the burner pipe.

We have performed tests varying the moisture and ash. We have burned the lignite when it was wet. It does decrease the ignition efficiency and increase the overall fuel consumption, but not as much as we thought it would. The lignite we are using varies in ash content from 16 to 50 percent, depending on the amount of clay mixed with the lignite. The Btu content of the lignite ranges from 5,800 to 7,000 Btu/lb at about 33 percent moisture and 16- to 20-percent ash when it is kept unmixed from clay in the mining process.

Since some lignite is lost in mining at the lignite, clay, or overburden contact, the amount of lignite waste in mining will depend on how much clay impurity we can burn. We also have a great deal of lignite stockpiled that has clay impurities. We do feel that if we add another lignite feeder, we can blend in lignite with larger percentages of clay, eliminate almost all waste incurred in mining, and still maintain a low ignition fuel requirement.

Sulfur dioxide emissions in the type of system we have are not a problem from a regulatory standpoint. The only real problem is particulate emission. We used a 5-inch pressure drop through an improvised water-operated bubble tray scrubber and have achieved 99.7-percent efficiency. Our initial costs were low, but we found that SO_2 and chlorides are presenting real corrosion problems. We will be replacing everything with fiberglass and even may have to neutralize our recirculated scrub water. Mild steel will not last 3 days in the system, No. 304 stainless steel lasts longer, and No. 316 stainless steel is much better. We feel that fiberglass is even more durable, and we are currently replacing scrubber components with fiberglass.

Our firing system cost less than $30,000, and our scrubbing system initially cost about $25,000. By the time we solve the corrosion problem we will have another $20,000 in the scrubbing system. Had we known what we know now, the firing and scrubbing system would have cost about $50,000. We estimate we are saving about $350 per day, with natural gas costing $1.85 per thousand cubic feet and lignite valued at $9.00 per ton.

ENVIRONMENTAL GEOLOGY OF THE EAST TEXAS LIGNITE BELT

C. D. Henry[1] and E. H. Kastning[1]

ABSTRACT

The dramatic increase in lignite mining of the past few years is expected to continue in Texas. Surface mining of coal in other parts of the United States has created severe environmental problems. Careful planning of future mining to avoid environmental degradation will require an understanding of how mining can affect the environment and a thorough inventory of land and water resources which could be affected.

To provide basic planning data the Bureau of Economic Geology has mapped the environmental geology of the Wilcox-Carrizo outcrop belt between the Colorado and Trinity Rivers. The area was selected because (1) the Calvert Bluff Formation of the Wilcox Group is the major lignite-bearing unit, (2) the area includes two active strip mines, a probable 3 billion tons of near-surface lignite, and at least two more mines planned to be in operation by about 1980, and (3) the Wilcox-Carrizo aquifer is recharged through the lignite-bearing area.

Criteria for defining and mapping environmental geologic units are substrate, soil, biologic assemblage, geomorphology and geologic process. Three groups of units cover a majority of the lignite areas and are the most critical to mining. Sandy clays are the substrate in which most mining will occur and must be evaluated on their potential for reclamation. The sandy clays have been subdivided by soil associations to indicate a relative need for preservation of soils during mining. Flood-prone areas are hazardous for mining, could have ground-water-discharge problems, and have highly fertile soils requiring preservation. Sands are aquifer-recharge areas to the major aquifers of East Texas. Mining, which intersects sands, could have ground-water-discharge problems and could lead to pollution of the aquifers.

The environmental geologic map (1) identifies problem areas for mining, (2) provides basic information for planing of reclamation, and (3) provides a regional framework for detailed studies at individual mine sites.

INTRODUCTION

In our enthusiasm for lignite, we must not forget that land and water are also resources and that mining for lignite has a considerable potential for damaging those resources. Preventing damage will require careful planning of mining based on a knowledge of the location and abundance of lignite, an understanding of how mining can affect the environment, and an inventory of land and water resources as thorough as our inventory of lignite resources. Decisions on where and how to conduct mining must be based on as precise information as can be obtained.

The work of Kaiser (1974 and this volume) and that of numerous energy companies have done much to provide the necessary lignite inventory. Studies of past coal mining in Appalachia and the Midwest have shown us the kinds of problems that can arise from lignite mining. Identical problems with erosion and water pollution and difficulties with reclamation and revegetation may not necessarily occur in Texas; nevertheless, they are the problems that we need to consider.

The other necessary ingredient for planning of mining is an inventory of land and water resources of the areas likely to be affected by the mining process. As a step toward providing an inventory, the Bureau of Economic Geology is preparing a map of the environmental geology of East Texas lignite lands. The map identifies environmentally sensitive areas and problem areas for mining, provides basic information for planning of reclamation, and provides a regional framework for detailed studies at individual mine sites.

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ENVIRONMENTAL GEOLOGIC MAPPING

The criteria used for defining and mapping environmental geologic units are substrate, soil, biologic assemblage or native vegetation, geomorphology (land form and slope intensity), and geologic process (Henry and Kastning, 1975; Henry, 1976). This approach is different from some previous studies that separated those criteria to produce a suite of maps, one for each variable: a slope map, physical properties map, or process map (Alabama Geological Survey, 1971). We have used our approach because we have found it to be effective.

Because the motivation for this study was lignite, we defined all units with emphasis on, but not limited to, their usefulness in planning mining and reclamation. Our mapping was done mostly from black-and-white aerial photographs, scale 1:20,000, with extensive field checking. Other sources, such as Soil Conservation Service soil maps, were consulted where appropriate.

We have completed mapping of the Wilcox-Carrizo outcrop belt between the Colorado and Trinity Rivers (fig. 1). We selected this initial area for several reasons: (1) the Calvert Bluff Formation of the Wilcox Group is the major lignite-bearing unit in Texas; (2) the area includes a probable 3 billion tons of near-surface lignite (Kaiser, 1974, table 4), two active lignite strip mines, and several more mines planned to be in operation by the early 1980's; and (3) the Wilcox-Carrizo aquifer is recharged through the map area. We are continuing mapping along the Wilcox-Carrizo outcrop into northeast Texas and into the Sabine uplift area of East Texas. Wilcox and Carrizo sands are major aquifers in East and South Texas and are hydraulically connected (Guyton and Associates, 1972).

Twenty-three different environmental geologic units have been mapped. Three groups of units cover a majority of the area mapped, show the general character of the lignite lands, and are the most significant units in relation to surface mining (table 1). What an environmental geologic map is, how units are selected, and how the different criteria for defining and mapping units are significant will be illustrated. Most importantly, an attempt will be made to show how knowledge of the environmental geology can be applied in the planning of lignite mining not only to preserve land and water resources but also to minimize problems for mining.

MAP UNITS AND APPLICATIONS

SANDS

The first group of units is composed of sands. We have distinguished two sand units, sand hills and low-rolling sands. The substrate for each consists of white or varicolored, fine to coarse, quartz sands with rare clay lenses. Soils are highly leached, loose sands supporting post oak forests. In the sandiest areas, vegetation is thin; the light-colored sands are easily seen through the thin cover. Sand hills stand up as distinct rounded hills with moderate to steep slopes (fig. 2). The low-rolling sands have gentler slopes with some large flat areas (fig. 3). The dominant process is recharge; both units are recharge areas for the major aquifers of East Texas.

Why distinguish two very similar units purely on the basis of a difference in slope? The difference in slope has implications for both present land use and mining. Sands with lesser slopes, low-rolling sands, are more commonly cleared for pasture or cultivation than are sand hills with steeper slopes.

The difference in the two units for mining is shown in schematic cross section in figure 4. At the top of the figure the lignite bed is overlain by sands forming sand hills. A mining company extracting the lignite would probably not mine very far beneath the sand hills because the sudden large increase in overburden thickness would greatly increase the cost of extraction. At the bottom of the figure, low-rolling sands overlie the lignite; overburden thickness increases more gradually. Mining can extend much farther downdip and the thickness of sand alone would probably

Table 1. Environmental geologic units.

1. Sands	Sand Hills Low-Rolling Sands
2. Sandy Clays	Prairie Soils Forest Soils
3. Flood-Prone Areas	Floodplains Mixed Alluvium and Colluvium Low Terraces

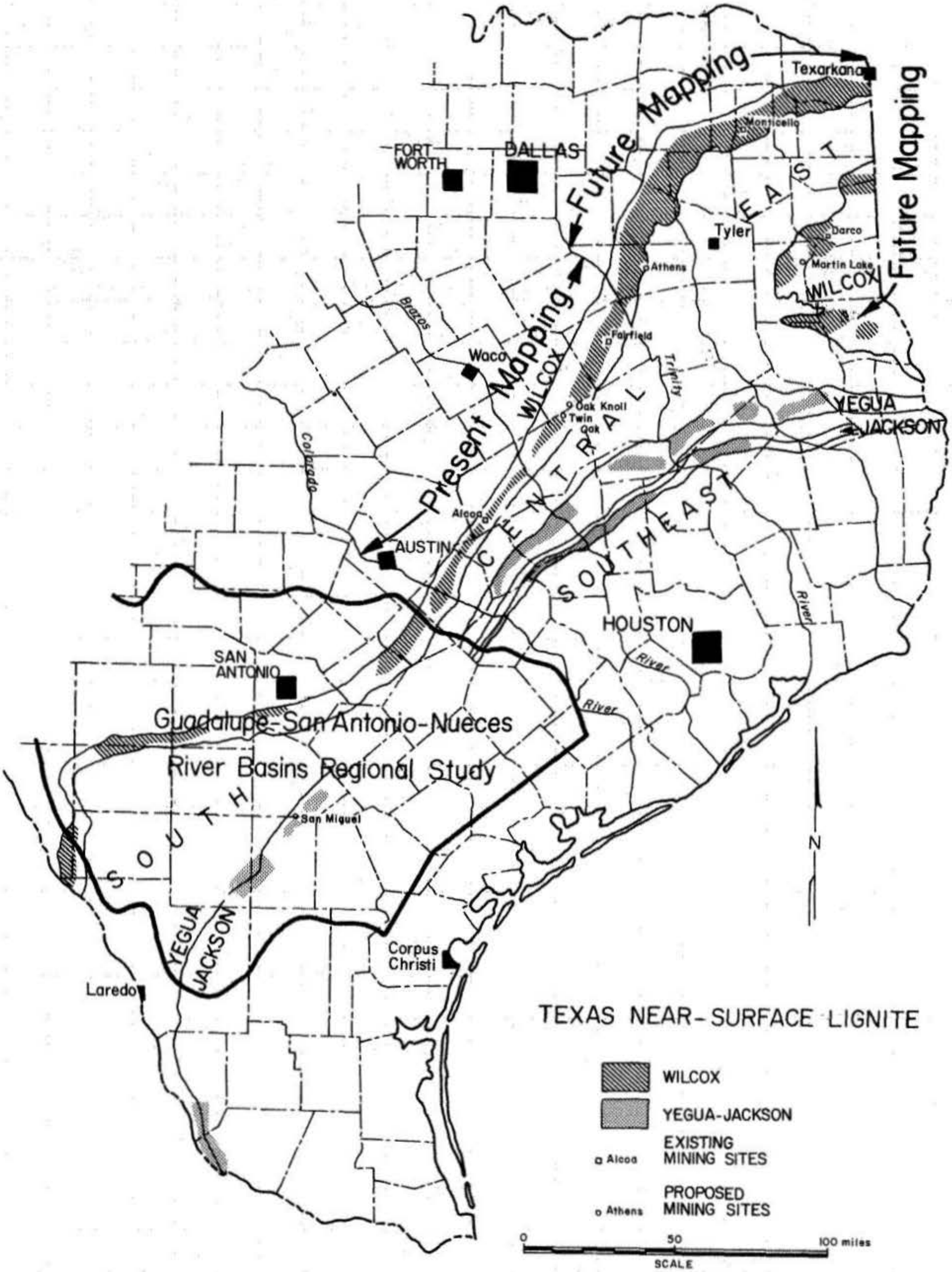

Figure 1. Map of East and South Texas showing distribution of near surface lignite, active and planned lignite mines, and present and future environmental geologic mapping.

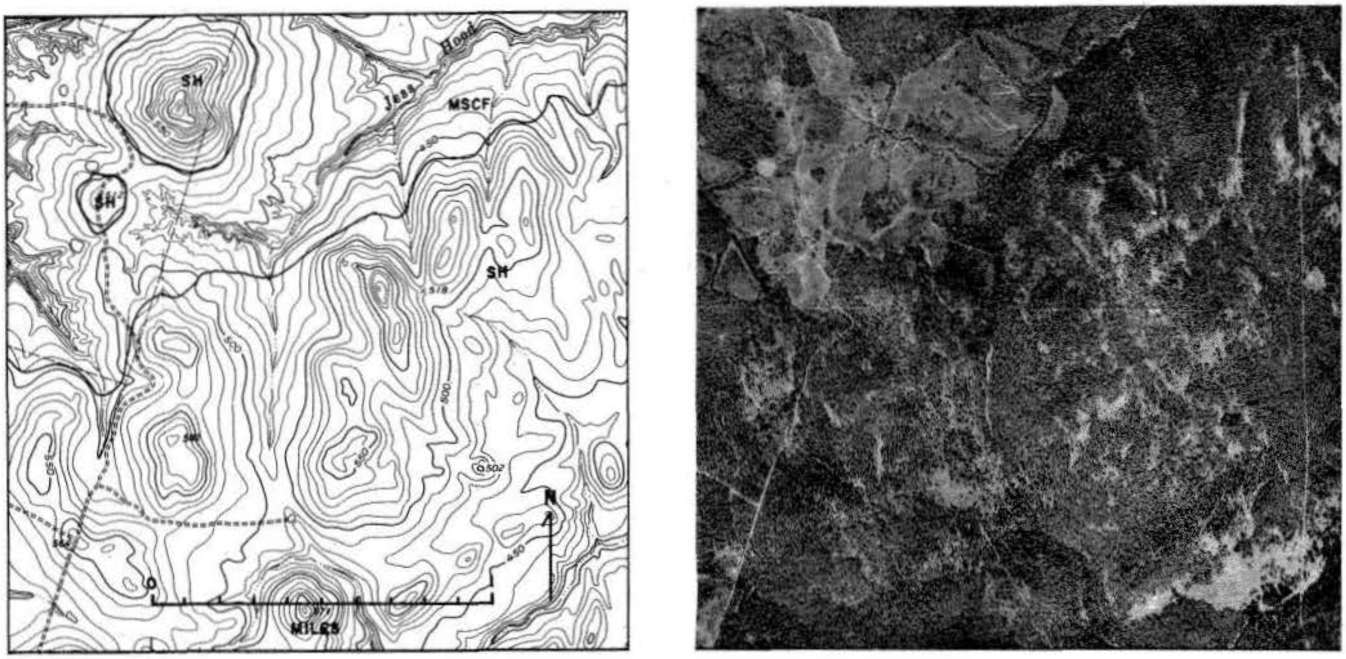

Figure 2. Topographic map and aerial photograph of sand hills (SH) and moderate-relief sandy-clay-forest soils (MSCF), Hanover Quadrangle, Texas.

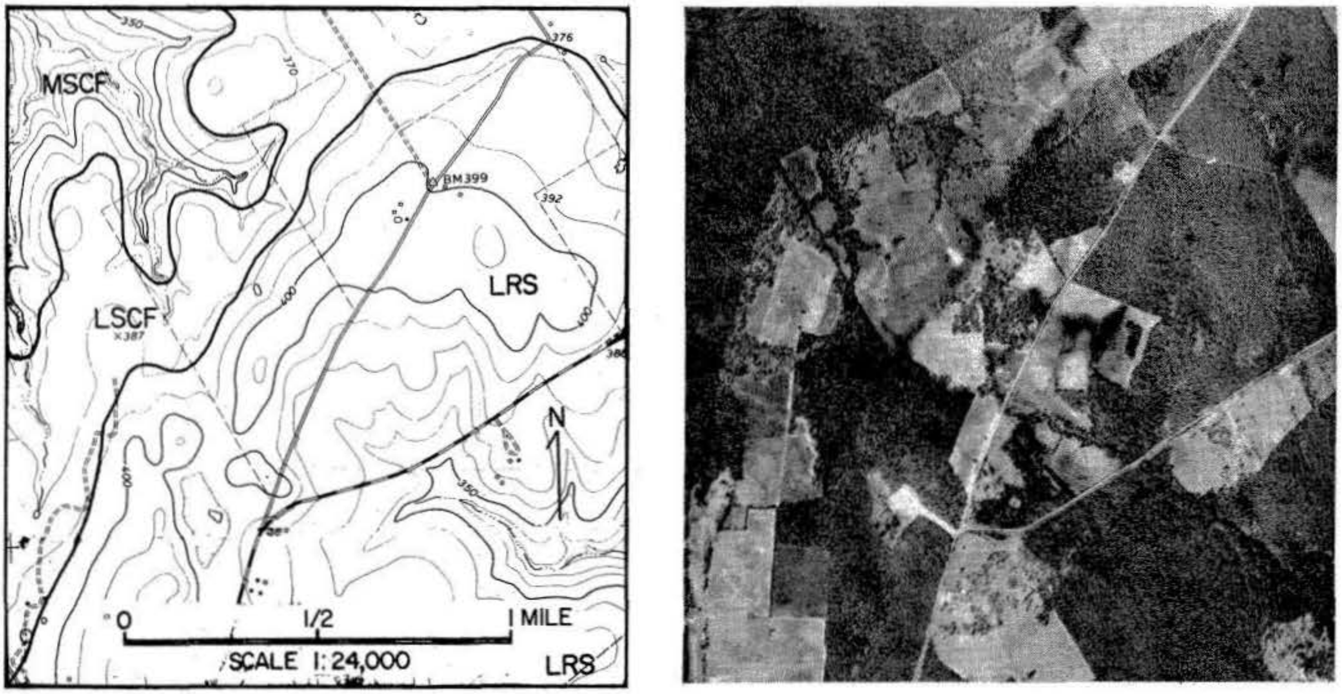

Figure 3. Topographic map view and aerial photograph of rolling soils (LSCF and MSCF) Stewards Mills Quadrangle, Texas.

not be the limiting factor in terms of overburden thickness. Thus mining could extend through large areas of sand.

Several problems can result from strip mining through either type of sand unit. First, the sands are saturated with ground water almost to the land surface and will discharge into the pits. The amount of water discharged will be a function of the hydrologic parameters of the intersected sand and can vary widely from pit to pit. The water will have to be pumped from the pits, an added cost for mining, and much ground water could be lost.

Sands also present two important environmental problems: aquifer disruption and groundwater pollution. Once mining is completed and the pits are filled in, recharge to any sands intersected by the pit will occur only through the reworked overburden. A clayey, well-compacted overburden could effectively seal off the sand from any recharge. More likely the overburden material will be at least moderately permeable. The sand body will be recharged, but only by water that has passed through the spoil material. This water will be of poorer quality than the original recharge and will diminish the quality of water within the aquifer. The exact chemical nature of the water will depend on the chemistry of the spoil through which it passes.

The environmental geologic map identifies sand-recharge areas and can be used as the basis for determining ways to deal with these problems. Mining could be restricted in regions near sand bodies and recharge areas. Sand bodies, however, are common throughout the Calvert Bluff and Wilcox and restricting mining in these areas would remove some lignite from potential use.

Rerouting mine drainage away from the sands is another possible solution. For a mine pit, rerouting would require sealing the sand body along the walls of the pit with impermeable material, cutting off the sand from recharge. This method is impractical.

A third possibility requires monitoring mine drainage (fig. 5). The geometry of sand bodies adjacent to a mine can be determined from the environmental geologic map and from core information from exploratory drilling. Wells, then, can be placed to monitor the flow of mine effluent and its effect on ground-water quality.

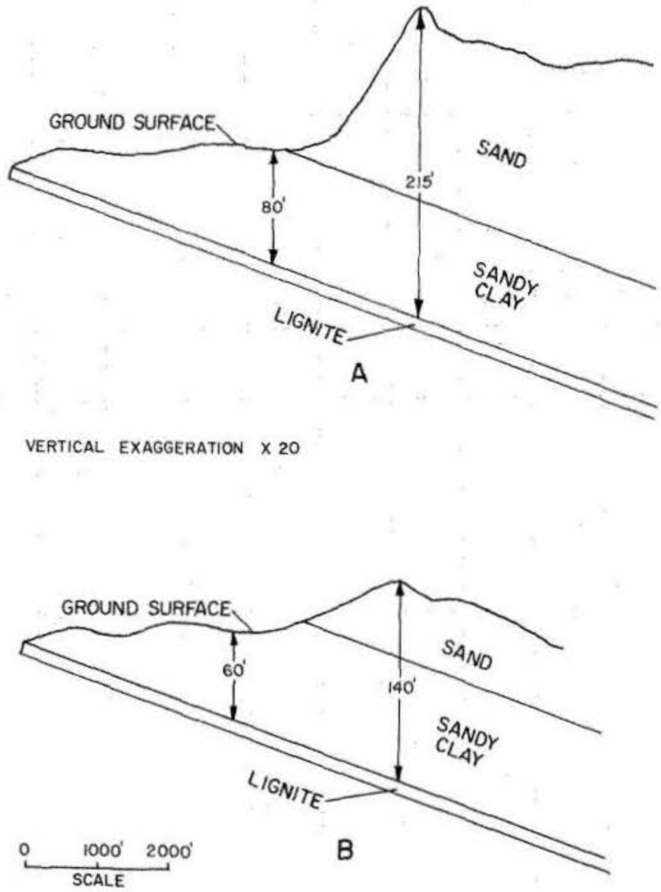

Figure 4. Schemtic cross sections illustrating change in overburden thickness above lignite bed. (A) Sand hills; (B) Low-rolling sands.

There are some problems even with this approach. A sand body intersected by mining will only receive recharge after the pit is filled in, after most preventive work is possible. Monitoring may identify ground-water contamination but it will not prevent it. Information gained from monitoring, however, will show whether or not mine drainage is a significant problem. If it is, future mining practices (such as isolating pyritic material) can be employed to avoid it.

Figure 6 illustrates the regional sand geometry of the Calvert Bluff. The shaded areas within the Calvert Bluff outcrop area or low-rolling sands recharge areas identified by the enviromental geologic map. The sinuous areas extending southeast from the Calvert Bluff outcrop area are channel complexes from Kaiser (this volume). They represent areas in the Calvert Bluff containing more than 55-percent sand. Notice that the subsurface channel complexes and the surface sand outcrops match exceptionally well.

The significance is that the channel sands are probably the most important sources of ground water in the Calvert Bluff Formation. Sites for monitor wells can easily be selected from this information and, of course, from the location of lignite mines. The channel sands are also the best sites for wells for maximum development of ground water. This is one illustration of the application of the environmental geologic map beyond the problems of lignite mining.

SANDY CLAYS

Much of the Wilcox Group is underlain by sandy clays or finely laminated sands and clays. In the context of Kaiser's (this volume) depositional model, most of this material is probably overbank material deposited between major channel systems. Lignite seams are dominantly within this kind of substrate.

We have distinguished two general kinds of sandy clays on the basis of their soil associations called prairie soils or forest soils from the native vegetation they support (tables 1 and 2). Prairie soils are clay loams or fine sandy loams with thick clay "B" horizons. Native vegetation consists of prairie grasses and mesquite. Forest soils have sandy "A" horizons up to several feet thick over clay loams. They support thick post oak forests. The difference in soils probably reflects a slight difference in substrate composition (sand-clay ratio), but basically substrates are very similar.

Both sandy clay units form a low to moderate relief, rolling topography, extensively cleared for improved pasture for grazing cattle. Very little is presently cropland. Both units have severe erosional problems which were aggravated by past agricultural practices. In fact, runoff and erosion are the dominant processes of these units. Extensive steep-walled gullies have removed top soil and made large areas unsuitable for any use.

What is the importance of these units to mine planning and why have we differentiated similar materials on the basis of soil type? The major lignite seams are interbedded with sandy clays, hence a large part of the lignite mining will occur in areas of sandy clays. Thus, the environmental geologic map provides an inventory of materials, especially soils, which will be directly involved in mining and reclamation. The inventory also indicates a relative need for preservation of the soils, looking beyond simple present land use.

Quantitative Soil Conservation Service data (U. S. Department of Agriculture Soil Series)

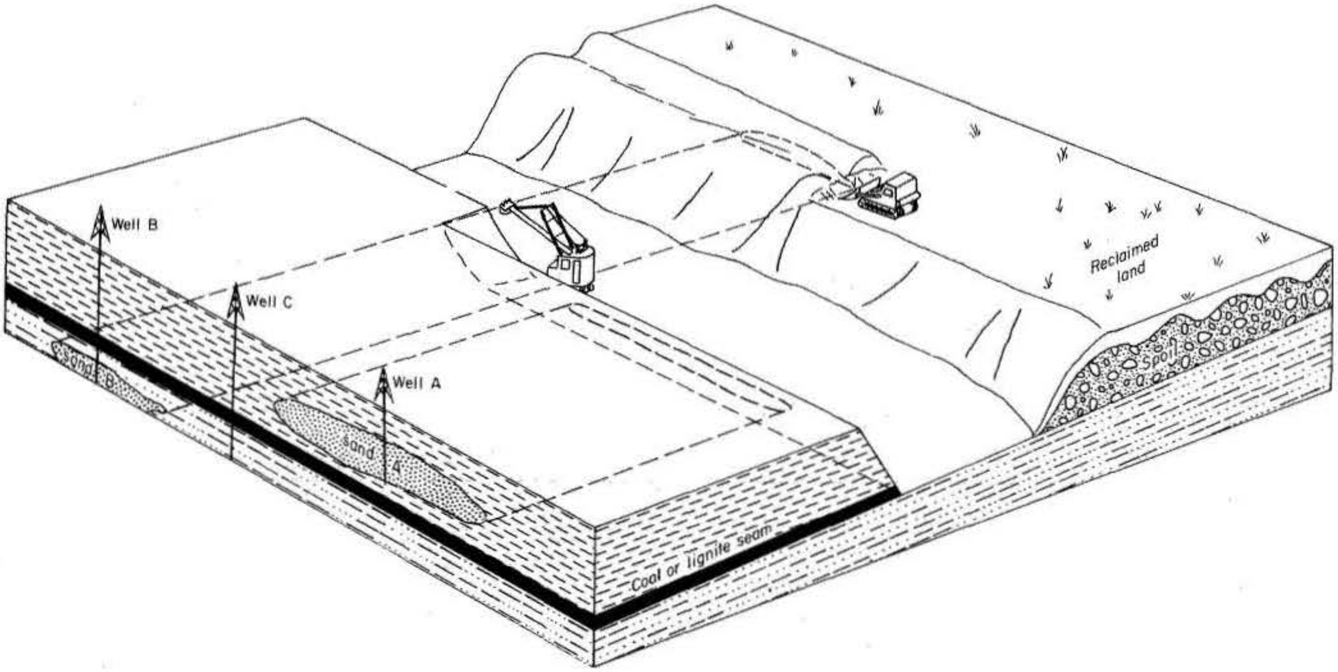

Figure 5. Schematic diagram of hypothetical lignite mine showing water-quality monitoring in sand body intersected by mining (sand A) and sand body beneath lignite (sand B). Well C does not intersect either sand body and would not be useful in monitoring mine drainage.

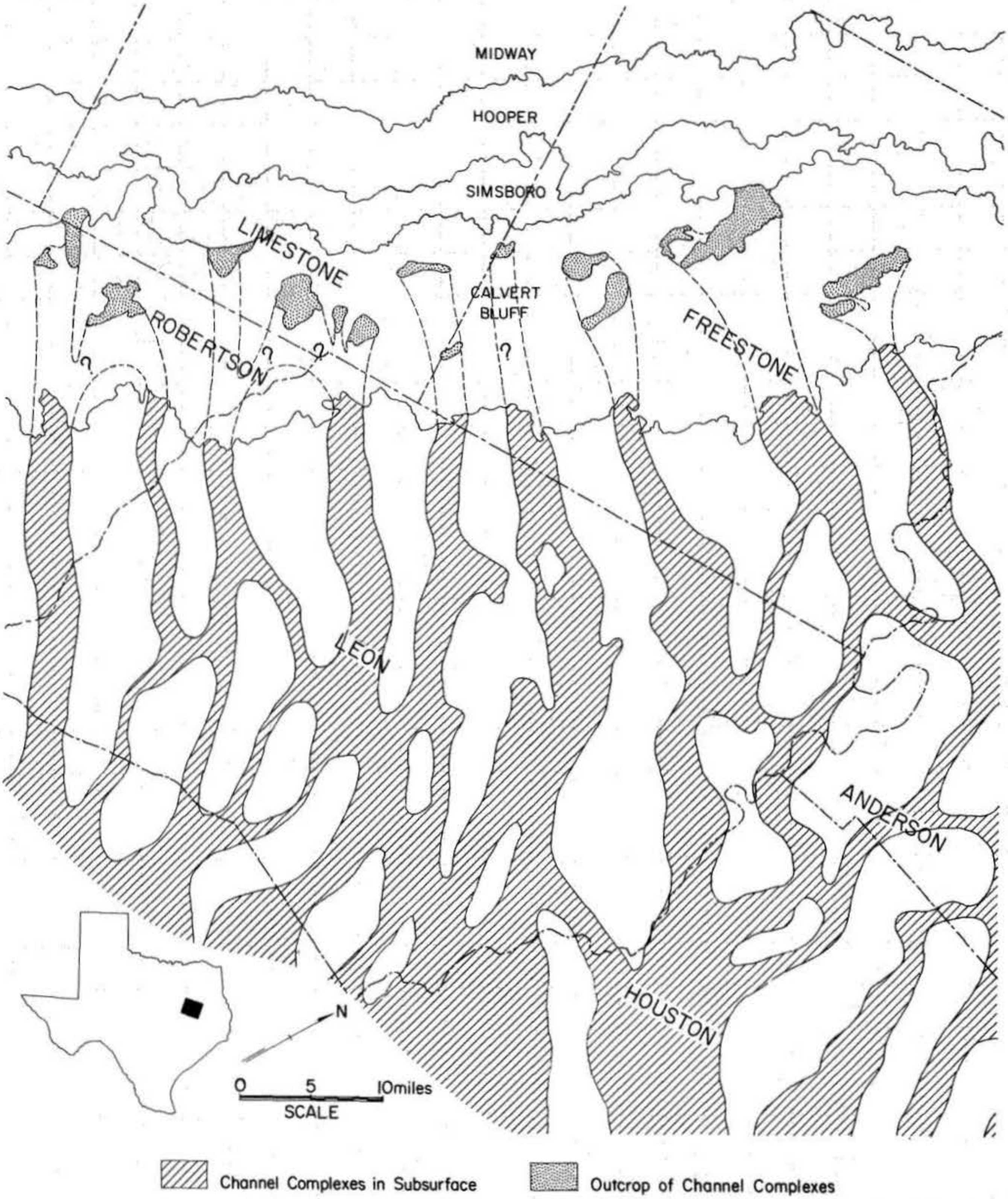

Figure 6. Map of subsurface channel complexes (Kaiser, this volume) and their surface outcrops (from environmental geological mapping, Calvert Bluff Formation).

Table 2. Sandy clays.

	Native Vegetation	Production Potential Per Acre
Prairie Soils	Prairie grasses Mesquite	400 lbs. cotton 5000 lbs. air-dry herbage
Forest Soils	Post Oaks	250 lbs. cotton 3000 lbs. air-dry herbage

From Soil Conservation Service established soil surveys.

show that productivity of the prairie soils considerably exceeds the productivity of the forest soils under equal levels of management (table 2). However, both are usable soils. Because East Texas is also an area of abundant water, both units have potential to be productive farmland. Much of the lignite land was used extensively for cropland as late as the 1950's. Though not presently used for cropland because more fertile lands are available, they may need to be used as cropland in the future as increased demands are placed on agriculture in the United States. Purely on a relative basis, prairie soils are suitable for higher intensity agriculture and in general are more productive than forest soils; prairie soils would need to be separated and saved for reclamation during mining in preference to forest soils.

None of the areas presently mapped supports commercial timber production. However, in much of East Texas, timber is a major industry; the capability of the soils to support pine and hardwoods will need to be considered there.

The presence and restriction of gullies to areas of sandy clays indicate that among the various substrates in the lignite area the sandy clays are the most susceptible to erosion. Disruption of the land surface by strip mining will increase the potential for erosion. Thus, overburden composed of sandy clays will need to be regraded and revegetated soon after mining to avoid excessive erosion.

FLOOD-PRONE AREAS

Flood-prone areas comprise the final group of units (table 1). They include (1) floodplains, (2) mixed alluvium and colluvium, and (3) low terraces. Flooding is the overriding criterion for classification of floodplains as an environmental geologic unit. Substrates are commonly silts and clays near the surface grading downward into coarser material including gravels near the base of the alluvium. Soils reflect the substrate upon which they developed and are commonly very fertile and highly cultivated. Recognition on air photographs is based on a number of factors including evidence of active erosion and deposition. Floodplains are nearly flat, commonly have a sharp topographic break at their boundary with adjacent uplands, and show a distinct tonal difference between the dark-toned water-saturated clayey soils of the floodplain and the lighter toned drier soils of the uplands (fig. 7). Flooding in these areas is frequent. For many medium-sized rivers, a 4-inch rain in 24 hours is sufficient to produce a flood which will cover most of the floodplain. Such a rainfall and flood can occur once every few years or possibly several times in one year. In mapping these flood-prone areas we do not imply any quantitative flood-recurrence interval. We are simply recognizing that these areas have been flooded in the past and will be again. We have mapped natural floodplains without consideration of flood-control structures.

The second flood-prone area is underlain by interfingering alluvium deposited by streams and colluvium washed down from the slopes above the streams (fig. 8). This mixed unit commonly occurs along smaller streams where the contribution of sediments from colluvial and alluvial processes is relatively equal. Mixed units generally have concave-upward surfaces, and the break between pure colluvial and pure alluvial material cannot be precisely located. Some areas are small floodplains which are not distinguishable at the scale of our mapping. Flooding on these areas is as frequent as that on the larger floodplains; however, the volume of water involved is considerably smaller.

The third flood-prone area consists of numerous low terraces adjacent to the floodplains of medium- to large-sized rivers. Several different terrace levels exist; most are above any present day flood levels. We have designated as low-probability flood-prone areas those terraces no more than 10 ft above the floodplain. They do not show the geomorphic evidence of flooding that true floodplains do, and there is commonly a distinct, though low, topographic break between the two. Although 10 feet seems to be a relatively arbitrary figure, historical data, U. S. Geological Survey water stage records, and personal recollections of local residents indicate that these low terraces have been flooded during large floods.

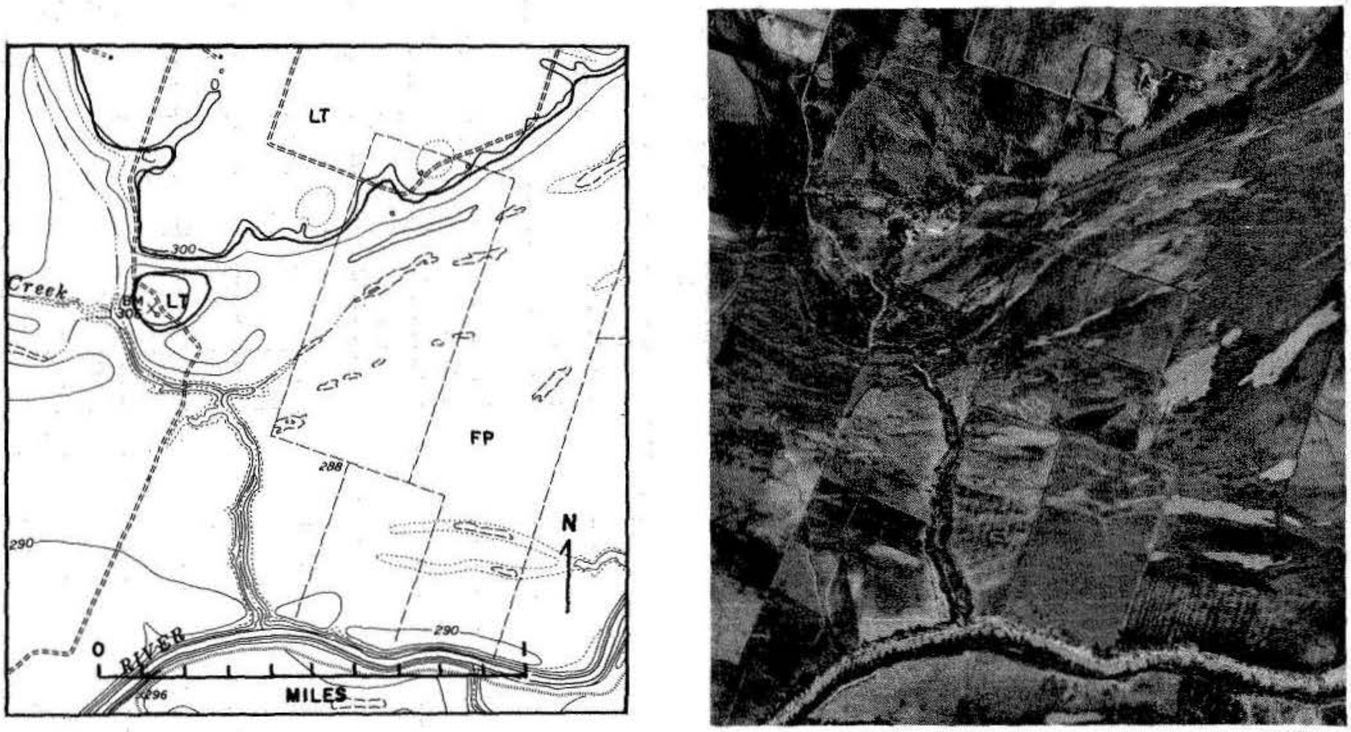

Figure 7. Topographic map view and aerial photograph of floodplain (FP) and low terrace (LT), Hanover Quadrangle, Texas.

Use of most floodplains in rural parts of Texas has been restricted to agricultural activities which can withstand occasional flooding. In fact, floodplains and terraces contain some of the most productive soils in Texas. As an example, the Brazos floodplain is heavily farmed; primary crops are cotton and grain sorghum. Some other floodplains, for instance along the Trinity River, have fertile soils, but the lowest lying areas are not cultivated extensively at present because of frequent, prolonged flooding. These soils are important resources in their own right. If mining is undertaken in flood-prone areas it would appear that the agricultural productivity of the floodplains and terraces requires that soils be segregated and preserved during mining and restored afterwards.

Flooding provides some obvious hazards for mining, and mining on floodplains could create some major environmental problems. Flood waters obviously could severely damage mining operations and large quantities of suspended solids would be added to the flood waters by mine areas, further increasing problems of siltation.

Another significant factor in mining on floodplains is ground-water discharge into the mine. Mining will first intersect a thick blanket of alluvium deposited by the river. This alluvium commonly includes much coarse material, is saturated with ground water, and is highly permeable; ground-water discharge into the mine pit could be considerable. The water would need to be pumped, an added expense to mining, and the discharge and pumping could lead to significant drawdown in neighboring wells. Some mine drainage will enter the alluvial aquifer as a result of mining. Alluvial water is of variable quality but is suit-

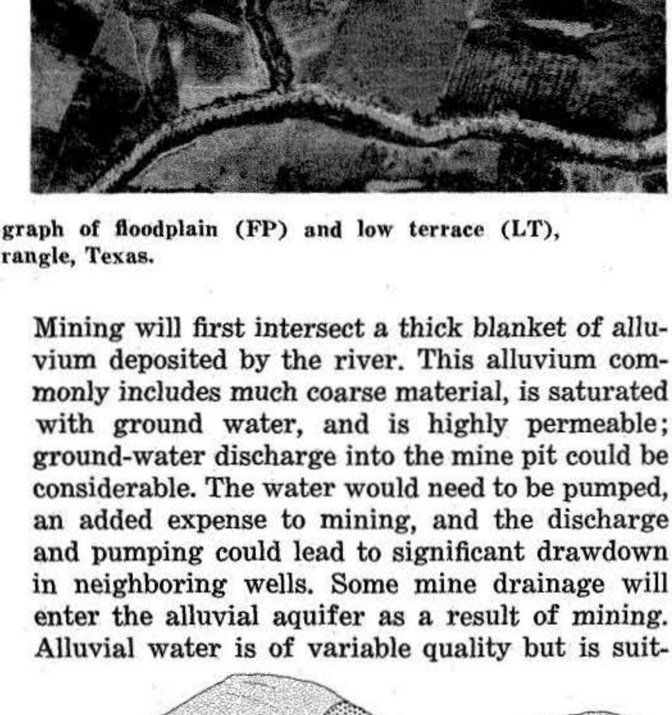

Figure 8. Schematic diagram of mixed deposition of colluvium washed down from slopes above the stream and alluvium deposited by the stream.

able for agriculture, its dominant use. The magnitude of the drainage problem would depend on a number of factors, including the chemistry of the drainage, the rate at which it moves through the alluvium, and the amount of dilution that occurs.

CONCLUSIONS

The maps we have produced and will produce are regional maps. Though they are relatively detailed, more detailed studies will be necessary at individual mine sites. For example, some sands were simply too small to be mapped at the scale of our work. They have necessarily been included with the laminated sands and clays. These sands could be identified by onsite studies. Some information necessary for mine planning such as geochemistry of the lignite and overburden and permeability and transmissivity of individual sands cannot be determined from aerial photographs. In all these situations, though, the environmental geologic map provides a framework to guide onsite studies.

Our completed mapping covers only a part of the lands underlain by lignite. Texas is a large, variable state. Geology, climate, vegetation, and lignite vary from region to region in Texas. Other Gulf Coast States are also different. Although the concept of this work is applicable anywhere, the exact details may not be. However, the Bureau of Economic Geology is about to publish a study of the environmental geology of much of South Texas including most of the lands underlain by lignite in that area. Though not aimed initially at the particular problems of lignite mining, the study is applicable to those problems.

There is going to be extensive lignite mining in Texas in the future. Even with the most thorough planning, there will be some problems. With the kinds of information and planning outlined in this report the major problems can be avoided.

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LAND RECLAMATION IN TEXAS — AN OPPORTUNITY[1]

R. L. White[2]

ABSTRACT

Surface mining for lignite is increasing in Texas in order to meet the State's energy needs. But the strip-mining recovery technique has historically aroused a negative reaction in the public because of lands left unreclaimed and nonproductive. Texas lignite lies in a northeast-to-southwest band across the State, but the deposits of commercial importance, recoverable by surface mining, lie principally in East Texas. This low-rank coal occurs in areas where the climatic and physiographic conditions favor land reclamation. Through research, planning, and application, Texas Utilities Generating Company has established a successful land-reclamation program whereby environmental effects are minimized and the land's productivity is restored. Although problems occur periodically, they have been overcome through utilization of the benign factors naturally afforded by the area as well as corporate commitment. Land reclamation is an opportunity that should be approached on an objective, informed basis.

INTRODUCTION

Texas, being a mineral-producing State, displays a number of techniques for recovering minerals. Surface-mining activities in the form of open-pit mines, quarries, and strip mining are utilized to gather resources such as clays, gravels, limestone, and lignite. Although each of these recovery methods differs in many respects, each shares a common characteristic, namely, disturbance of the land, be it temporary or long term.

Groat (1973) indicated that surface mining or strip mining for lignite would experience a significant growth in Texas in the next few decades. Although lignite has been a rarely used resource in Texas, the strip-mining recovery technique has an advance reputation which triggers a most negative public reaction in the State. Stories and pictures of past environmental problems resulting from eastern and midwestern strip mining have brought about the assumption that only disaster awaits Texas lands. But taking a more positive posture, today's surface-mining operations have learned from past mistakes and profited from advanced technology and equipment. With these tools and the proper commitment, land reclamation in Texas need not be a problem, but an opportunity.

But what precipitated the emergence of strip mining in Texas? Why lignite? Lignite production flourished during the early 1900's, but for the last few decades, power generation in the State has been primarily fueled by oil and gas. Their relative abundance and economy made these fuels the appropriate choice for the electric utility industry. Without getting involved in a discussion of the energy crisis, it can be stated that in Texas, as in most other states, alternate sources of fuel have now become mandatory. Consequently, an almost forgotten resource, lignite, has again become one of the State's most important raw materials. Now lignite is considered to be the vehicle which will transport power generation in Texas from the oil and gas era to the nuclear era.

TEXAS LIGNITE

Fisher and Kaiser (1974) describe Texas lignite as "a low-rank, brownish-black coal with a high moisture and volatile matter content, and with a heating value on the order of 7,500 Btu/lb on an as-mined basis." From an environmental standpoint, it is important to note that Texas lignites have a relatively low sulfur content, thus precluding many of the acid-related problems characteristically associated with surface mining.

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[2] Texas Utilities Generating Company; Fairfield, Texas 75840.

As can be seen in figure 1, lignite deposits begin in the extreme northeast area of the State and continue in a southwesterly direction. These deposits occur in lower Tertiary (Eocene) rocks subdivided into the Wilcox Group (lower Eocene) and the Yegua Formation-Jackson Group (upper Eocene). Fisher and Kaiser (1974) report

> The lignites formed as parts of ancient fluvial, deltaic, and lagoonal systems. Wilcox lignites north of the Trinity River accumulated in river swamps; Wilcox lignites between the Trinity and Colorado Rivers along with the Yegua and Jackson lignites formed largely on delta plains; the Wilcox and Yegua-Jackson lignites south of the Colorado River mainly formed in ancient lagoons. The significance of origin is reflected in size of deposits, in thermal value, and in quality, especially variations of sulfur and ash.

The lignites in the Wilcox Group north of the Colorado River are considered to have the highest commercial value because in comparison with the more southerly formations, they exhibit a higher Btu value, as well as a lower sulfur and ash content.

OPERATIONAL AREAS

Thus, the majority of the proposed and active surface mining for lignite in Texas will concentrate in central East Texas. As of November 1, 1974, active lignite mines are located at Rockdale

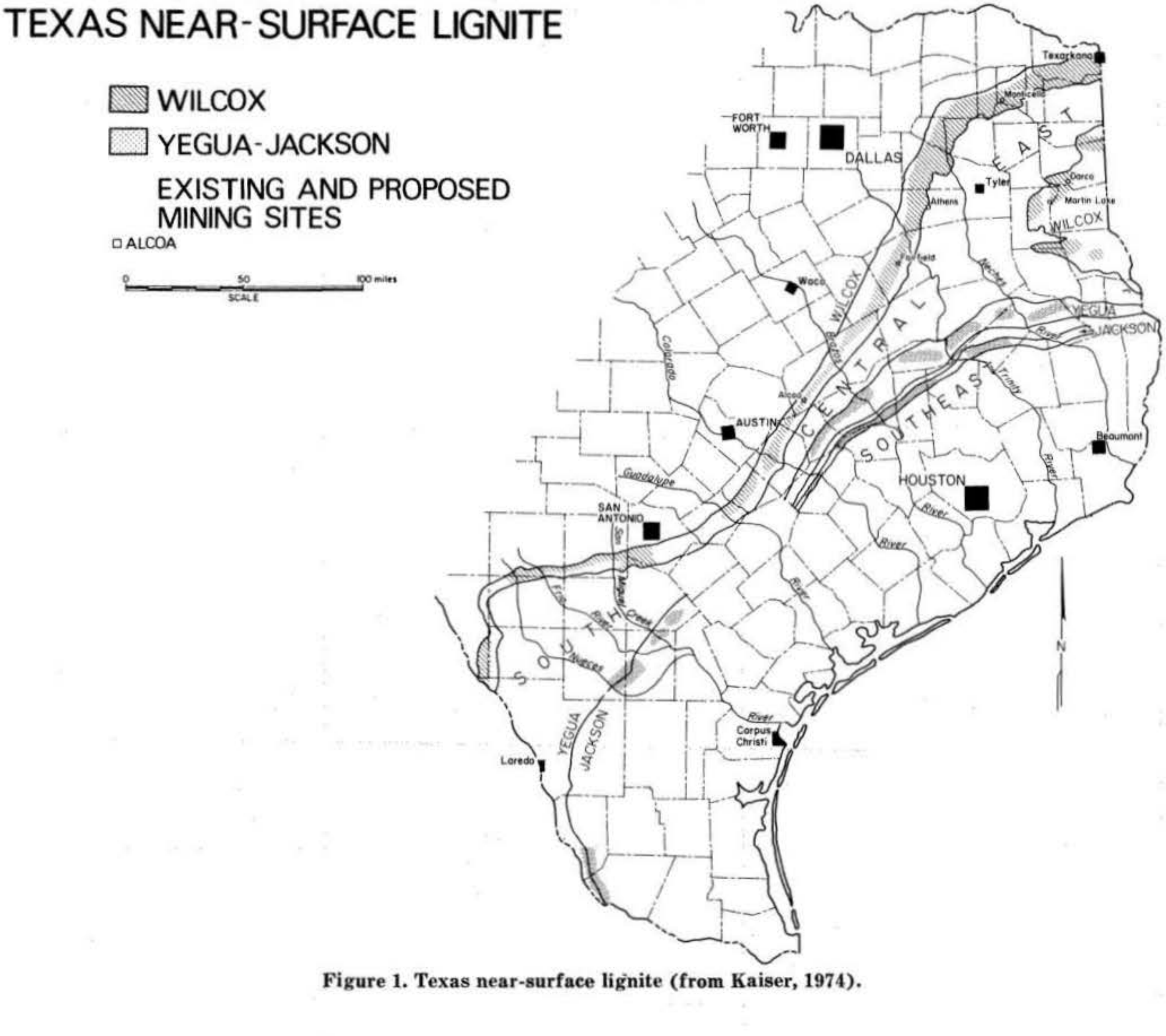

Figure 1. Texas near-surface lignite (from Kaiser, 1974).

(Milam County), Fairfield (Freestone County), Monticello (Titus County), and Darco (Harrison County) as shown in figure 1. Similar operations have been announced for locations at Martin Lake (Rusk and Panola Counties) as well as Athens (Henderson County). The Darco facility recovers the lignite for use in the manufacture of activated carbon, whereas the others are mine-mouth operations for power generation. These operations lie within two major ecological or vegetational regions of the State, namely, the Pineywoods and the Post Oak Savannah areas depicted in figure 2.

THE PINEYWOODS

The Pineywoods area, also known as the Timber Belt, is characterized by gently rolling forested land ranging in elevation from 60.96 to 152.4 m. The southwestern edge of a vast pine hardwood forest that extends to Florida and Virginia, the area is considered to be one of the most mesophytic areas of the State. The 88.9 cm to 127 cm annual rainfall is evenly distributed on a monthly basis. Mild winters, high summer temperatures, low incidence of a persistent wind, and high humidity are representative of this area which enjoys 235 to 265 frost-free days annually.

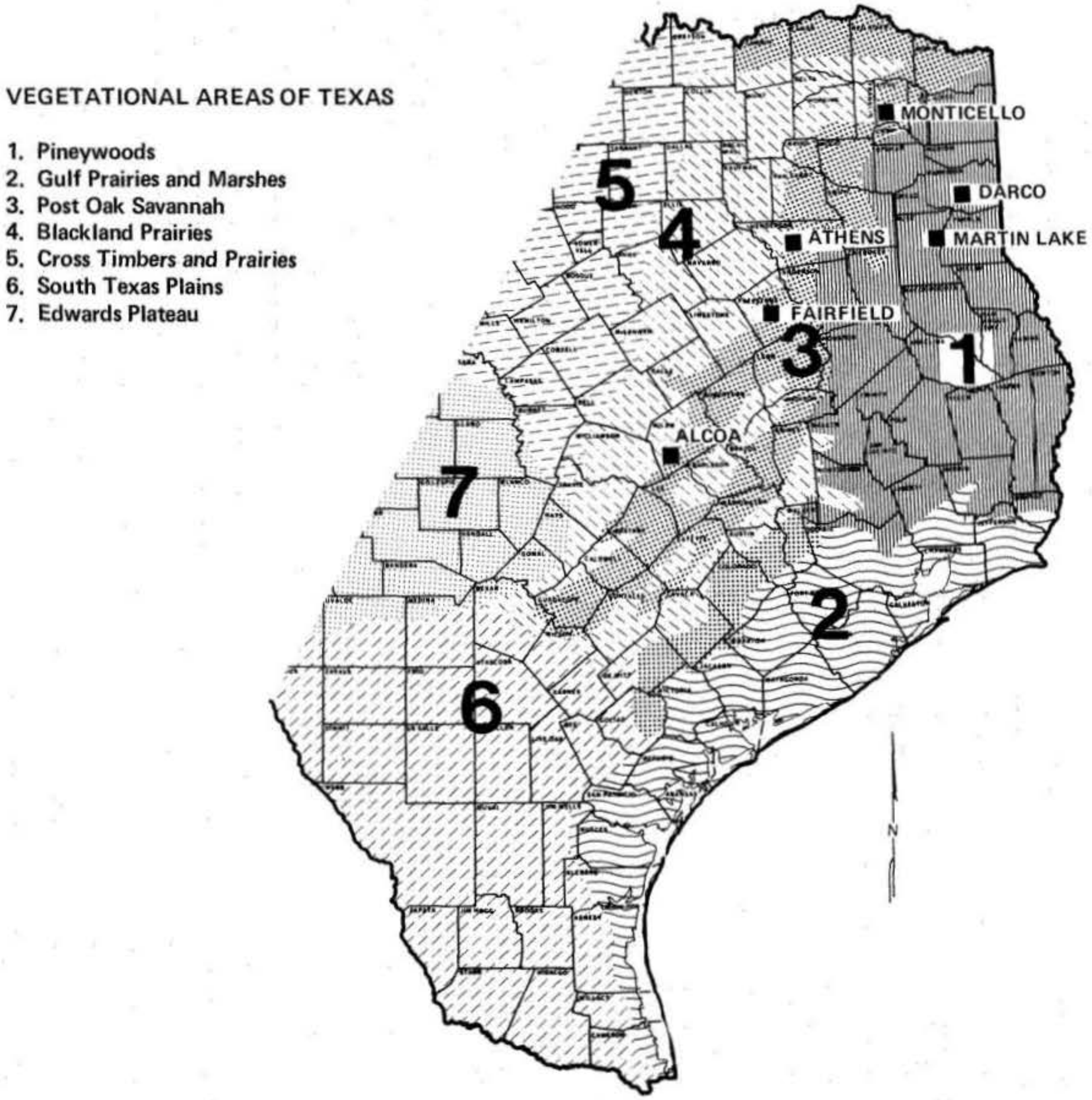

Figure 2. Vegetational areas of Texas (from Gould, 1962).

The soils, usually acid in nature, are light to red sands or sandy loams in the uplands, whereas the bottomlands exhibit acid to calcareous, light-brown to dark-gray, loamy to clayey alluvial soils. Rock outcrops in the region are rare.

The uplands overstory is composed of commercial timber species such as loblolly (*Pinus taeda*), shortleaf (*Pinus echinata*), longleaf (*Pinus palustris*), and slash pine (*Pinus Elliottii*) interlaced with associated hardwoods, mainly oak (*Quercus spp.*). Hardwoods, primarily oak and sweetgum (*Liquidambar styraciflua*) with some pine, bald cypress (*Taxodium distichum*), maple (*Acer sp.*), and hickory (*Carya sp.*) are representative of the bottom-lands of the region. Forage species include bluestems (*Andropogon spp.*), panicums (*Panicum sp.*), lovegrasses (*Eragrostis sp.*), Indian grass (*Sorghastrum sp.*), and various legume species. Many other grasses and herbs found in the area provide a quite complex plant association. Greenbriar (*Smilax sp.*) and yaupon (*Ilex sp.*) are considered to be two of the more common invaders. Introduced species, mostly for grazing, include coastal Bermudagrass (*Cynodon dactylon*), dallisgrass (*Paspalum dilatatum*), and various legumes.

The principal animal species include white-tail deer (*Odocoileus virginianus*), squirrels (*Sciurus sp.*), rabbits (*Sylvilagus sp.*), bobcats (*Lynx rufus*), skunks (*Spilogale sp. and Mephitis sp.*), opposum (*Didelphis marsupialis*), raccoons (*Procyon lotor*), and armadillo (*Dasypus novemcinctus*). Dove (*Zenaidura macroura*), bobwhite quail (*Colinus virginianus*), wild turkey (*Meleagris gallopavo*), hawks (*Accipiter sp., Circus sp., and Buteo sp.*), and various waterfowl species are examples of the diverse bird population in this timberland area.

Forestry and ranching are the primary land uses of the area, with the latter industry increasing annually. Consequently, development of improved pasture has resulted in an increased rate of clearing in the Pineywoods.

POST OAK SAVANNAH

Although its topography is similar to that of the Pineywoods area, the Post Oak Savannah's gently rolling to hilly terrain has an elevation range of 91.44 to 243.84 m above sea level. Authorities differ in their classification of this plant association, as it represents an area of significant mixing of species. Specifically, grasses representing the plains and prairies west of the area are intermixed with the deciduous tree species representative of the mixed forests to the east.

The Post Oak Savannah has an annual rainfall of 88.9 to 114.3 cm with May or June typically being the wettest months. The geography of the region is such, in its north-to-south axis, that winds, humidity, and temperature ranges are quite diverse. But the annual frost-free period of the area is 235 to 280 days.

Representative soils range from light colored sandy loams or sands on the uplands to light-brown to dark-gray sandy loams to clays on the bottomland. All of the soils usually exhibit a slightly acid reaction and a low incidence of rock formations.

Post oak (*Quercus stellata*), blackjack oak (*Quercus marilandica*), and elm (*Ulmus sp.*) are most representative of the upland overstory, whereas in the bottomlands these species are supplemented by some growths of water oak (*Quercus nigra*), hackberry (*Celtis occidentalis*), and elm. The woodland areas are now characterized by many small trees with an average height of 10.7 to 13.7 m, a thick understory or midlayer in most upland woods, and a sparse growth of ground cover made up of forbes and grasses of low nutritional value to domestic livestock and big-game animals. Where scattered stands of timber exist on the uplands, tall bunch grasses prevail.

Climax grasses in the Post Oak Savannah include little bluestem, Indian grass, purpletop spike (*Tridens flavus*), uniola (*Uniola sp.*), and longleaf uniola. As with the Pineywoods area, the introduced grass species of prime importance are coastal Bermudagrass and dallisgrass.

The fauna of the Post Oak Belt is similar to that of the Pineywoods. However, because of the plant association mixtures mentioned earlier, a greater species diversity is found in the former.

Diversified farming and livestock raising comprise the primary economy of the area. However, much of the land, especially the uplands, is leased for deer hunting; hence, land management for wildlife has become a consideration.

RECOVERY TECHNIQUES

These lands will undergo area strip mining as opposed to contour strip mining. The latter method, utilized where the desired layer of lignite is exposed on the side of hills, is characteristic of the Appalachian area. However, the flat to gently rolling terrain of the Texas lands to be mined make area stripping more suitable. This technique employs draglines with large buckets (26.8 to 76.5 m^3) to remove the overburden and smaller shovels to load the lignite into haul trucks. Briefly, a series of long adjacent pits are employed until the lignite deposit is depleted. Whatever the method, obviously the landscape is disturbed, and reclamation of these lands poses a task. But it is not an insurmountable task, as has been demonstrated by the Texas Utilities operation near Fairfield, Texas.

FAIRFIELD RECLAMATION PROGRAM

The Big Brown Steam Electric Station, composed of two lignite-fired 575 megawatt (MW) units, is located near Fairfield, Freestone County, Texas. This facility is owned by Dallas Power and Light Company, Texas Electric Service Company, and Texas Power and Light Company and is operated by Texas Utilities Generating Company. A mine-mouth operation, both the fuel recovery and the power generation are functions of Texas Utilities.

Figure 3 depicts the approximate 6,475.2 hectares of land which will be involved in the operation for its projected 35- to 50-year life. Of this total acreage, 952.3 hectares are involved in the reservoir constructed by the company for cooling water for the plant, 590.9 hectares have been leased for a $1.00 fee to the State of Texas for a park, and approximately 4,654 hectares of land (fig. 3, patterned area) comprise lignite deposits which will be utilized during the next few decades. These deposits, part of the Wilcox Group, lie in the Post Oak Savannah region of Texas. Since these geological and vegetational aspects have been described in other presentations, further description will not be provided.

The company's decision to utilize these lignite deposits to meet the public need for electrical energy was closely followed by another decision, the company's commitment to the public to minimize any detrimental effects on the environment by this mine-mouth operation. A significant aspect of this promise was to restore the land's productivity despite the absence of regulations requiring this action. The approach to meet this commitment by Texas Utilities has been one of research, planning, and application.

With the lignite production operation, the thermal discharges, and stack emissions into the atmosphere, it was apparent that the facility would have an effect on the environment. But just what would the effect be? It was evident that speculation heavily outweighed solid fact where environmental effects were concerned, so as plans were formulated for the construction of the plant, the company began investigating the feasibility of an additional facility. From this, an environmental research program and an accompanying research center were derived.

The basic concept of the program is to determine through bonafide research the effects of the lignite production and powerplant operation on the environment. This is not "company guided" research but rather a program designed by a committee of university professors renowned in land, air, and water research. Once the objectives are defined, the work is assigned to a student as a master's thesis or a doctoral dissertation. A fellowship is provided to the student by the company, and working and living facilities are provided at the Environmental Research Center at the Big Brown Steam Electric Station.

The continuing and varied research projects conducted in the mining area have played a significant role in the land-reclamation program. General discussion of some of this research will be included in the following text, but the various authors and respective universities should be contacted for detailed information.

The fuel engineering staff began planning a mining scheme to facilitate reclamation before the mining equipment was ordered. Core drilling procedures had defined the lignite deposits, and this provided the basis for design. What evolved was an area-stripping mechanism, but with leveling and reclamation to follow the pitch back as shown in figure 4. Thus, size and quantity of the drag-

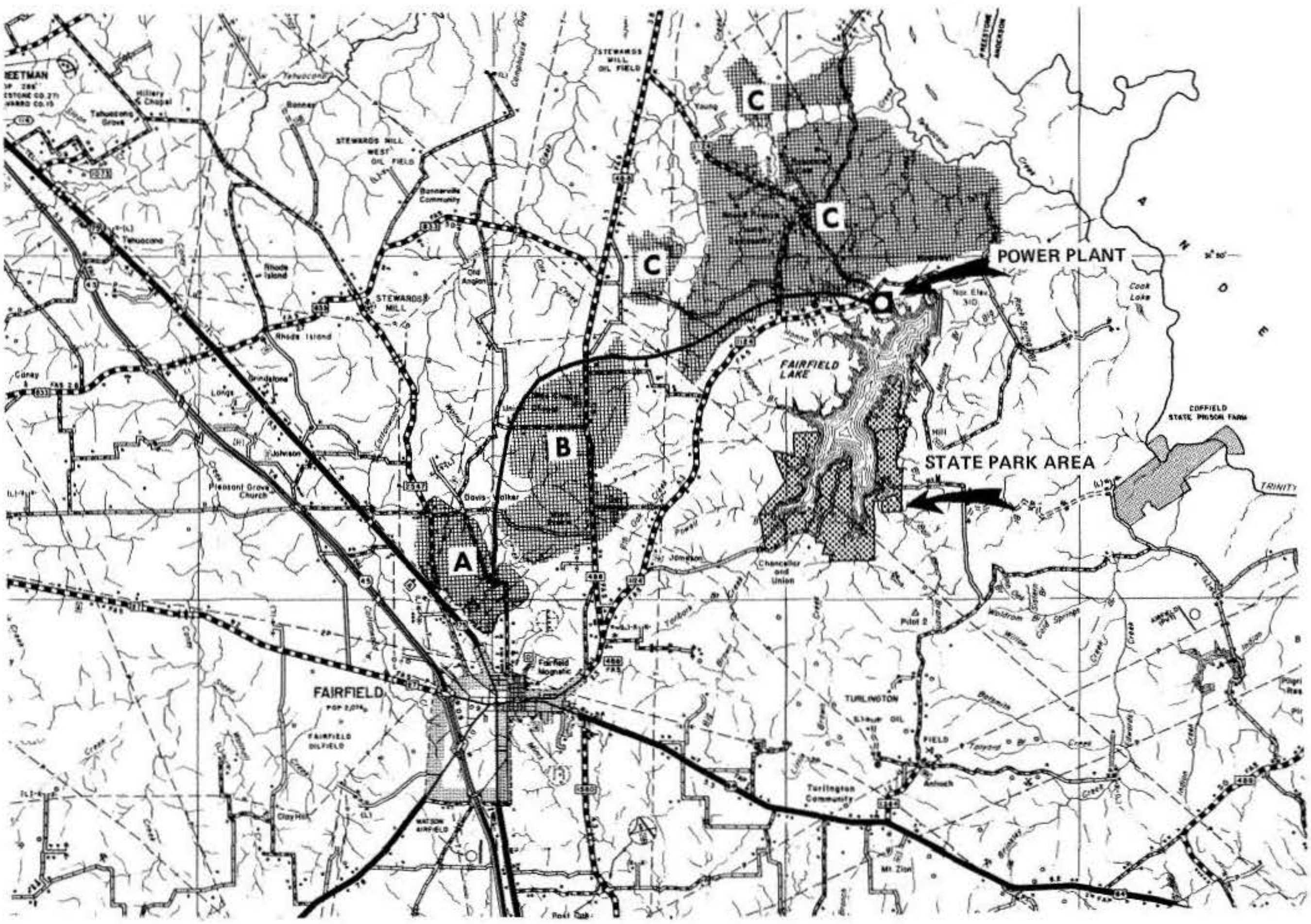

Figure 3. Area map of TUGCO's Fairfield operation. Areas A, B, and C designate lignite deposits.

lines, dozers, and scrapers were based not only on lignite recovery, but also on the spoil placement. For example, the boom length (86.9 m) of the dragline allows the pitched back overburden to be laid out in a lower "herringbone" profile rather than in sharp peaks which would inhibit leveling. A significant factor in this mining plan was to insure that the reclaimed land was returned to its gently rolling topography. These considerations were met through the use of contour maps, aerial photographs, and extensive field work by the survey crew.

Overlapping this planning, an ecological survey of the entire area to be affected by the mining operation was initiated through the environmental research program. The purpose of the study was to document the present flora, fauna, and land use of the area so that the land reclamation would have a baseline with which to work. Truett (1972) found that the diversity, abundance, and distribution of the higher plants as well as the major vertebrate animals in the mining area closely paralleled that characteristic of the Post Oak Savannah area. He reported that four major vegetative types had developed at Fairfield: (1) the upland wooded areas (28 percent of the total lignite mining area); (2) bottomland woods or riparian areas (4 percent of the total area); (3) old fields (8 percent of the area); and (4) improved pastures (57 percent of the area). The remaining percentage represented ponds, small lakes, and so forth. This indicated the land use trend and that the improved pasture acreage was increasing because it represented the primary economy of the area. This obviously influenced the land reclamation planning toward emphasis on revegetation for pastureland or hay farming. However, dedication of suitable areas of reestablishment of wildlife habitat was also an integral part of the land-reclamation strategy. Vegetative-type maps, (fig. 5), prepared in this study were most vital in the planning process, but will also be valuable for future reference in conducting a diverse reclamation program.

In mid-1971, the initial cut or box pit was begun in the "A" area (fig. 3). As soon as the dragline opened the first hundred meters of the 30.48 m wide by 40 m deep pit by pitching the overburden to the outside, soil analysis began. Samples taken from each level of the high wall as well as from a mixture of the profiles were analyzed and found to be similar in pH (range 5 to 7), salinity hazard, and available nutrients. Although low pH soils are considered characteristic of spoil banks, the low sulfur content (0.6 percent) of the lignite did not lend itself to this reaction. Based on this figure, the decision was made not to store the shallow layer of topsoil nor to segregate the other profiles but rather to pitch back the overburden at random. The absence of rock in the overburden also added to the practicality of this decision. This initial area was leveled and disced to prepare it for a short-term testing of grasses. Using the soil analyses, fertilizer quality and quantity requirements were derived. Interestingly, the recommendations received from the soil-testing agency (136 kilograms of 12-12-12, N-P-K, per hectare) were identical to the area soil requirements for improved pasture establishment. Coastal Bermudagrass proved to be the most suitable because of its rapid growth and spreading characteristics. In the fall, these areas were overseeded with a legume, crimson clover (*Trifolium incarnatum*), to provide not only a winter cover but also fertility to the soil with its nitrogen-fixing processes.

However, because of the need for more extensive work, an in-depth analysis of the soils was initiated in early 1972. Angel (1973) determined the physical and chemical properties (the texture, reaction, moisture content, available phosphorus, Kjeldahl nitrogen, and exchangeable cations) of the spoil-bank material as well as of soils on adjacent undisturbed land. The study revealed that the random pitch back and resultant mixture of the different layers of overburden (sands, silts, clays, and shale) produced a sandy clay loam of a slightly acid nature. This composite soil was classified as an Arent, defined by soil taxonomists as strip-mine soil derived from any of all strata between the surface of the Earth and the coal seam. Neutron probe readings for soil-moisture percentage indicated a high moisture-holding capacity in the spoil. Available phosphorous was found in adequate amounts on the spoil bank, and although the mean concentration of nitrogen was somewhat low, it differed little from that of undisturbed areas.

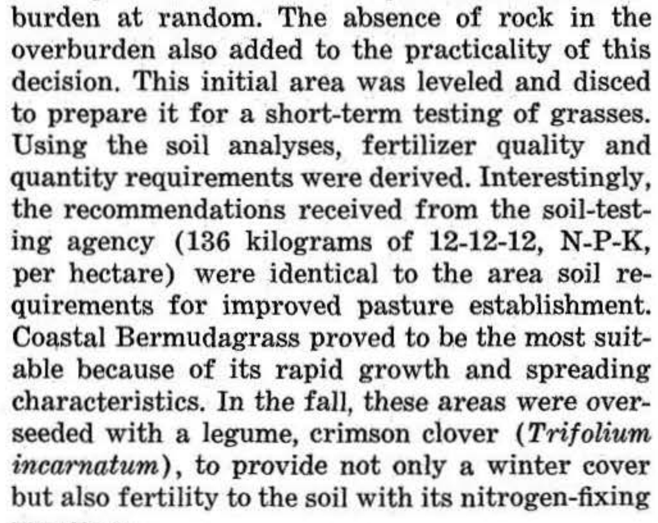

Figure 4. Surface-mining design for Fairfield operation.

The exchangeable cations, magnesium, calcium, potassium, and sodium concentrations were such that Angel reported general improvements in the concentration of these plant nutrients following the mining. In summary, Angel concluded that, "Compared to the adjacent undisturbed land, the spoil bank has a higher productivity potential and is highly suitable for revegetation in all respects."

Supported by this information, the land-reclamation processes continued in the "A" area, and when the "B" area was opened in mid-1972, the same program applied there. Briefly, the process begins as dozers and scrapers work the non-segregated spoil down to contours and drainage patterns benchmarked in premining survey operations. It should be noted that the mean depths of the overburden and lignite seam in these areas have been approximately 12.2 m and 1.82 m, respectively. A 20-percent soil-expansion factor is induced by handling, and although the land elevation is slightly increased, the leveled area maintains its previous rolling terrain and original drainage patterns. No rigid time frame is exercised on the leveling, but weather permitting, this process goes on 24 hours a day, 7 days a week so that the areas are leveled within 6 to 8 months after mining. Following the leveling, the areas are fertilized, disced, and sprigged with coastal Bermudagrass during the spring and overseeded with crimson clover in the fall. The latter provides not only fertility, but also some aesthetic value as the vivid crimson flowers cover the landscape during the early spring. The year following

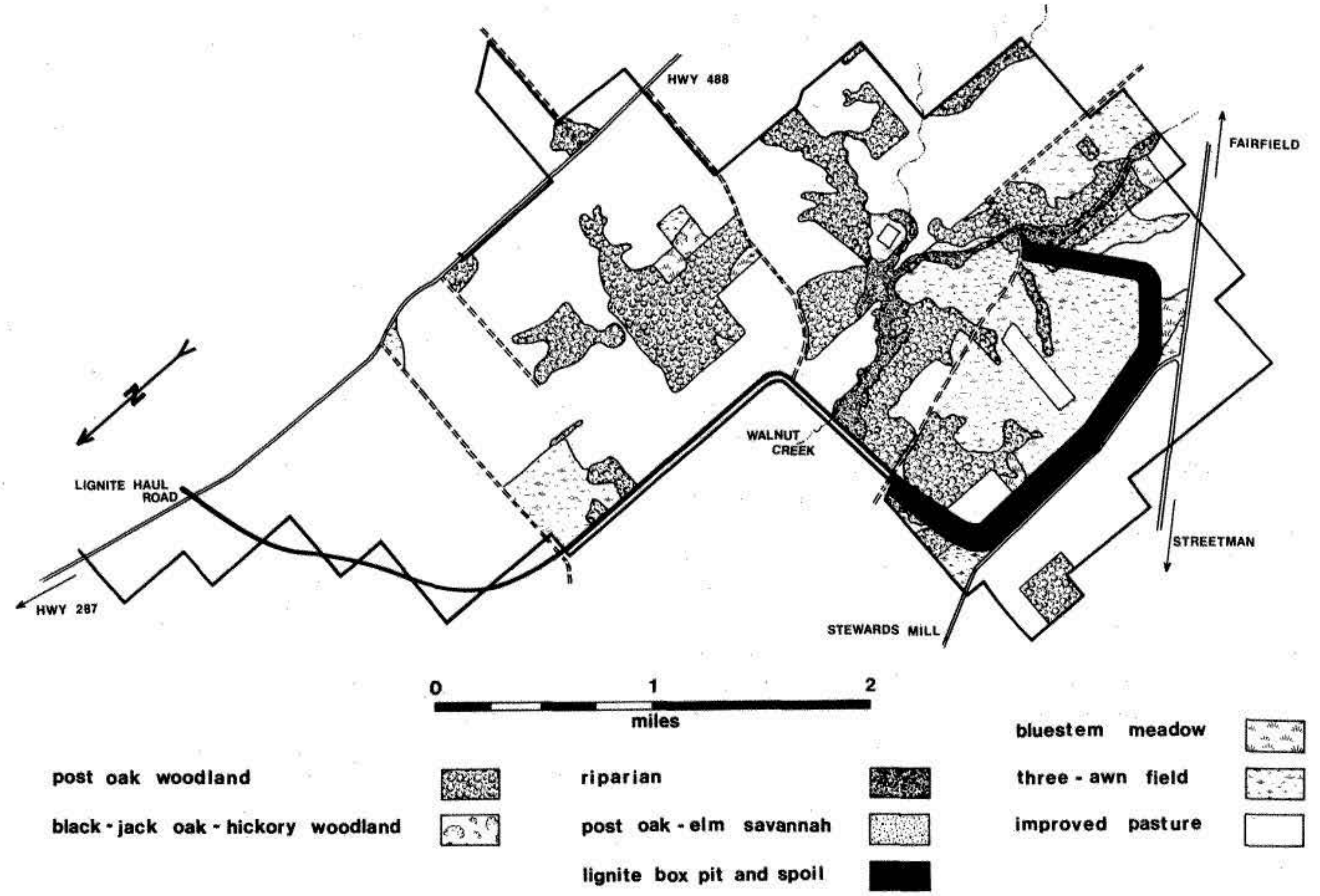

Figure 5. Vegetative type map of Big Brown Steam Electric Station, lignite-mining area, southwest segment (October 1971). From Truett (1972).

planting, the reclaimed land is returned to agricultural production. For example, in 1973, 16,000 bales of quality (12-percent crude protein) coastal Bermudagrass hay were harvested from reclaimed land in the two areas, and in 1974 cattle were grazing 91 hectares of this land which had been surface mined in 1971-72.

Although these cover crops prevent soil erosion and return the land to excellent agricultural use, the program does not end there. As the drainage patterns are reestablished, small lakes (0.80 to 6 hectares) are constructed to provide water for domestic stock and wildlife. The periphery of the lakes as well as the channels leading to them are scheduled for the planting of additional vegetative species to provide both food and cover for wildlife.

Research by Bryson (1973) evaluating early survival, total height, and foliar analysis of 11 tree species grown on the reclaimed land has provided a starting point for the reforestation program. In summary, his results indicated that the spoil banks were as acceptable for the establishment of forest tree species as the undisturbed soil. Since the reforestation was pending completion of Bryson's research, winter 1975-76 will mark the initiation of this program utilizing black locust (*Robinia pseudoacacia L.*), green ash (*Fraxinus pennsylvanica var. lanceolata*), Chinese elm (*Ulmus parvifolia*), sycamore (*Platanus occidentalis*), cottonwood (*Populus deltoides*), sweetgum (*Liquidambar styraciflua*), and, if available, sawtooth oak (*Quercus acutissma*). Supplementing the above plantings will be browse species such as Russian olive (*Elaeagnus augustifolia*), autumn olive (*Elaeagnus umbellata*), and yaupon holly (*Ilex vomitoria*).

Additional research on the reclaimed land includes a row-crop production study, a mammalian-succession study, and a determination of the effects on ground water of sulfides in the overburden.

The reclamation program has been successful, but it has not been without its problems or challenging opportunities.

As the initial cut in the "A" area was being mapped, it became apparent that a property line would inhibit the pitch-back mechanism. The proximity of the line was such that there was not adequate space to pitch all the overburden to the outside and maintain a less than 5-percent slope. The fuel-engineering staff designed the rehandling scheme as shown in figure 6 so that a gentle grade was established over the first six pits.

The next misstep in the land reclamation program occurred when the leveling and revegetation process was conducted too near the active operation. Subsequently, as the heavy equipment leveled the new spoil, the dozers and scrapers had to encroach on freshly sprigged or seeded land. So a buffer zone a minimum of two pit widths was established between the active recovery operation and the reclamation processes.

Then the opposite occurred as the lignite recovery began full-time operation in both areas, and the reclamation lagged considerably more than two pit widths behind the active operation. Contributing factors to this situation included underestimation of equipment requirements, inexperienced equipment operators, and the diesel curtailment. Solutions involved the purchase of additional machinery, dedication of equipment specifically to reclamation, and assignment of personnel so that an informal training program could step up the operators' efficiency. Although the curtailment situation was one which could only be "waited out," storage provisions were made to alleviate such occurrences in the future.

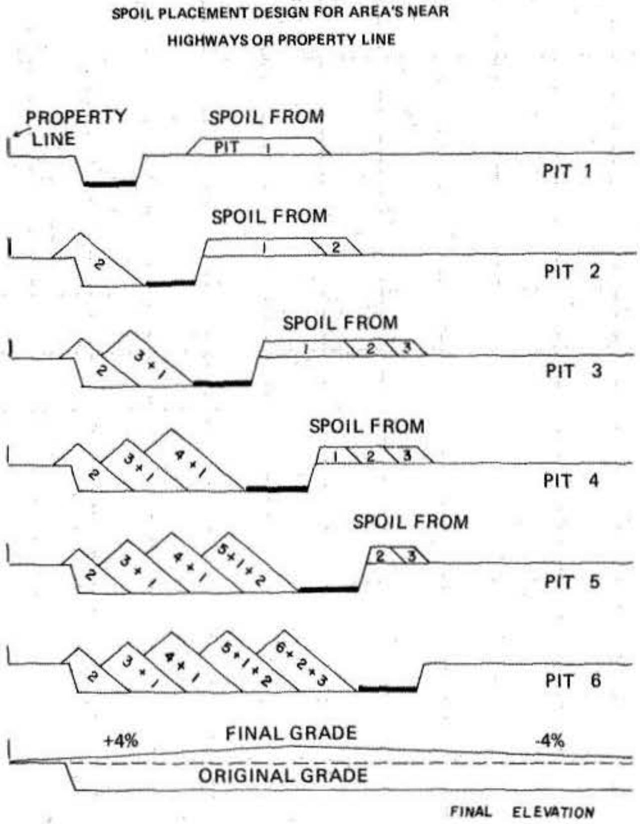

Figure 6. Spoil placement design for areas near highways or property line.

The paper has been a rather brief description of the land-reclamation program at Fairfield, but the life of the operation has been brief also, being only 3 years old. The successes have heavily outweighed the failures to date, and the benign conditions for surface-mining reclamation here should prevent the reversal of this trend. But such welcome factors as low sulfur content in the lignite, absence of extreme slopes to mine, or absence of rock in the overburden did not by themselves make a good reclamation program. They were combined with research and planning with commitment serving as a catalyst.

CONCLUSION

The range of the lignite formations in Texas is such that a variety of climatic, ecological, and economic settings is provided. Reclamation in the Pineywoods and Post Oak Savannah areas can be accomplished with relative ease because of such factors as adequate rainfall. However, lignite deposits do occur in drier southern areas of the State, and reclamation could prove to be more difficult if the proper approach were not employed.

What is the proper approach? Essentially, it is to plan the program on an informed basis. Too often, the only thought given to mined land is to return it to its previous use, but this is not always the most productive, either economically or environmentally. By the same logic, there are unique areas that should not be disturbed or, if so, should be returned as closely as possible to premining condition. In these situations, objective reasoning should not be overruled by emotions, but lack of information can and usually does favor the latter. Therefore, research should be conducted to ensure reclamation programs that will not only meet the needs of each specific area but will also provide a land use selection for future generations.

Achieving this condition requires a commitment by all concerned to remain objective, explore the opportunities afforded, and apply the knowledge gained so that land reclamation in Texas becomes an opportunity—not a problem.

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PHYSICAL AND CHEMICAL PROPERTIES OF LIGNITE SPOIL MATERIAL AS IT INFLUENCES SUCCESSFUL REVEGETATION

F. M. Hons,[1] P. E. Askenasy,[1] L. R. Hossner,[1] and E. L. Whiteley[1]

ABSTRACT

Lignite surface-mine spoils at Fairfield, Texas, contain more than adequate amounts of calcium, potassium, and magnesium to sustain plant growth, but nitrogen and phosphorous must be added in order to obtain proper revegetation. Forage grasses and legumes including NK-37, coastal Bermudagrass, Bahiagrass, Kleingrass, alfalfa, Uchi arrowleaf, and crimson clovers have been successfully established on the reclaimed soils. Corn, grain sorghum, and soybeans have also been established, with grain sorghum being the most promising of the row crops.

The sulfate concentration in the mined soils increases with time after mining due to the oxidation of pyritic minerals near the soil surface. Pyrite oxidation results in increased soil acidity.

Biological oxidation of $NH_4{}^+NO_3{}^-$ via the nitrification pathway is restricted in these mined soils, thereby affecting the use and efficiency of ammonium forms of fertilizer.

INTRODUCTION

The Big Brown Steam Electric Generating Station, owned and operated by Texas Utilities Generating Company and located in Freestone County, Texas, is fueled by a surrounding lignite surface-mining operation. This mining operation offered the opportunity to study environmental factors associated with the chemical and physical properties of the overburden spoil banks and their subsequent revegetation. The research efforts reported in this paper were initiated at the Big Brown reclamation site in 1973 to not only revegetate the mined areas, but to also determine the feasibility of producing agricultural crops.

The mineable lignite reserves in Texas are located primarily in the claypan and East Texas Timberlands Land Resources areas (fig. 1). The surface-lignite mining operation in Freestone County is situated entirely in the claypan area of Texas. The major soil association in the mining area is Edge-Tabor with competing associations being Crockett-Wilson and Lakeland-Cuthbert (fig. 2). The mining areas have been designated "A", "B", and "C". The research in this report was conducted in areas "A" and "B". Mining has begun on the "C" area. The majority of these soils have sandy loam surface horizons above dense, clayey, plastic subsoils. These soils have not been extensively used for intensive agriculture because of drought, poor physical properties associated with the claypan, and low fertility. Row-crop agriculture is essentially nonexistent. Vegetation in the unmined areas consists of native grasses and improved pastures, intermixed with scattered post oaks and mesquite. The average annual rainfall of the area is 38.5 inches with approximately 20 inches falling from April through September. The distribution of rainfall throughout the warm growing season of the year is extremely important in the determination of crop yields.

TEXTURE AND WATER-HOLDING CAPACITY

The surface-mining process, involving the mixing of the entire soil profile above the mineable lignite beds, has resulted in soils of an intermediate texture often approximating silty clay loams and clay loams (table 1). Because of an increase in silt and clay in the leveled mine spoils, the water-holding capacity of the surface of the mined soil is increased when compared with unmined surface soils (table 2). Soil samples from

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the "A" and "B" areas, mined in 1972 and 1973, respectively, and a fresh spoil sample mined in 1975 exhibited a field moisture capacity of nearly 30 percent, whereas an unmined surface soil retained only approximately 17-percent moisture at the minus one-third bar potential.

AVAILABLE SOIL NUTRIENTS

The sandier textured surface horizons of the unmined soil are generally characterized by low amounts of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, P, and N. The low levels of the first four elements are attributed to leaching by rainfall and plant uptake. The low supply of phosphorus is due to the coarse texture of the soil and a lack of phosphorus in the parent materials from which the soils were formed. Nitrogen is in short supply as in most other Texas soils.

The surface-mining process has increased the content of exchangeable bases in the mined soils by the mixing and movement to the surface of cations which have leached into lower horizons or were released from parent materials at lower soil depths (table 3). The exchangeable Ca^{2+}, Mg^{2+}, and K^{+} contents of the spoil material are high, normally being greater than 6,000, 500, and 300 kilograms per hectares (kg/ha), respectively. Available nitrogen and phosphorus remain low to very low and must be added in sufficient amounts for adequate revegetation. The mineralogy of the soil is primarily montmorillonitic with lesser amounts of kaolinite, mica, and vermiculite also being present.

Figure 1. Location of major lignite deposits in relation to the land resource areas in Texas.

Table 1. Particle-size distribution of mined and unmined soils.

Sample	Particle Size Percent Sand	Percent Silt	Percent Clay	Textural Class
"A" area	2.8	48.2	49.0	Silty clay
"B" area	0.5	67.8	31.7	Silty clay loam
Unmined surface soil	59.5	31.6	8.9	Sandy loam

Table 2. Percentage moisture of mined soils at field capacity (minus one-third bar).

Soil	Moisture (Oven dry soil basis)
"A" area	29.5
"B" area	28.2
Fresh spoil	29.3
Unmined	16.9

CrW - CROCKETT WILSON SOILS
  Crockett—dark-brown to yellowish-brown friable acid sandy loam to clay loam surface, 7-12 inches thick over mottled yellowish-brown and red, very firm and very plastic blocky acid clay. Surface soil very tight and crusty when dry. Calcium carbonate concentrations below 50 inches. Nearly level to gently sloping (1-5% slopes).
  Wilson—very dark gray to gray or grayish-brown acid sandy loam to clay loam surface, 4-12 inches thick, over dark-gray, very firm blocky to massive neutral clay; alkaline to calcareous below about 30 inches. Surface soil very tight and hard when dry. Nearly *level to gently sloping* (0-4%).

ETa - EDGE-TABOR FINE SANDY LOAMS
  Edge—grayish-brown to pale-brown acid fine *sandy loam surface*, 4-12 inches thick over mottled red, very firm compact blocky acid clay grading with depth through a mottled reddish-brown to a brownish-gray clay or sandy *clay. Surface soil crusty and tight* when dry. Nearly level to gently sloping (1-5% slopes).
  Tabor—pale-brown acid sandy loam to loamy sand surface, 8-15 inches thick, *over* brownish-yellow or yellowish-brown, very firm and very plastic blocky acid clay with or without reddish-brown mottling that grades into mottled yellowish-brown and light-gray *clay*. Surface soil crusty and tight when dry. Nearly level to gently sloping (0-3% slopes).

TKa - TRINITY-KAUFMAN SOILS
  Trinity—very dark gray crumbly calcareous clay surface, 20-40 inches thick, over dark-gray, firm calcareous clay. Moderately well drained, nearly level floodplains.
  Kaufman—dark-gray to black, crumbly, slightly acid clay surface, 10-15 inches thick, over dark-gray, firm subangular blocky noncalcareous clay; some small areas of clay loam. Moderately well drained; level floodplains.

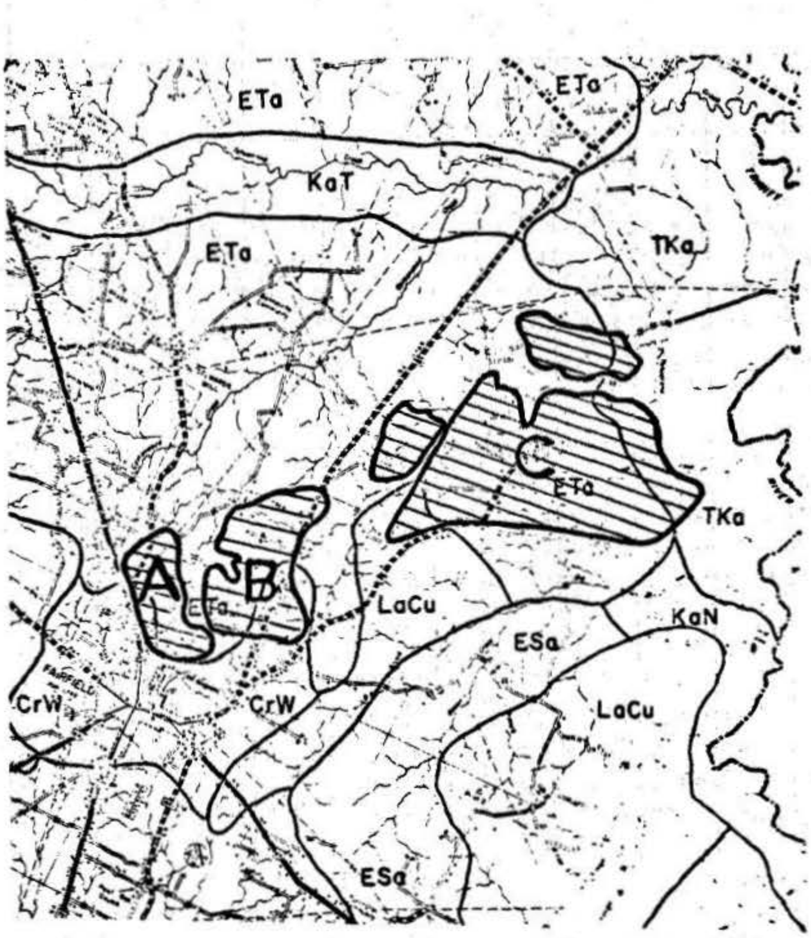

Figure 2. Major soil series near fairfield in Freestone County and the location of the lignite deposits presently being mined. The A, B, and C mining areas are referred to in the text.

ACIDIFICATION IN MINE SPOIL

Pyrite (FeS_2) is generally found in varying quantities in association with the lignite. When exposed to the atmosphere, the sulfide in the pyrite oxidizes to the SO_4^{2-} form. Exchangeable SO_4^{2-} (Bardsley and Lancaster, 1965) is increasing in the soil with increasing time intervals after mining (fig. 3). The "A" area soil, mined in 1972, has an SO_4^{2-} concentration of more than 6,000 parts per million (ppm) at approximately the 35 cm depth with lesser amounts being found in areas mined in 1973 and 1975. The most recently mined soil shows that the oxidation of $S \rightarrow SO_4^{2-}$ and the concurrent movement of SO_4^{2-} into the profile has not begun to a considerable extent. The downward movement of SO_4^{2-} is marked in the other two profiles, however, with a concurrent decrease in soil pH. The area mined in 1972 also possesses more SO_4^{2-} because of a higher pyrite content and more residual lignite than is commonly found in other areas.

The oxidation of sulfur found in these mined soils results in more acid soil conditions. The oxidation of pyrite and the subsequent hydrolyses of ferrous sulfate and hydroxide can be illustrated by equations 1, 2, and 3.

$$FeS_2 + 3\tfrac{1}{2}O_2 + H_2O \rightarrow FeSO_4 + 2H^+ + SO_4^{2-} \quad (1)$$
$$FeSO_4 + 2H_2O \rightarrow Fe(OH)_2 + SO_4^{2-} + 2H^+ \quad (2)$$
$$Fe(OH)_2 + H_2O \rightarrow Fe(OH)_3 + H^+ \quad (3)$$

Theoretically, for each mole of pyrite oxidized, 5 moles of acid (H^+) and 1 mole of SO_4^{2-} can be produced (Caruccio, 1967). A portion of the SO_4^{2-} produced also results from the oxidation of sulfur in the lignite located on or near the soil surface after mining. This oxidation most likely produces less acidity per mole of SO_4^{2-} produced than does pyrite. A strongly negative correlation exists between the amount of SO_4^{2-} produced and the pH of the soil (fig. 3). As the SO_4^{2-} concentration in the soil increases, the soil pH decreases. When this decrease is great enough, aluminum and manganese may be solubilized from soil clays in amounts large enough to become toxic to plants.

Soil reaction is generally acidic, but highly variable, in sampled areas mined before 1975. Soil pH may range from 3.8 to 6.0 within a 1 acre area, denoting the extreme heterogeneity of these mined soils. The average soil pH of one area mined in 1972 is 4.8, whereas that of one area mined in 1973 is 5.2. The pH value of a spoil mined in 1975 is 7.6, whereas that of an unmined surface soil is 6.3. (These values were obtained in small areas under cropping study and may not be totally representative of all areas mined during any given period.) The pH values of the surface soil in the areas mined in 1972 and 1973 have not declined significantly during 1975-76. These data support the theory of a rapid initial oxidation of the sulfur in pyrite and lignite near the soil surface resulting in a rapid drop in soil pH. The lowest pH that will be obtained with the oxidation of sulfur in more resistant pyrite minerals or in those minerals located below the soil surface in less favorable oxidizing environments is not presently known. Sulfate, pH, and total acidity in the soil profile should be monitored to enable an estimate of final soil pH and acidity.

EXCHANGEABLE ALUMINUM

Exchangeable aluminum in the mined soils increases with decreasing pH as might be anticipated (Hsu, 1963). Most reclaimed soils sampled contained less than 1.0 milliequivalent (meq) Al/100g of soil, although one sample with a pH of 3.8 contained 4.5 meq Al/100g (table 4). This amount of exchangeable aluminum should not be detrimental to the growth of most crops, however.

NITROGEN REACTIONS IN MINED SPOIL

Nitrification, the biological oxidation of $NH_4^+ \rightarrow NO_3^-$ brought about by certain special-purpose bacteria, appears to be severely retarded in these soils. The complete reaction is a two-step process and is shown in the following equations.

$$2NH_4^+ + 3O_2 \xrightarrow[\textit{Nitrosomonas}]{\text{Biological oxidation}} 2NO_2^- + 2H_2O + 4H^+ + \text{energy} \qquad (4)$$

$$2NO_2^- + O_2 \xrightarrow[\textit{Nitrobacteria}]{\text{Biological oxidation}} 2NO_3^- + \text{energy} \qquad (5)$$

This result might be expected because of the mixing of the soil profile and the extremely low amount of organic matter present in the surface soil after mining. Preliminary data have shown that almost all the organic carbon determined in these surface soils may be attributed to residual lignite. Surface-soil samples were taken from areas mined in 1972, 1973, and 1975 ("A", "B", and recent spoil area, respectively), along with an unmined surface soil. Ammonium sulfate was added to each soil at a rate of 100 ppm nitrogen. The samples were brought to a moisture content of field capacity and were incubated at 25°C for periods ranging from 1 to 16 weeks. At the end of each incubation period, the soils were analyzed for NH_4^+, NO_2^-, and NO_3^-. The unmined soil nitrified approximately 97 percent of the applied NH_4^+ after 8 to 10 weeks, whereas the mined soils converted a maximum of 7 percent of the applied NH_4^+ to NO_3^- during the 16-week incubation period (fig. 4). To substantiate these findings in the field environment, soil samples were taken in January 1976 from forage fertility plots which had received 224 kg of N/ha as NH_4NO_3 and from plots receiving no nitrogen. The samples were analyzed for exchangeable NH_4^+ and NO_3^- at soil depths of 0 to 1.3, 1.3 to 2.5, 2.5 to 5.1, and 5.1 to 7.6 cm. When amounts of nitrogen found in the soils receiving no added nitrogen were subtracted from the soils receiving 224 kg

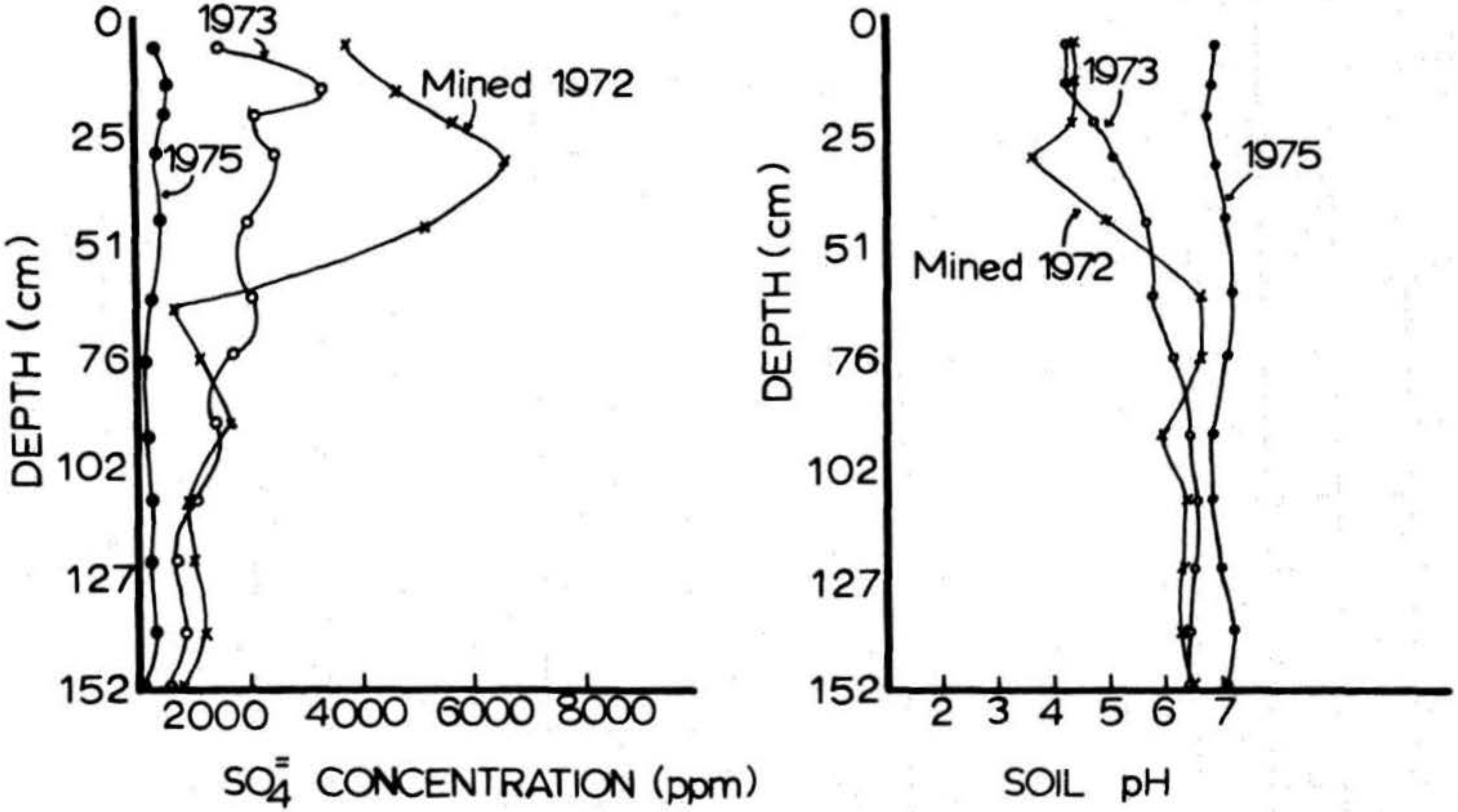

Figure 3. Soil pH and sulfate concentrations in surface mined spoil banks at various times after mining. Determinations were made in 1976.

N/ha, 57 percent of the applied NH_4^+ was recovered within the first 1.3 cm of soil (table 5). The next 1.3 cm increment contained 18 percent more of the applied NH_4^+. When the entire 7.6 cm depth was summed, 90 percent of the applied NH_4^+ was recovered. Therefore, the applied NH_4^+ was not being converted to NO_3^- in the field, nor was it being utilized by the forage. The fertilizer was surface applied with no incorporation since it was added to a grass sod. Also, these soils tend to be droughty during the summer months and have little rooting activity within the first 2.5 cm of soil. These reasons may account for the lack of uptake of NH_4^+ by the crop. Nitrate (NO_3^-), on the other hand, had either been removed by the crop or had moved below the 7.6 cm sampling zone (table 6). These data suggest that with the usage of NH_4NO_3 as a nitrogen source, approximately 50 percent of the applied nitrogen is unavailable to plants because of the low use efficiency of the added NH_4^+. Nitrate forms of fertilizer, such as $Ca(NO_3)_2$ or KNO_3, could be used as a substitute for NH_4NO_3 in order to increase the use efficiency of added nitrogen. Precautions such as employing split applications of the fertilizer during the growing season should be used to prevent loss of NO_3^- caused by runoff or leaching. These findings may be applicable to many surface-mined soils in the State of Texas.

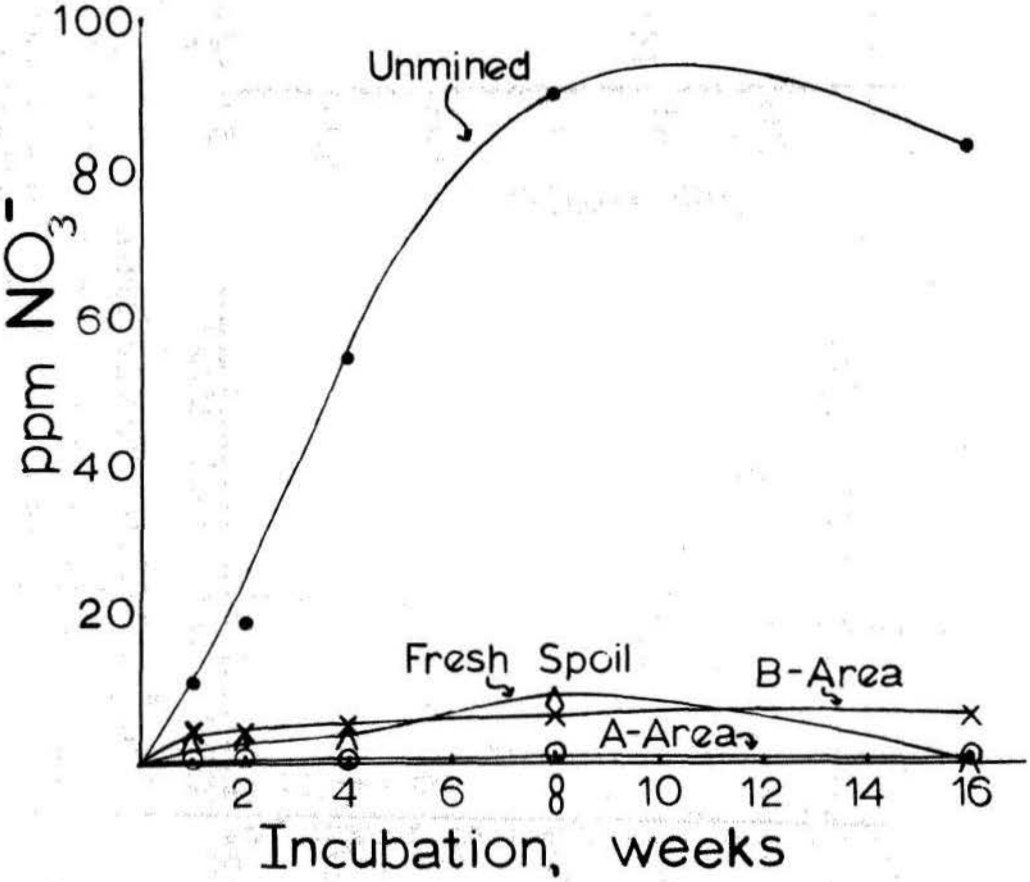

Figure 4. Nitrification of applied NH_4^+ to NO_3^- when soils were incubated for 16 weeks at 25°C and optimum moisture.

SOIL AERATION

Adequate soil aeration in spoil-bank material for maximum crop production is a factor often overlooked during reclamation. Water and nutrient uptake by plant roots is restricted as the soil oxygen content declines below 10 percent (Lal and Taylor, 1970; Stolzy and others, 1961) resulting in decreased root proliferation and crop growth (Patrick and others, 1969, 1973). Diffusion of oxygen into a soil profile may be inhibited by a high moisture content, by compaction or increased bulk density, or by crusts that form following intense rainfall (Gornat and Goldberg, 1971). The bulk density of the mined soils is increasing because of machinery compaction and settling, and soil crusts formed by the dispersion of soil particles upon raindrop impact are prevalent. Crusting is aggravated by the low amount of organic matter found in these soils which normally would serve as a cementing agent to bind soil particles, thereby decreasing crust formation. Soil-aeration monitors consisting of perforated plastic bottles were installed at various depths ranging from 15 to 122 cm within the soil in Bermudagrass sod and bare soil areas. Copper tubing, 1/8 inch outside diameter, extended from the soil surface into the bottles. Cylindrical holes, approximately the diameter of the bottles, were bored to the desired depth. The bottle with the tubing was installed, and one layer each of plaster of paris and paraffin was applied to the top of the bottle to ensure a seal from atmospheric oxygen. The remainder of the bore hole was then backfilled with the soil which had been initially removed. Finally, a serum cap was affixed to the end of the tubing extending above the soil surface to prevent the movement of atmospheric oxygen into the tubing. A special stainless steel cell was designed to thread onto the tip of an oxygen electrode probe for the field measurement of soil oxygen. Measurements were initiated in January 1976 and have continued through the present. In almost all instances, the percentage of oxygen in the soil decreases with depth (table 7). Readings were generally higher in January, but decreased through February and April due to high rainfall during the latter 2 months. The bare soil monitors generally contained higher concentrations of oxygen with depth than did the monitors placed in the grass plots. The bare soil profiles were most likely drier than the grass profiles due to surface closure, decreased infiltration, and increased runoff during heavy rainfall. The grass roots, on the other hand, created channels for the movement of water into the soil, resulting in a wetter soil profile. Nonetheless, the soil oxygen concentration was usually below 10 percent at the 46 cm level, possibly resulting in decreased crop growth (Hopkins and Patrick, 1969). The percentage of oxygen in the soil will increase as the soil profile dries during the summer months.

Table 3. Concentrations of exchangeable bases in the surface of a site in the "B" area mined in 1973.

Basic Cation			
Ca^{2+}	Mg^{2+}	K^+	Na^+
kg/ha			
6242 ± 418	550	324 ± 24	507 ± 75

Table 4. Exchangeable aluminum concentrations in mined soils as influenced by soil pH value.

Soil pH	Exchangeable Aluminum meq/100g soil
6.0	0.00
5.2	0.00
5.0	0.00
4.7	0.00
4.5	0.02
4.3	0.02
4.3	0.58
4.3	0.88
4.2	0.73
4.2	2.01
4.1	0.15
4.0	1.34
4.0	1.42
3.8	4.50

Table 5. Exchangeable NH_4^+ recovered from NK-37 forage plots 20 weeks after application.

Depth,	Applied N, kg/ha		Difference,	Recovery of applied
cm	224	0	ppm	NH_4^+, percent
	N, ppm as NH_4^+			
0-1.3	42.1	13.7	28.4	57
1.3-2.5	20.2	11.4	8.8	18
2.5-5.1	15.3	11.8	3.5	7
5.1-7.6	12.8	9.0	3.8	8

Table 6. Exchangeable NO_3^- recovered from NK-37 forage plots 20 weeks after application.

Depth,	Applied N, kg/ha		Difference,	Recovery of applied
cm	224	0	ppm	NO_3^-, percent
	N, ppm as NO_3^-			
0-1.3	5.6	5.4		0
1.3-2.5	4.2	4.4		0
5.1-7.6	4.6	3.5	1.1	2
2.5-5.1	3.0	2.1	1.1	2

Forages such as coastal Bermudagrass are normally used in Freestone County to revegetate the spoil banks following mining. Various forage species including coastal Bermudagrass, Bahiagrass, Kleingrass, NK-37 (a nonrhizomatous variety of common Bermudagrass), Uchi Arrowleaf clover, crimson clover, and alfalfa have been established in fertility trials on the reclaimed overburden material. Proper seedbed preparation and fertilization is essential for adequate stand densities of forage.

In the year of establishment of the forage plots (1975), NK-37 yielded 2,900 kg/ha of dry matter when fertilized with 224 kg N/ha as NH_4NO_3 and 134 kg/ha of P_2O_5. Nitrogen applied at 112 kg/ha along with 134 kg/ha of P_2O_5 yielded 1,000 kg/ha of forage dry matter while treatments of 0 kg N/ha and the above rate of phosphorus produced only 224 kg/ha of dry matter. These results suggest that although phosphorus must be added for growth and stand survival, nitrogen may be the dominating factor in production of grasses.

Legumes, however, may require larger additions of phosphorus than nitrogen because the symbiotic relationship that exists between legumes and certain nitrogen-fixing bacteria supplies the majority of the plant's nitrogen requirement. Uchi Arrowleaf clover produced 36,100 kg/ha of green matter when fertilized with 112 kg N/ha as NH_4NO_3 and 224 kg of P_2O_5/ha. In contrast, 29,400 kg/ha were produced with the same rate of nitrogen, but only half the rate of phosphorus, whereas only 14,000 kg/ha of green matter were produced at the same rate of nitrogen with no phosphorus being applied. The highest yield of crimson clover was 3,300 kg/ha of green matter yield.

Coastal Bermudagrass yielded 1,700 kg/ha of dry matter in the year of establishment when fertilized with 336 kg/ha as NH_4NO_3 and 269 kg P_2O_5/ha. Excellent surface coverage was achieved within the same season with the high rates of fertilizer application. Poor grass cover was achieved when nitrogen and phosphorus fertilizer was not applied or when they were applied at low rates. Kleingrass, receiving the high amount of fertilizer, yielded 1,120 kg/ha of dry matter that same season. Bahiagrass was not cut for yields the first year because of poor surface coverage which was attributed to the large amount of dormant seed found in Bahia.

Table 7. Percentage oxygen at various depths in mined soil atmosphere.

Crop	Depth, cm	January	March	April	May
		Month			
NK-37	15.2	18.4	12.1	13.6	17.4
	30.5	13.2	4.2	7.0	8.4
	45.7	11.5	6.3	6.4	8.7
	61.0	7.3	1.0	3.4	3.4
	91.4	6.0	3.8	4.8	1.5
	122.0	6.3	1.0	3.4	1.7
Coastal	15.2		9.2	14.9	20.1
	30.5		10.2	10.7	16.1
	45.7		6.1	7.4	11.4
	61.0		0.0	7.8	11.4
	91.4		0.5	3.6	1.3
	122.0		0.0	5.7	5.1
Bare soil	15.2	20.1	10.6	15.8	18.9
	30.5	17.0	7.5	10.3	12.2
	45.7	14.8	7.2	10.4	7.9
	61.0	11.5	6.2	9.3	10.8
	91.4	9.3	5.8	8.6	7.8
	122.0	5.9	6.5	7.0	5.9

Only one cutting of each of the grasses has been made thus far in 1976. This first clipping, however, has produced more forage than all cuttings for 1975 combined. For example, at the highest fertilizer rates reported for each grass, NK-37, coastal Bermudagrass, and Kleingrass

Table 8. Average dry matter and grain yield ranges of row crops in 1974 and 1975.

Crop	1974 No Fertilizer (kg/ha)	1974 N + P[a] (kg/ha)	1975 No Fertilizer (kg/ha)	1975 N + P (kg/ha)
CORN				
Grain		0	0	2885
Dry matter	50	1872	727	8360
GRAIN SORGHUM				
Grain		0[b]	0	4153
Dry matter	376	4417	437	8833
SOYBEANS				
Hill	12.5	176	213	753
Lee	169	395	188	753

[a] N applied at a rate of 168 kg N/ha as NH_4NO_3 and P was applied at a rate of 112 kg P_2O_5/ha as ordinary superphosphate.

[b] Severe bird damage prevented grain harvest.

yielded 4,900, 5,400, and 9,900 kg/ha of dry matter, respectively. These initial yields for 1976 make the potential total yields extremely promising.

Row crops (corn, grain sorghum, and soybeans) have also been established in fertility trials, with each crop showing significant responses to applications of both nitrogen and phosphorus. Crop yields for the 1974 and 1975 seasons are presented in table 8. Where two numbers occur in the same row, the number to the left represents the mean treatment yield where no nitrogen or phosphorus was applied, whereas the number to the right is the mean treatment yield where 168 kg N/ha as NH_4NO_3 and 112 kg P_2O_5/ha were added. Crop yields were poor in 1974 because of an extended drought which occurred throughout the growing season. For both years, the highest fertilizer application rates also corresponded to the highest yields, indicating that still higher yields might be achieved with larger fertilizer additions. Sorghum appears, from an economic viewpoint, to be the most promising row crop tested.

CONCLUSIONS

1. The spoil material, because of a more favorable texture than the unmined soil, has greater water and nutrient holding capabilities.
2. The spoil material contains adequate amounts of Ca, Mg, and K to sustain plant growth.
3. The spoil material is deficient in organic matter, phosphorus, and nitrogen. These deficiencies can be corrected with proper fertilization and cropping systems.
4. Acidification of the soil surface layers is caused by the oxidation of sulfides to sulfate.
5. Nitrification is retarded in the mined soils with a low use efficiency of applied NH_4.
6. The spoil material has the tendency to form surface crusts which inhibit oxygen diffusion and seedling emergence.
7. On the average, Freestone County receives adequate rainfall for revegetation with a reasonably good distribution.
8. With proper fertilization and management, the yield potential of forage grasses, legumes, and grain sorghum on the mined soils appears excellent.

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HYDROGEOLOGIC FACTORS WHICH INFLUENCE THE RECLAMATION OF LIGNITE MINES

D. Pennington[1]

ABSTRACT

Large lignite reserves and the resultant rapid expansion of mining activities in response to energy needs increase the potential for contamination of surface waters and ground waters in the Gulf lignite province. Reclamation of these new mine areas is complicated by the variations in climate of the region. Lignite deposits of Texas, in particular, are emphasized.

Surface mining can intercept aquifers and disrupt the ground-water flow pattern. The magnitude of this disruption is dependent on the lateral extent of the aquifer and whether the aquifer is a major or minor source of water. The hydrologic impact of mining activities in semiarid to arid environments and the hydrologic changes associated with surface mining are related in this paper to reclamation. Factors discussed include the hydrologic effects of shaping spoil piles, movement of water in underground mines, subsidence fractures, and water requirements for revegetation. Reclamation also can cause blocking or disruption of the ground-water system. Techniques to minimize this disruption are discussed including the construction of artificial aquifers.

INTRODUCTION

The purpose of this paper is to identify hydrogeologic factors which may affect reclamation of lignite mines in the Gulf lignite province. Potential problems discussed do not mean that these problems are common or that vast areas of lignite deposits may not be available to meet energy demands. The hydrogeologic problems identified are the factors which should be evaluated to ensure the success of any reclamation plans.

Problems of mining coal vary widely in the various coal provinces of the United States. In the eastern United States, large amounts of iron sulfides in coal and the overlying rocks, topography, and a complex structural geology contribute to the major problem of acid mine drainage. The rocks in the eastern part of the province have been greatly disturbed by folding and faulting, particularly in the anthracite region. In the western half of the province, the coal-bearing rocks have been subjected to less deformation. The province is mountainous and contains numerous folds, faults, and steeply dipping strata. Although mountain peaks often are not more than 5,000 ft high, a well-developed drainage system has caused a relatively rough topography. Conversely, the Gulf lignite province is a coastal plain composed primarily of unconsolidated detrital sediments and limestones. Essentially a lowland area, most of the area is gently sloping to relatively flat land.

Lignite mining in the Gulf province can avoid many of the problems associated with coal mining in the eastern and interior coal provinces. In addition to the obvious differences in topography, climate, and geology, the infancy of coal mining as an industry offers a unique opportunity to preplan mining operations to minimize or avoid environmental degradation. Coal operators, because of recent legislation or a sincere environmental awareness, can reclaim mine sites in a cost-effective manner with new technology and proper engineering plans. The Gulf lignite province does not have the long history of underground and strip mining that is characteristic of the eastern coal province. There are only relatively small areas of abandoned spoil piles. Although shallow underground mining of lignite has occurred, primarily in Texas, the amount of land underlain by mines is relatively small. Therefore, without the complications of extensive areas of underground mines and abandoned spoil piles, reclamation of surface lignite mines is not as com-

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plex a problem as sites in the eastern coal province.

Future mining operations can be planned to reduce or eliminate potential pollution from coal mine drainage. By planning, areas where aquifers are near the surface or where the coal bed itself is the aquifer could be avoided. The impact on ground-water flow and the water table, therefore, can be minimized or eliminated. If there are good-quality topsoils, segregation of overburden into soil, clean fill, and pollution-forming material can be practiced.

Mining techniques also can be modified to regulate lignite extraction in potentially high pollution areas. Of the many lignite beds in a region, only a few may contain pollution-forming materials. The lateral variability in a lignite bed may result in acid waters in one area and neutral to basic waters in adjacent areas. Water sampling and rock sampling can be used to determine "trouble" areas of lignite beds. Sulfur content of lignite in Texas, for example, is variable and can be correlated with the geographic occurrence of the lignite (Fisher, 1968; Kaiser, 1974). High sulfur contents are associated with lagoonal deposits of lignite. Deltaic and fluvial lignite contain moderate and low sulfur contents, respectively.

GEOLOGY

Geologic rock units with surface exposures in the Gulf Coastal Plain of Texas range in age from Cretaceous to Recent. Cretaceous rocks comprise limestone, shale, and sandstone. The Tertiary rocks are primarily shale, clay, and sand and include the commercial deposits of lignite. Rocks of the Gulf Coastal Plain dip gently toward the Gulf of Mexico at rates from about 160 ft/mile in the older rocks to 10 ft/mile in sediments near the coast (Cronin and others, 1973). Folds and faults are common and can interrupt the regional southeast dip of the rock units. A major structural feature of the Gulf Coastal Plain in Texas is the East Texas embayment or syncline. This structural trough is a dominant influence on ground-water conditions in Eocene rock units throughout East Texas. Other structural features are salt domes which are found throughout the Gulf Coastal Plain and the Luling-Mexia-Talco fault zone (Milam and Lee Counties).

AQUIFERS

The Wilcox Group, Carrizo Sand, Queen City Sand, and the Sparta Sand are the most important water-bearing units in the Gulf Coastal Plain of Texas (fig. 1). Among these, the major sources of water are the Wilcox Group and the Carrizo Sand. Most municipal and industrial ground-water supplies are from the Wilcox Group and Carrizo Sand, for example, in Freestone, Anderson, Henderson, and Cherokee Counties. In the Brazos River basin the Wilcox Group and Carrizo Sand have a similar lithology and are characterized by similar water-bearing properties. The combined thickness of the Wilcox Group and Carrizo Sand ranges from 1,500 to 4,340 ft. Other minor water-bearing units, from oldest to youngest, are rocks of the Cretaceous (Trinity and Navarro Groups); Midway Group; Reklaw, Weches, Cook Mountain, and Yegua Formations; Jackson Group; and alluvium. Only those units directly affected by surface mining will be discussed in this paper.

The Wilcox Group consists primarily of fine- to medium-grained sand (unconsolidated) interbedded with lignite and silt. Throughout east-central Texas, the principal bed of the Wilcox Group is the massive Simsboro sand which is a prolific aquifer. Lateral facies changes complicate the correlation of individual beds. Sand beds are lenticular and may grade laterally to clay, lignite, and silt. Lenticularity of the strata generally does not isolate water in one lense from that in another lense (Cronin and others, 1973).

In the vicinity of Freestone, Anderson, Henderson, and Cherokee Counties the largest capacity wells and deepest wells are in the Wilcox Group. Sand units are relatively thin-bedded, fine-grained, and silty. However, some of the sand units are thick bedded and medium to coarse grained. Most of the Carrizo Sand in eastern Texas consists of a white, massive fine to medium quartz sand with a few thin clay lenses.

RECHARGE AND MOVEMENT OF GROUND WATER

Aquifers in the Texas Gulf lignite province receive recharge from precipitation and streamflow in their surface exposures. A large amount of this recharge, however, is rejected because the

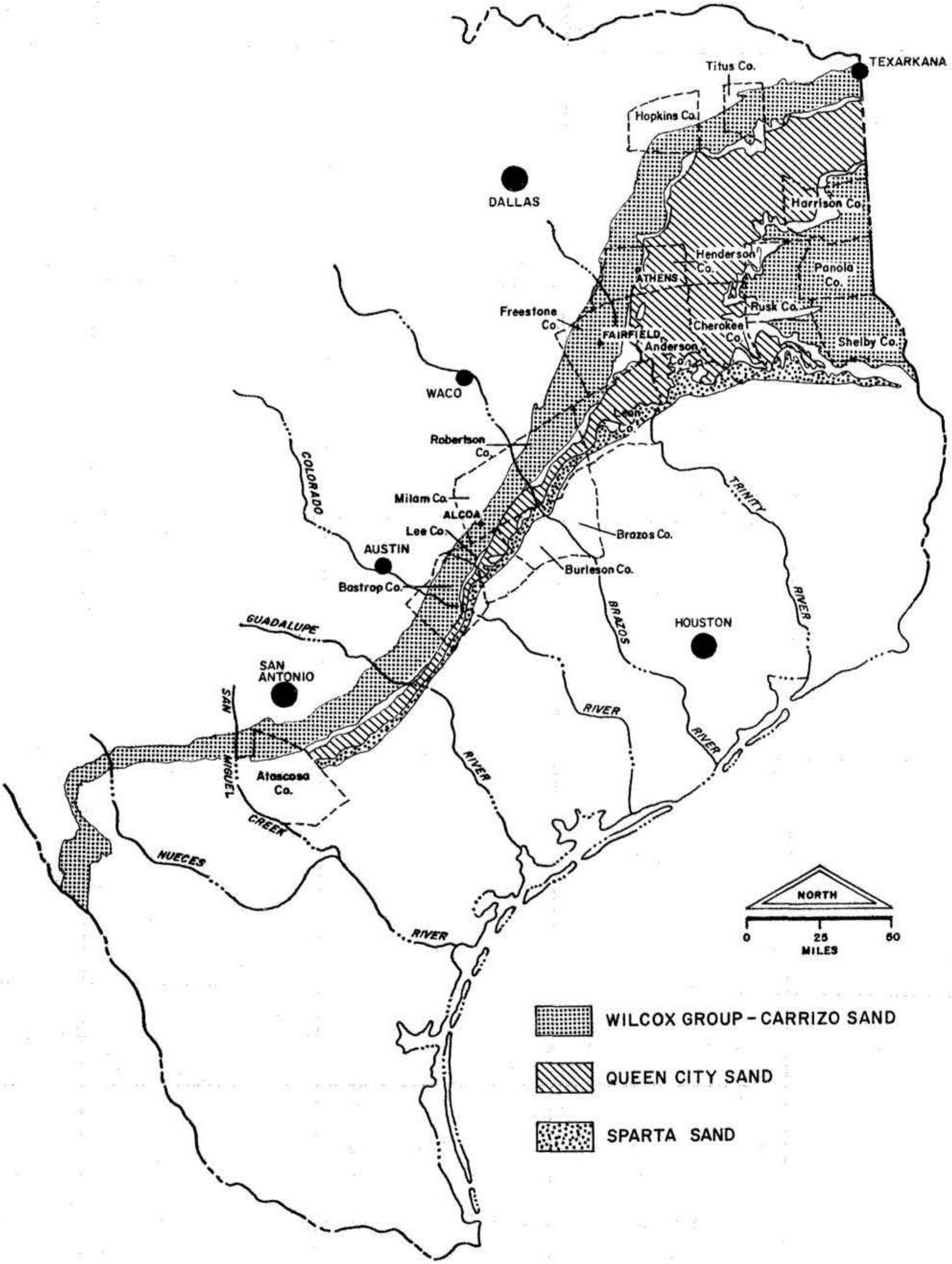

Figure 1. Important water-bearing units (modified from Texas Water Development Board aquifer maps).

aquifers are saturated. Most of the small streams that flow across the outcrops contain this excess water, which sustains base flow in many of these streams. The rejected water also is released by seepage and evapotranspiration in stream valleys that cross the outcrops. The quantity of water rejected probably exceeds the equivalent of 2 inches of the total annual precipitation of 38 to 46 inches (Texas Water Development Board, 1972).

Some of the recharge, however, does move down the dip of the rock units. A small amount of the recharge may move for long distances in this manner. Along the way water may seep upward through confining beds and be discharged as a seep or by evapotranspiration, or both. Groundwater movement also may be affected by geologic structures. The southeastward movement of water downdip in the Wilcox Group and Carrizo Sand of the Brazos River basin, for example, is affected by the Luling-Mexia-Talco fault which partly restricts the movement of water across the faults.

Movement of water in the formation is variable. Under natural conditions water movement can range from negligible to more than several hundred feet annually. The rates of movement in most of the sand formations are between 10 and 100 ft per year (Texas Water Development Board, 1972). The coefficient of transmissibility is highest for the Wilcox Group and Carrizo Sand. Near Rockdale, Milam County, the coefficient of transmissibility of these formations averaged 24,000 gal/day/ft and at the Bryan well field it was 87,500 gal/day/ft. The coefficient of transmissibility may be higher because not all of the sand beds were screened at each location. (Cronin and others, 1973). Locally the coefficient of transmissibility can be much higher. An average coefficient of transmissibility for the Wilcox Group and Carrizo Sand in this region has been assumed to be 50,000 gal/day/ft by Cronin and others (1973) for the calculation of total water availability. For other areas, such as Anderson, Freestone, Henderson, and Cherokee Counties, the coefficient of transmissibility for these formations generally is lower.

Yields of individual wells range from 400 to 1,500 gallons per minute for the water-bearing units in Anderson, Freestone, Henderson, and Cherokee Counties. Maximum yields for the Wilcox Group and the Carrizo Sand, assuming at least 100 ft of available drawdown to the top of the producing section of the well, average 1,500 gpm. These yields assume that there will be little head loss caused by turbulent flow in the wells and that all sands in the producing section are screened.

LIGNITE

In the Gulf Coast area, most of the lignite is located in Texas, but deposits are found in Arkansas, Louisiana, Mississippi, and Alabama (figure 2). Data on lignite for the most part are insufficient to describe lignite reserves or detail the importance of lignite in most Gulf Coast states. Texas and, to some extent, Arkansas are the exceptions. Arkansas lignite occurs in the Wilcox, Claiborne, and Jackson Groups. The Wilcox Group contains approximately 85 percent of the reserves in Arkansas. Many of the lignite beds are thin and lenticular. Sulfur content generally is less than 1 percent.

Texas, the only State with recent production of lignite, is rapidly expanding the development of lignite as an important source of energy. Near-surface lignite is found in two elongate bands and an area centered in Panola and Harrison Counties (figure 3). Large-scale mining operations which began in 1954 in Milam County have continued to expand with production in 1974 from Freestone, Harrison, Titus, and Milam Counties totalling 7,684,000 tons. Lignite is associated with ancient fluvial, deltaic, and lagoonal depositional environments in the Gulf Coastal Plain of Texas (Fisher, 1968). Many of the lignite beds which are widely distributed in the Wilcox, Claiborne, and Jackson Groups of Eocene age are thin (less than 4 ft thick) and of small areal extent. The major commercial deposits primarily are found in the Wilcox Group. Secondary deposits of lignite are found in the Yegua Formation of the Claiborne Group and the Manning Formation of the Jackson Group.

The geologic occurrence of lignite has been correlated with the grade of lignite (Kaiser, 1974). The highest quality of lignite is associated with fluvial-deltaic deposits. Fluvial-deltaic lignite occurs in Central Texas (Wilcox Group) and southeast Texas (Yegua and Manning Formations). The principal Wilcox deposits have a low ash content (approximately 10 percent), moderate sulfur (1.4 ± 0.7, dry basis), Btu values of 6,500 to 7,500 Btu/lb (as received), and may ex-

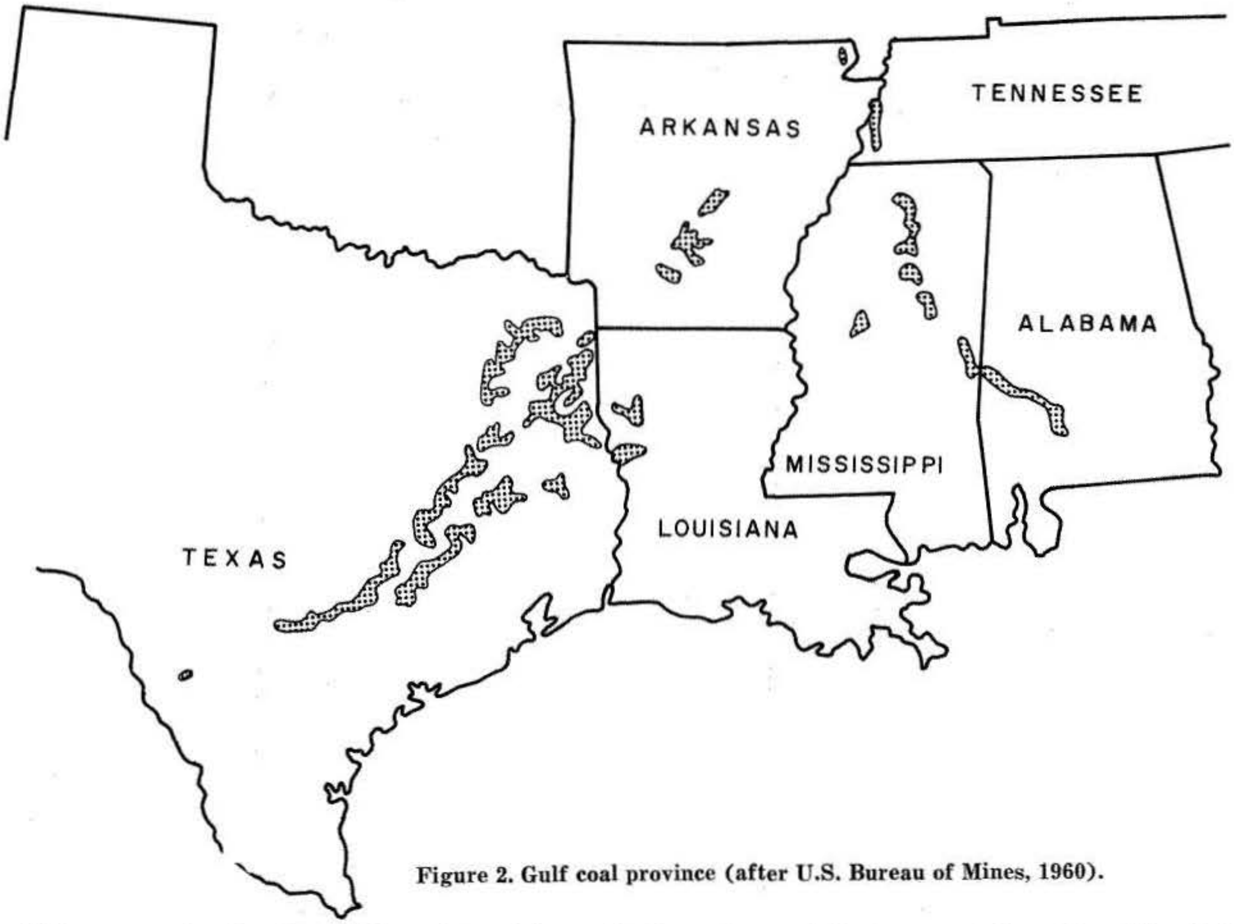

Figure 2. Gulf coal province (after U.S. Bureau of Mines, 1960).

tend for distances up to 10 miles. Although fluvial lignite in East Texas has a low sulfur content (1.0 ± 0.4 percent), it generally has a moderate ash content (10 to 25 percent) and Btu values of 6,500 to 7,500. The lowest grade of lignite is lagoonal lignite which occurs in South Texas in the Wilcox Group, upper Yegua Formation, and lower Jackson Group. The lagoonal deposits of the Wilcox Group are lower in sulfur content (1.7 ± 0.5 percent) than lagoonal deposits of the Yegua-Jackson (1.9 ± 0.8 percent). Lagoonal lignite generally has a high ash content (30 to 40 percent) and low Btu values (less than 6,000).

MINING

All lignite mined in the Gulf lignite province currently is strip mined. In Texas, area strip mining is utilized because of the flat to gently rolling topography, dip of the strata, areal extent of lignite, and relatively shallow, unconsolidated overburden. Approximately 3,175 acres have been disturbed by lignite mining in Texas (Groat, 1973).

Strip mining has increased rapidly since the 1950's and with new mines recently opening or which will open in the near future in Panola, Titus, Henderson, and Robertson Counties, the size of the area affected by mining will increase. Energy demands also will probably result in an increased production at existing mines in Milam and Freestone Counties. Exploration activity has increased recently and will ensure the development of additional lignite deposits.

Currently, stripping operations remove the overburden which can be 200 ft thick and pile it in the preceding mine cut. Mining and backfilling operations are conducted concurrently. Backfilling by this method minimizes spoil handling while eliminating spoil piles. Past mining (underground and strip) usually left spoil where it was laid and little reclamation was accomplished. The major areas of abandoned spoil piles include the Rockdale district and the area around Darco. The affected areas are minor because mining operations were never widespread. Abandoned spoil piles, therefore, occur locally and are not a major problem.

Although no underground mining is being conducted now, lignite in the past has been mined by underground methods. Some of the more important areas were the Malakoff district in Henderson County, the Rockdale district in Milam County, the Sayersville-Butler district in Bastrop County, the area around Darco in Harrison County, and the Lytle district in Atascosa County. Mine waste from these underground mines has long since been abandoned. Underground mining was conducted on a small scale, and, therefore, the area underlain and affected by underground mines is small.

CLIMATE

A warm, humid climate predominates over most of the Gulf Coast States. The climate of Texas, however, ranges from a humid climate in the east to a semiarid to arid climate in the south and west. Rainfall varies from less than 20 inches per year in South Texas to more than 48 inches per year in East Texas. A large percentage of this rainfall may be consumed by evapotranspiration. Potential evapotranspiration is moderately high for most of the Gulf lignite province. The average annual potential evapotranspiration rate ranges from 36 to 48 inches (Geraghty and others, 1973). Average annual surface runoff in Central and East Texas can be from 5 to more than 15 inches. In the arid areas of South Texas the average annual surface runoff may be less than 1 inch.

Climate influences the degree of environmental degradation produced by mining operations. Soil formation and the establishment of vegetation are the result of temperature and rainfall. The success of revegetation is dependent on the amount and quality of soils and adequate rainfall to establish plant growth on the mine areas. In warm, humid climates revegetation generally will not be a problem, whereas in semiarid to arid environments, revegetation of a mine area may be impossible. Without revegetation of mine areas in an arid climate erosion may become a problem, natural drainage may be disrupted permanently, wildlife habitats may be permanently altered, and scars left from mining activities may dot the landscape.

In areas where lignite beds or overburden, or both, contain high amounts of iron sulfides, a humid climate will cause the formation of acid mine drainage. Because of a low sulfur content in lignite and overburden currently being mined, acid mine water has not been a problem in Texas. Climatic conditions, however, do favor the production of acid mine water in lignite containing large amounts of iron sulfides throughout most of the Gulf lignite province.

RECLAMATION

Surface mining may disrupt ground-water movement and consequently may cause many of the same pollution problems as underground mining does. These problems may include the disruption of ground-water flow, lowering of the water table, interception of aquifers, pollution of water-bearing units, production of acid leachates from spoil piles, and the toxicity of spoil materials to vegetation. In the eastern coal province these problems may be caused by both underground and surface mining at the same mine site. Underground mining may disrupt aquifers which become a major source of water to mine discharges. Some attempts at reducing mine discharges by restoring the natural hydrologic characteristics of the surface have failed because the ground-water system was not investigated. One reason is that the major proportion of water entering some mine pools has been from aquifers and not surface infiltration (Pennington, 1975). Underground mining for lignite in Texas has not been widespread and has been at shallow depths. The effect of underground mining, therefore, has not had a major impact on the ground-water system as mining has in the eastern coal province.

The techniques for reclamation and associated problems are significantly different in Texas from that in the eastern and interior coal provinces. Topography is not an obstacle in Texas as it is in Appalachia. The flat to rolling hills of Texas can be restored easily by regrading the parallel rows of spoil piles left by area mining. For many areas in Texas the physical and chemical characteristics of soils are not much different from the parent rocks and, therefore, segregation of

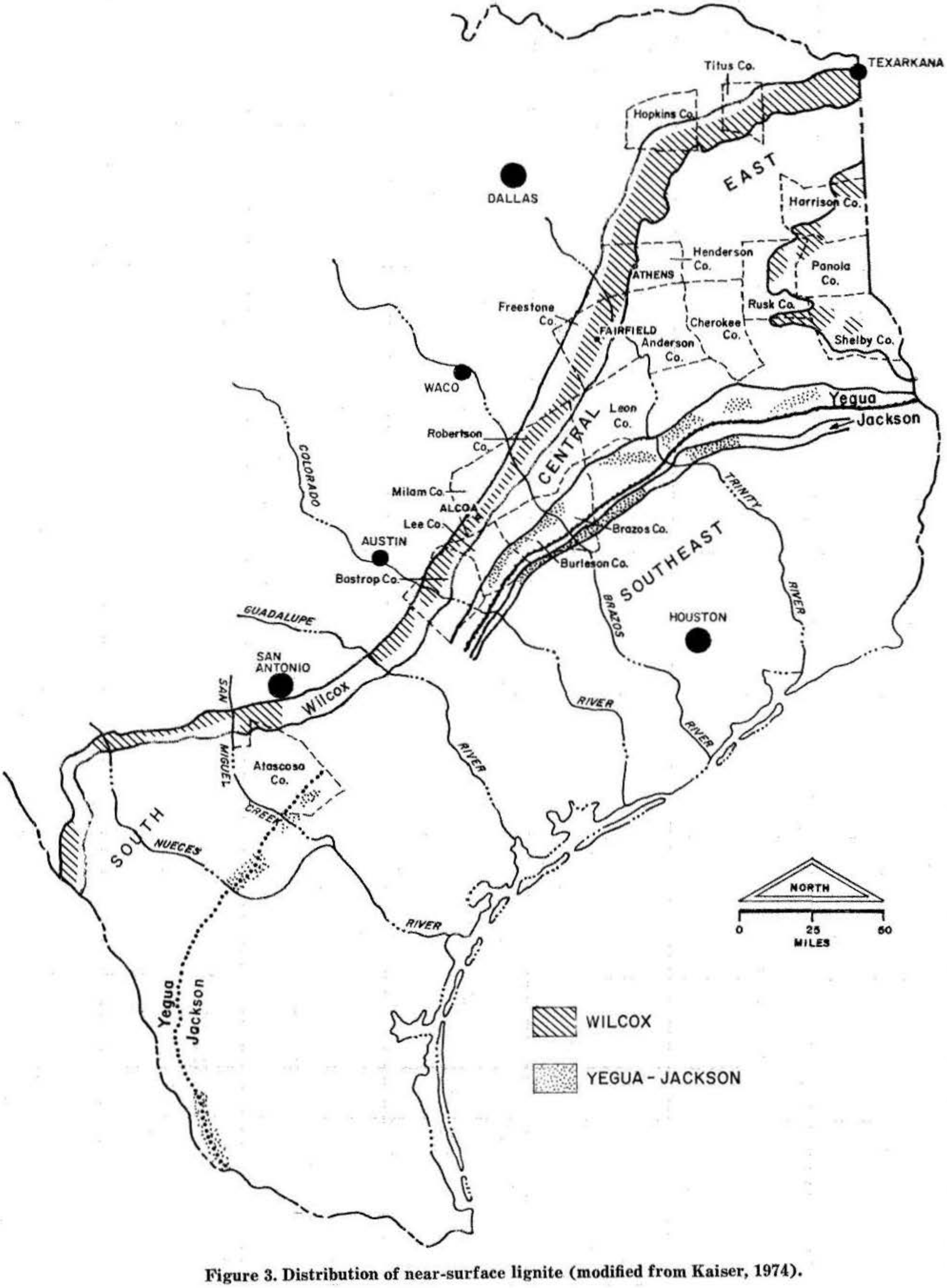

Figure 3. Distribution of near-surface lignite (modified from Kaiser, 1974).

topsoil is not required. Where iron sulfide content is high, acid waters may be produced. Surface infiltration may have to be controlled to prevent water contamination. In the arid areas of South Texas, however, some infiltration may be desirable and would help efforts at revegetation by increasing soil moisture. The decision to control surface infiltration, then, is dependent on the characteristics of the site.

Area mining generally has a greater potential for ground-water pollution than contour mining. As the name implies, area mining removes large blocks of lignite and overburden. Where lignite beds are close to the surface (within 200 ft) and because of the continuity and geometry of the lignite, strip mining may cover several square miles. The areal extent of individual lignite beds ranges from 1 to 15 square miles (Kaiser, 1974). A mine-mouth powerplant would require several of these lignite beds within a close radius of the plant location. The potential for the disruption of ground-water flow for such a large area can be very high. The stage of the local water table and, if present, perched zones of water may be reduced by strip mining. Yields from domestic and other shallow wells may be reduced if the lowering of the water table is sufficient. Ground-water flow in the unsaturated zone also may be changed by a strip mine. Water normally flowing to an aquifer or aquitard may be routed to a strip mine.

Surface mining may intercept aquifers. Changes in flow patterns in these aquifers could result in some wells completed in them being dewatered. In addition, reclamation of mines which have intercepted aquifers may cause blocking of an aquifer. The backfilling of the mine may result in finer material being deposited which may impede the flow of water in the restored aquifer. Backfill material also can become more compacted than the original material as a combined result of a mixing action and by repeated movements of backfilling equipment. The hydrologic characteristics of the backfill material including porosity, permeability, and the coefficient of transmissibility can be quite different from the original aquifer.

In many areas of East Texas, water-bearing units are within 200 ft of the surface. The water tables of the Carrizo Sand and Wilcox Group in areas of Henderson County are within 150 feet of the surface (Texas Water Development Board, 1972). Mine operation at the Big Brown mine in Freestone County which was removing about 40 to 120 ft of overburden in 1975 probably is shallow enough to avoid problems associated with the regional water table. The water table in the area of Fairfield, for example, is between 140 to 190 ft below the surface. Removing 180 and 200 ft of overburden in other areas of Freestone County where recent well records indicate water tables lie less than 60 to 100 ft below the surface will result in ground-water seepage to the strip mines. Ground water discharged to the strip pit in some areas may require the pumping of the water to nearby ephemeral streams. In addition to the added cost of pumping, the additional flow may cause erosion problems and could change downstream water quality. At existing strip mines in Texas, ground-water inflow has not been a serious problem. With the expansion of lignite mining, however, the potential for ground-water problems will increase.

Because large lignite reserves in Texas are readily accessible by strip mining, underground mining and its associated problems do not appear to be factors in the development of lignite deposits in the near future. Reclamation of surface mines in most areas will not have to consider problems of subsidence or mine openings which could have served as conduits for surface water to enter underground mines.

Other effects from area mining, excluding ground-water problems previously discussed, are soil erosion, changes in surface drainage, deterioration of water quality, stream channel changes caused by erosion or sedimentation, and changes in aquatic and terrestrial habitats. Erosion on the mine site may be severe, but in properly planned mines most of the sedimentation occurs within the mine. The development of the strip mine cannot avoid temporary and sometimes permanent disruption of surface drainage. Surface runoff trapped by the mine site may result in a decrease of base flow of some streams. Where iron sulfides are present in a mine, water may become acid and, if not impounded before leaving the site, may decrease water quality of nearby streams.

Channel erosion also may result from significant quantities of water being discharged from mine sites. Downcutting and channel widening caused by excessive storm-water runoff may produce a new channel. Removal of alluvial deposits of valley floors or channels also may result in a lowering of the local water table. Problems resulting from these changes include unused tributary channels and excessive quantities of sediment which may accumulate in reservoirs. Where there is a decrease in storm-water runoff, recharge to alluvial aquifers will be decreased. This also may cause a lowering of the water table.

Altered drainage patterns and a loss of recharge to alluvial aquifers can be particularly important in areas of semiarid to arid climates. Decreases in streamflow caused by an increase in consumptive use at the strip mine will decrease recharge and generally lower ground-water levels. This decrease in recharge may be in addition to the loss of recharge to alluvial aquifers caused by decreased storm-water runoff. Lowering of the water table may result in a decrease in soil moisture which can be more important than rainfall in the development of soils and plant growth. Any decrease in soil moisture probably will result in more difficulty in the establishment of vegetation in the affected mine areas.

The success of reclamation and the minimization of adverse effects on the ground-water system will depend, in part, on how well the natural drainage pattern can be restored. The design of spoil piles and the eventual regrading of the soil, therefore, is important. In arid areas, where evaporation rates are high, surface mining can have a major impact on the environment. Vegetation usually is sparse, and the potential for new growth, poor. To minimize the effects of mining in these areas the spoil piles may have to be designed and regraded to duplicate the original hydrologic conditions at the mine site. For other less critical environments it may be desirable to continue to redirect surface runoff, where water diversion has been utilized, from the mine site after mining operations have ceased. The effort would prevent the contamination of surface waters and ground waters. At some mine sites surface runoff could be impounded to provide water for wildlife or recreation or both. A roughened spoil surface or an increase in the porosity of the spoil material during regrading operations can be utilized to impede surface runoff where desired. Surface runoff then can infiltrate the spoil material and increase soil moisture. Surface manipulation of spoil materials can be used to reduce erosion, loosen compacted fill material caused by regrading equipment, and increase the amount of precipitation available to support vegetation on the regraded site. The techniques used for surface manipulation include terracing, pitting, ditching, listering, and disking.

Relocation of spoil material to avoid contact with water and air can be accomplished to minimize acid production from leaching processes. In areas where overburden contains iron sulfides, spoil can be isolated by burial or located in sections of the mine which are relatively free of water. Improper selection of a burial site can result in the pollution of ground waters. The burial site should not contain seepages of ground water or be located in an area where surface runoff can collect and infiltrate into the soils.

ABATEMENT

Techniques of abatement depend on geology and soils, climate, topography, type and extent of mining, and accessibility of the mine site. In the Gulf lignite province, preplanning mining operations to minimize environmental degradation can be an effective abatement technique. Sections of lignite beds having a high pollution potential can be avoided. Mining techniques also can be selected which facilitate the backfilling of spoil with a minimum of spoil handling.

Mineral barriers in areas where the potential for pollution is high can be used to control water pollution. The mineral barrier (lignite bed) is left in the downslope side of a mine to retain surface water and mine water in the mine. The barrier also is used to confine ground water in a reclaimed surface mine after mining is completed.

The technique of water diversion involves the collection and diversion of water around mine sites. Drainage ditches in surface mines also trap mine water to convey it from the mine. The common methods utilized for water diversion are ditches, flumes, pipes, and embankments. Inflowing ground water also can be diverted from its flowpath, if necessary, before it enters the mines by controlled pumping of the aquifer.

The disruption of the ground-water system may be the most significant problem associated with lignite mining in the Gulf lignite province. The period required for restoration of aquifers is difficult to determine, predict, or control. Intercepted aquifers could be restored by the construction of an artificial aquifer consisting of a sorted gravel or coarse-grained sand overlying an impermeable clay layer. The effects of changes in thickness of the aquifer, the exposure of the aquifer to the surface after confining layers are eliminated by mining, and different hydrologic characteristics are factors which must be evaluated before an artificial aquifer can be constructed.

SUMMARY

Potential problems of reclamation in the Gulf lignite province are variable because of the different climates which exist in the region. In both semiarid to arid and humid climates, however, mining above the regional water table generally will minimize potential environmental degradation. In semiarid to arid climates the effects of mining may cause:

1. Lowering of the water table that then may limit the potential success of revegetation, which already is low in arid climates.
2. Disrupted aquifers which may cause wells in areas adjacent to mining to be dewatered.
3. Reduction of recharge to alluvial aquifers and other aquifers.
4. Soil moisture reduction.
5. Altered drainage patterns, thus cause abnormal problems or erosion and sedimentation in stream channels.

The warm, humid climate for the remainder of the Gulf lignite province generally will result in similar problems caused by mining as in areas of arid climates. The conclusions of this paper for humid climates are:

1. Higher amounts of precipitation generally will ensure adequate amounts of water for the revegetation of regraded mine sites.
2. Recharge to alluvial aquifers and other aquifers may be reduced. The reduction for alluvial aquifers, however, may not be as large as in arid climates, because the amount of surface runoff trapped by surface mines will be a smaller percentage of the total runoff of a watershed.
3. Increases in the rate of consumptive use at the mine site as in arid climates will decrease available water for recharge. The effect, however, may be minimal in comparison to areas in arid climates.
4. Aquifers may be disrupted by mining and, therefore, wells dependent on the disrupted aquifers may be dewatered.
5. Stream channel changes caused by different rates of erosion and sedimentation after mining may result, but the changes may not be as great as in arid climates.

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WATER FOR LIGNITE DEVELOPMENT IN TEXAS

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INTRODUCTION

Water requirements associated with lignite utilization and conversion may be a major factor limiting full potential development of lignite resources in Texas. The purpose of this paper is to demonstrate the magnitude of these water requirements and the impact water availability can have on the potential development and utilization of this resource in Texas.

WATER NEEDS FOR LIGNITE CONVERSION AND UTILIZATION

The water needs for lignite conversion and utilization vary substantially with the type of process employed. To provide a common basis for comparison, a hypothetical lignite mine producing 25,000 tons of lignite per day (9,125,000 tons per year) will be considered. This size mining operation is approximately equivalent to that needed to supply the coal- and lignite-conversion plants of the size now proposed as "unit plants" by the U. S. Energy Research and Development Administration (ERDA). This rate of production is also equivalent to the gross daily average per capita energy consumption of about 300,000 people in the United States. Such an operation would require strip mining of approximately 1.5 to 2 surface acres per day. Table 1 shows the energy output of various lignite-conversion processes using 25,000 tons of lignite per day.

Before discussing the subject of water needs, two terms must be clearly defined: water intake and water consumption. Water intake refers to the total amount of water that is withdrawn from a lake, stream, estuary, or aquifer, whereas water consumption refers to the amount of the water intake that is depleted (lost through evaporation, chemical conversion, or other means).

Water requirements for each of the lignite utilization and conversion processes are divided into five water-use categories, which include: (1) mining, (2) processing, (3) cooling, (4) miscellaneous, and (5) those water requirements resulting from the area population increase caused by the operation of the plant. These requirements are summarized in the following paragraphs.

MINING REQUIREMENTS

Water requirements for mining include water for dust control, both in the mining area and on roads, and for land reclamation if strip mining is practiced. Dust control at a 25,000 ton per day lignite strip mine is estimated to require approximately 500 acre-ft per year. By contrast, land

Table 1. Energy output of various lignite-conversion processes using 25,000 tons of lignite per day.[a]

Process	Billion Btu (per day)	Plant Output (per day)	Units
Steam-electric powerplant	120	36 million	kWh[b]
High-Btu Gas	230	230 million	scf[c]
Low-Btu Gas	300	830 million	scf[d]
Fischer-Tropsch	130	26,000	barrels
Synthoil and others	230	45,000	barrels[e]
Solvent-refined coal	280	38,000	barrels
Pipeline slurry	360	25,000	tons

[a] From ERDA (1975)

[b] Kilowatt hours. Is equivalent to a 2,000 MW powerplant operating at 80-percent capacity, 9750 Btu/kWh (35 percent efficiency, fuel 7500 Btu/lb).

[c] Standard cubic feet.

[d] A heat value of 300 Btu/scf is assumed.

[e] Direct catalytic hydrogeneration and hydrocarbonization have similar conversion efficiencies.

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reclamation and revegetation of a strip-mined area could require as much as 2 acre-ft of water per acre of land surface mined and reclaimed (irrigation plus rainfall). Thus, for a 25,000 ton per day mine with a mining rate of 12,500 tons per acre (approximately 7 ft lignite seam), total water requirements can exceed 4,000 acre-ft per year. Rainfall is an extremely important factor in determining the amount of water actually needed. In East Texas and in much of Central Texas, precipitation is normally sufficient to preclude irrigation. For instance, Texas Utilities Generating Company has found that irrigation thus far has not been necessary for reclamation and revegetation at the Big Brown powerplant located in Freestone County. Further south, periodic irrigation will probably be necessary for reestablishment and maintenance of vegetation. In determining water requirements, it has been assumed that there will be no water requirements for land reclamation (irrigation) in East Texas westward to the area of Freestone County, but that irrigation water needs in the central and southern climatic regions of Texas would range from 500 acre-ft to 2,000 acre-ft per year for the hypothetical 25,000 ton per day mining operation. No return flows are assumed, thus water intake and consumption are equal. Dust control for underground mining would have relatively small water requirements, and in situ gasification operations would have negligible water requirements.

PROCESS REQUIREMENTS

Process water requirements vary greatly with the type of lignite-conversion process used. In steam-electric powerplants, the principal water needs are for boiler makeup, ash handling, and stack gas scrubbing if the stack-gas scrubbing technique is used to control SO_2 emissions. It is important to note that water requirements for all types of stack-gas scrubbers (wet limestone, double alkali, magnesia, and so forth) are about the same. For a steam-electric powerplant using 25,000 tons of lignite per day, water requirements amount to about 200 acre-ft per year for boiler feed makeup and ash handling and approximately 2,000 acre-ft per year for stack-gas scrubbing. Thus, total process water used in such a plant amounts to about 2,200 acre-ft per year. Because essentially all of this water is lost through evaporation, intake and consumption are equal. Process-water requirements for lignite gasification and liquification vary with the process employed. A large part of the water used in gasification and liquification operations is chemically consumed in the conversion reactions to produce hydrogen. Plants producing high-Btu gas usually consume more water than low-Btu-gas plants because high-Btu plants employ shift conversion and methanation. Because process water is actually consumed, intake and consumption are equal. Liquification methods such as the synthoil process require less water than gasification processes because the molar ratio of carbon to hydrogen in the lignite is not significantly changed. The solvent-refined coal (SRC) process requires the least amount of water because total gasification or hydrogeneration is not accomplished. Review of the literature indicates that process water requirements for plants of the size indicated in table 1 could range from approximately 300 to 3,000 acre-ft per year. For most gasification operations, consumption rates of 1,000 acre-ft per year are common. Liquification processes normally require about 800 acre-ft per year and the SRC processes only about 300 acre-ft per year, or less if it is assumed that the ratio of process water to cooling water for these SRC plants is the same as that for liquification plants. Actual requirements can be affected by the moisture content of the lignite.

Available information suggests that water requirements for in situ gasification of existing deep-basin lignite in Texas will be minimal. Nonetheless, the gas produced will most likely be used on site for steam-electric power production. Therefore, water requirements for in situ gasification will be associated principally with electric power generation.

Lignite washing is not widely practiced because of its tendency to disintegrate during the washing process. Even if practiced, water requirements are small in comparison to lignite conversion process requirements.

Pipeline slurry transport of lignite is receiving study. However, because lignite, when slurried, tends to disintegrate into a fine powder which drains poorly and is difficult to handle, this method of transportation does not appear to be extremely useful for Texas lignite. If used, a pipeline slurry system transporting 25,000 tons of lignite per day would require about 5,000 acre-ft of water per year. This water would not be consumed as such but would be removed from the lignite-producing area.

COOLING REQUIREMENTS

Cooling-water intake and consumption rates are highly dependent on the type of cooling system employed. Both air- and water-cooling systems are available. If air systems are used, water use is minimal. By contrast, if water-cooling systems are used the cooling-water requirements will be substantial.

Air-cooling systems are generally not desirable for use at steam-electric powerplants because (1) they are much more costly than wet-cooling systems, (2) they result in a 12-percent reduction in powerplant efficiency, and (3) they require from 3 to 8 percent of the plant's electric power output to operate. Air-cooling systems are proving to be useful at many gasification and liquification operations because of the much higher cooling temperatures involved. Some gasification plants are currently planning to use air-cooling for as much as 75 percent of their cooling needs thus greatly reducing water requirements.

Types of wet-cooling systems available include wet-cooling towers, recirculating cooling ponds, and once-through systems using water from multipurpose reservoirs, streams, or estuaries. Cooling towers and cooling ponds consume from 30 to 100-percent more water than once-through cooling systems. It is highly advantageous to use once-through systems wherever possible.

Consumptive water requirements for a steam-electric powerplant using 25,000 tons of Texas lignite per day would total about 10,000 acre-ft per year if once-through cooling is used, but would amount to as much as 20,000 acre-ft per year if cooling ponds or towers are used. Consumptive water requirements for gasification and liquification plants of the size noted would range from about 3,000 to 15,000 acre-ft per year, depending on the specific process and amount of air-cooling used.

Water-intake rates also depend on the process used. If wet-cooling towers or cooling ponds are used for total waste heat removal in either steam-electric powerplants or gasification or liquification plants using 25,000 tons of lignite per day, water intake requirements will be on the order of 20,000 to 45,000 acre-ft per year. This requirement is equivalent to the amount of water needed to replace water lost through evaporation and blowdown from the cooling system. If air-cooling is used to remove as much as 75 percent of the waste heat from the latter two conversion processes, intake requirements can be reduced to as low as 4,000 acre-ft per year.

Once-through cooling systems withdraw water, recirculate it through the condensers and heat exchangers, and immediately discharge it to the receiving water. Because the total flow requirements of the condenser and heat exchangers must be met with once-through cooling methods, intake requirements are much larger than those for cooling ponds and towers. For both steam-electric powerplants and lignite-conversion plants, intake rates can exceed 1.5 million acre-ft per year. Such large requirements generally preclude the use of ground water. If located on a surface-water source, the water would be immediately returned to that body of water; therefore, these withdrawals do not represent an actual depletion of the water resource. Nonetheless, the widely varying flow rates of most streams and rivers in Texas limit the feasibility of using such cooling systems, particularly at sites located directly on undeveloped or unregulated stream reaches.

The situation is quite different for plants located directly on multipurpose reservoirs. Since one-through cooling systems merely circulate the water in a lake, the only requirements are that (1) sufficient water is impounded at any one time to provide adequate water surface area for heat dissipation, (2) the water level in the lake remains above the water intake structure for the powerplant, and (3) sufficient water is released from the reservoir to control dissolved solids concentrations at desired levels in the reservoir. It must be remembered, however, that water is consumed through forced evaporation as the warmer water from the powerplant effluent circulates through the lake and cools to ambient conditions. Once-through systems located on estuaries are, of course, even more advantageous.

The use of multipurpose reservoirs, instead of cooling ponds or single-purpose cooling reservoirs, provides for more efficient use of the water-storage capacity of a river basin. When single-purpose impoundments are built, the water thus stored is in many cases not available for other beneficial uses. Such impoundments may also preclude the most efficient downstream use of the water resources and can prove to be most disruptive to orderly statewide water-resource planning and development. In terms of water-resource management, single-purpose cooling reservoirs should be used only when absolutely necessary. However, use of such impoundments commonly provides a better alternative than the use of wet-cooling towers, if a surface water source is utilized.

SECONDARY POPULATION REQUIREMENTS

Recent estimates by the U. S. Federal Power Commission and ERDA indicate that operation of steam-electric powerplants and conversion plants of the size discussed above will require from 200 to more than 800 employees. Since many of the lignite operations in Texas are now planned for rural areas, creation of these new job opportunities will result in a migration of people to these areas. If it is assumed that 75 percent of the employees at a plant are married, then total direct population increases, including the workers and their families, could range from 400 to 2,000 new people. These employees and their families will create new demands for services and goods which also require more people. Therefore, such a plant could cause a population increase of as much as 2,000 to 6,000 people according to several ERDA reports. A population increase of this size could increase local municipal water-intake requirements by as much as 300 to 900 acre-ft per year and municipal consumption requirements by as much as 150 to 450 acre-ft per year. Although such water uses are not directly related to lignite resource development and utilization, they must be included when considering the overall water supply. For most installations, these associated population water requirements will be on the order of 600 acre-ft for intake and 300 acre-ft per year for consumption.

MISCELLANEOUS REQUIREMENTS

Miscellaneous requirements include water used for sanitary purposes, lawn watering around the plant, washing and maintenance, utilities, air-conditioning, and ancillary needs. As would be expected, there is wide variation in the literature concerning miscellaneous water requirements. For plants using 25,000 tons of lignite per day, intake rates of 500 to 1,000 acre-ft per year and consumption rates of 250 to 500 acre-ft per year should be more than adequate.

WATER REQUIREMENTS SUMMARY

To place the issue of water requirements and water availability into proper perspective, the total water requirements of the various lignite utilization and conversion processes must be examined. Table 2 summarizes the total water intake and consumptive needs of these various processes. Table 3 shows the consumptive water requirements of the various processes according to gallons per million Btu so that the relative water-use efficiencies can be compared. As these figures indicate, steam-electric powerplants have the highest rate of water use and consumption, whereas slurry pipeline and SRC processes use and consume the least. However, it must be remembered that slurry pipelines are transporta-

Table 2. Water needs for lignite conversion and utilization processes[a] (Theoretical plant using 25,000 tons of lignite per day).

Process	Output (Billion Btu per day)	Water Intake (1,000 acre-ft/yr)		Water Consumption (1,000 acre-ft/yr)	
		Minimum	Maximum	Minimum	Maximum
Steam-electric powerplant	120	23.3	1,503.0	13.2	25.3
Gasification	230-300	6.6	1,506.0	5.2	19.2
Liquification	130-230	6.4	1,504.0	4.0	19.0
In situ gasification[b]	70	12.0	752.0	6.6	11.6
Pipeline slurry	360	5.8	7.8	0.8[d]	7.8[d]
Solvent-refined lignite[c]	280	2.5	63.9	1.7	3.8

[a] These data include mining, process, cooling, miscellaneous, and associated population requirements.

[b] Assume that in situ gasification recovers 50 percent of the heating value of the lignite and that the gas is used on location to power a 1,000 MW powerplant. Therefore, water-use figures reflect powerplant water requirements.

[c] Information for the SRC process water requirements is scant; thus, these projections should be used with caution.

[d] 5,000 acre-ft/yr is exported from mine site.

tion tools, and the lignite, once delivered to its destination, will be used at that site. Thus, in many instances slurry pipelines merely transfer the water-use needs from the mining location to point of use. The same may be true for solvent-refined lignite. The product of the SRC process is a solid substance with a heating value of 16,000 Btu/lb. This product can either be burned in boilers of powerplants or liquified by hydrogeneration. These latter two processes will, of course, require additional water.

The water consumption figure indicated in table 3 for gasification operations are somewhat lower than those reported in many literature sources (U. S. Geological Survey, 1974). Recent literature available to the author indicates that previous estimates may be somewhat high. One point should be made concerning cooling systems. If wet-cooling systems are employed, once-through systems located directly on multipurpose reservoirs or estuaries will consume the least amount of water and offer the most advantageous means for effective water-resource management. However, if ground water must be used, wet-cooling towers are commonly the only alternative cooling mode available.

PROJECTED WATER NEEDS FOR LIGNITE PRODUCTION IN TEXAS

The projection of future water needs for lignite development and utilization is, like other types of industrial water-use projections, quite difficult. As of early 1976, there were 2,395 MW of installed steam-electric generating capacity in Texas using lignite as fuel. By 1985, the installed lignite-fired generating capacity should exceed 10,350 MW, if all powerplant additions now planned by electric utilities in Texas are built. By 1985, then, lignite will supply fuel for about 15 percent of the State's power-generating capacity.

Lignite-mining operations to supply this projected 1985 installed capacity in Texas could exceed 50 million tons per year or 137,000 tons per day. If growth continued at this rate, over 130 million tons of lignite would be mined annually by the year 2000. Consumptive water requirements for such a rate of production will be extremely high. If it is assumed that most of this lignite production will be used to fuel steam-electric powerplants, consumptive water requirements could exceed 300,000 acre-ft per year. Such large demands will strain available water supplies in Texas.

Table 3. Water consumption rates for lignite utilization and conversion.[a]

Process	Water Consumption (gallons per million Btu)
Steam-electric powerplant	98 to 188
Gasification	15 to 74
Liquification	16 to 130
In situ gasification[b]	84 to 148
Pipeline slurry	0.2 to 19
Solvent-refined coal (SRC)[c]	5.4 to 8

[a] This includes mining, process, cooling, miscellaneous, and associated population requirements.

[b] Assume that in situ gasification recovers 50 percent of the heating value of the lignite and that the gas is used on location to power a 1,000 MW powerplant. Therefore, water-use figures reflect powerplant water requirements.

[c] Information for the SRC process water requirements is scant; thus, these projections should be used with caution.

WATER AVAILABILITY FOR LIGNITE DEVELOPMENT IN TEXAS

Water requirements can be met from both ground-water and surface-water resources. In assessing water availability for lignite development, both the magnitude of the water resource and the total demand placed on that resource must be evaluated. Water is needed for cities, industries, agriculture, and maintenance of the environment including the highly productive estuaries of the Texas Gulf Coast. Agricultural water demands have already exceeded the renewable supply in some areas of Texas such as the High Plains and the Winter Garden area in the southern part of the Nueces River basin. Also, much of the available surface water in the State has already been legally claimed through the issuance of water-rights permits, which all major users of surface waters in Texas must obtain from the Texas Water Rights Commission.

Lignite deposits in Texas are found in the Wilcox Group, Yegua Formation, and Jackson Group of the Texas Gulf Coastal Plain. Therefore, these deposits stretch from the high-rainfall areas of East Texas to the arid regions of South Texas. Water availability therefore will depend on the climatic and hydrologic conditions in the area of the lignite deposits. For purposes of discussion, the lignite-bearing areas of Texas have been divided into three "climatic regions" as indicated in figure 1. The East Texas region covers the lignite-bearing areas of the Sulphur Creek, Cypress Creek, Sabine River, and Neches River basins; the Central Texas region consists of the lignite-bearing areas of the Trinity, Brazos, and Colorado River basins; and the South Texas region includes areas of the Guadalupe, San Antonio, and Nueces River basins. Deposits in the Red River and Rio Grande basins were considered to be negligible. Figure 1 also shows the river basins in Texas, and figures 2 and 3 show the locations of major and minor aquifers in the State. Water availability in each of these three "climatic regions" is summarized below.

EAST TEXAS

Annual rainfall in this area averages more than 45 inches; therefore, runoff is usually high. The combined annual average flow of these four rivers, as they cross the lignite-bearing regions, is over 6 million acre-ft per year. However, since these basins have relative small drainage areas within and above the lignite-bearing regions, streamflow is highly dependent on localized rainfall patterns. During periods of drought, both the Sulphur River and Cypress Creek have ceased to flow, and flow in the Sabine and Neches Rivers in these areas was reduced to a mere trickle. However, surface water is available in this area by impoundment of streams in order to develop a dependable supply. Unappropriated water still exists in these basins, but developers must be cautious not to infringe upon existing water rights.

Ground water is also available from the Carrizo-Wilcox, Queen City, Sparta, and other minor aquifers in the lignite-bearing areas. The sustainable yield of these aquifers approximates 250,000 acre-ft per year according to recent Texas Water Development Board estimates. Therefore, these aquifers represent another viable water source. Evaluation of these aquifers must be made on an individual basis, however, since competition for ground-water sources is already high in some areas.

CENTRAL TEXAS

Average rainfall in this area ranges from 35 to 45 inches. Because of the large drainage areas above the lignite-bearing regions in the Trinity, Brazos, and Colorado basins, streamflow is not as highly dependent on local rainfall as it is in East Texas. Nonetheless, flows during prolonged drought periods are greatly reduced. Reservoir development above the mining area and powerplant site does help to maintain some streamflow during these dry periods. Much of the surface water in these three basins is already committed through existing water permits. Those wishing to develop a surface-water source for a lignite operation in Central Texas may find they must purchase water from existing permit holders in the area.

Ground water is available from the Carrizo-Wilcox, Queen City, and Sparta aquifers and from local alluvial deposits. Recent estimates by the Texas Water Development Board place the sustainable yield of aquifers in the Central Texas lignite-bearing area at approximately 250,000 acre-ft per year. However, as in the East Texas area, the availability of ground water at each site must be closely evaluated on an individual basis.

SOUTH TEXAS

Average annual rainfall in the lignite-bearing areas of the Guadalupe, San Antonio, and Nueces River basins varies from 20 inches in the southwestern part of the Nueces River basin to over 30 inches in the Guadalupe River basin. Springflow helps to sustain the streamflow of the Guadalupe River, but because of the small drainage areas of these three basins in and above the lignite-bearing areas and the low rainfall, the average annual combined flow of these three rivers scarcely equals that of the Colorado River alone as it crosses the lignite outcrop belts. Current and future surface-water supplies in South Texas are already heavily committed to beneficial uses; thus, little water remains to be appropriated for lignite development. Therefore, those wishing to locate a lignite-fueled facility in South Texas will most likely have to acquire surface water from an existing permit holder or develop ground-water sources.

Ground water is available in the northern part of the region, but irrigators in the Winter Garden area of the Nueces River basin are already withdrawing water from the Carrizo-Wilcox aquifer at a rate greater than that at which the aquifer is being recharged. Therefore, ground-water supplies in the South Texas area, though available, must be evaluated with caution.

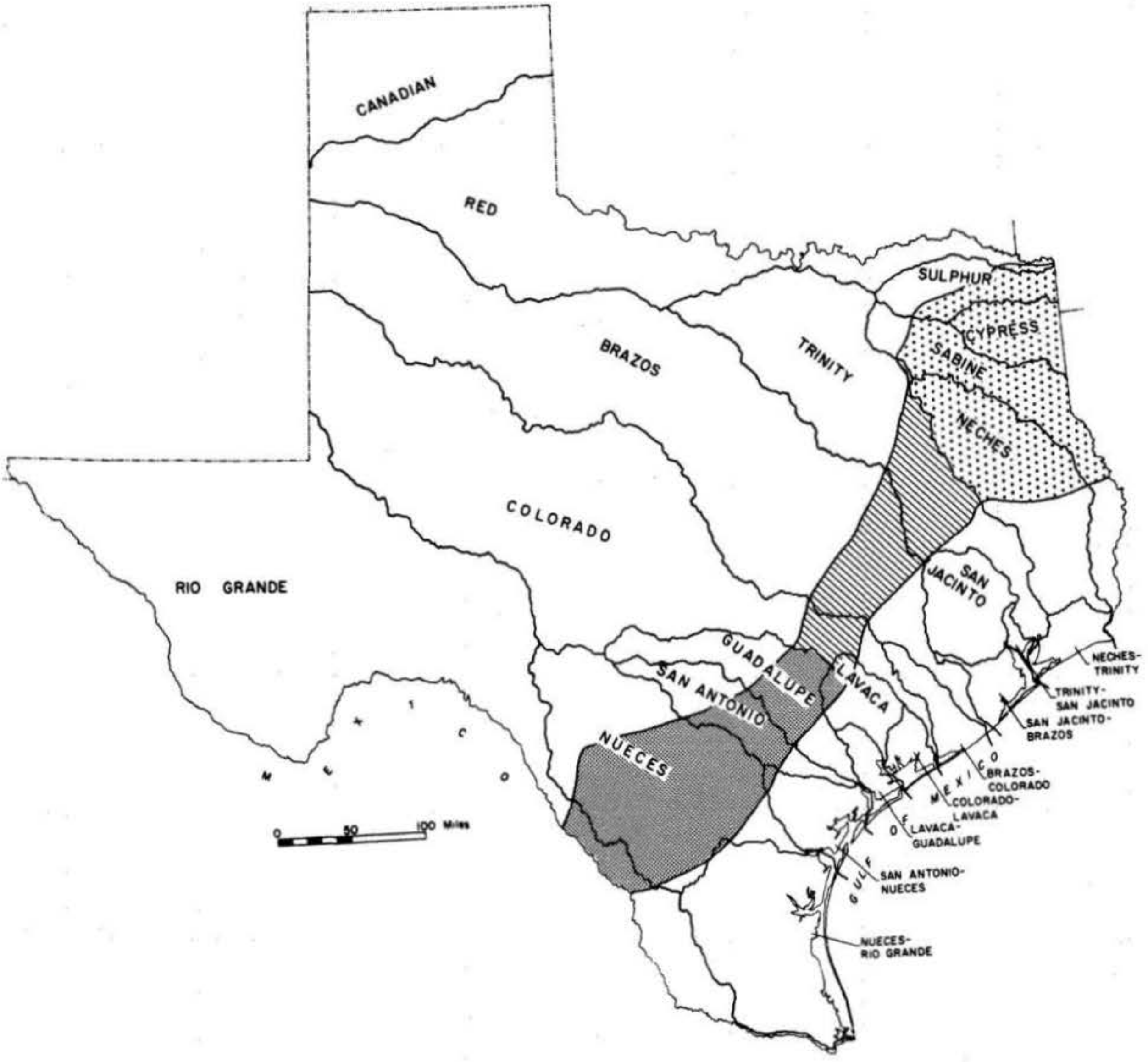

Figure 1. Climatic region in the lignite-bearing areas of Texas.

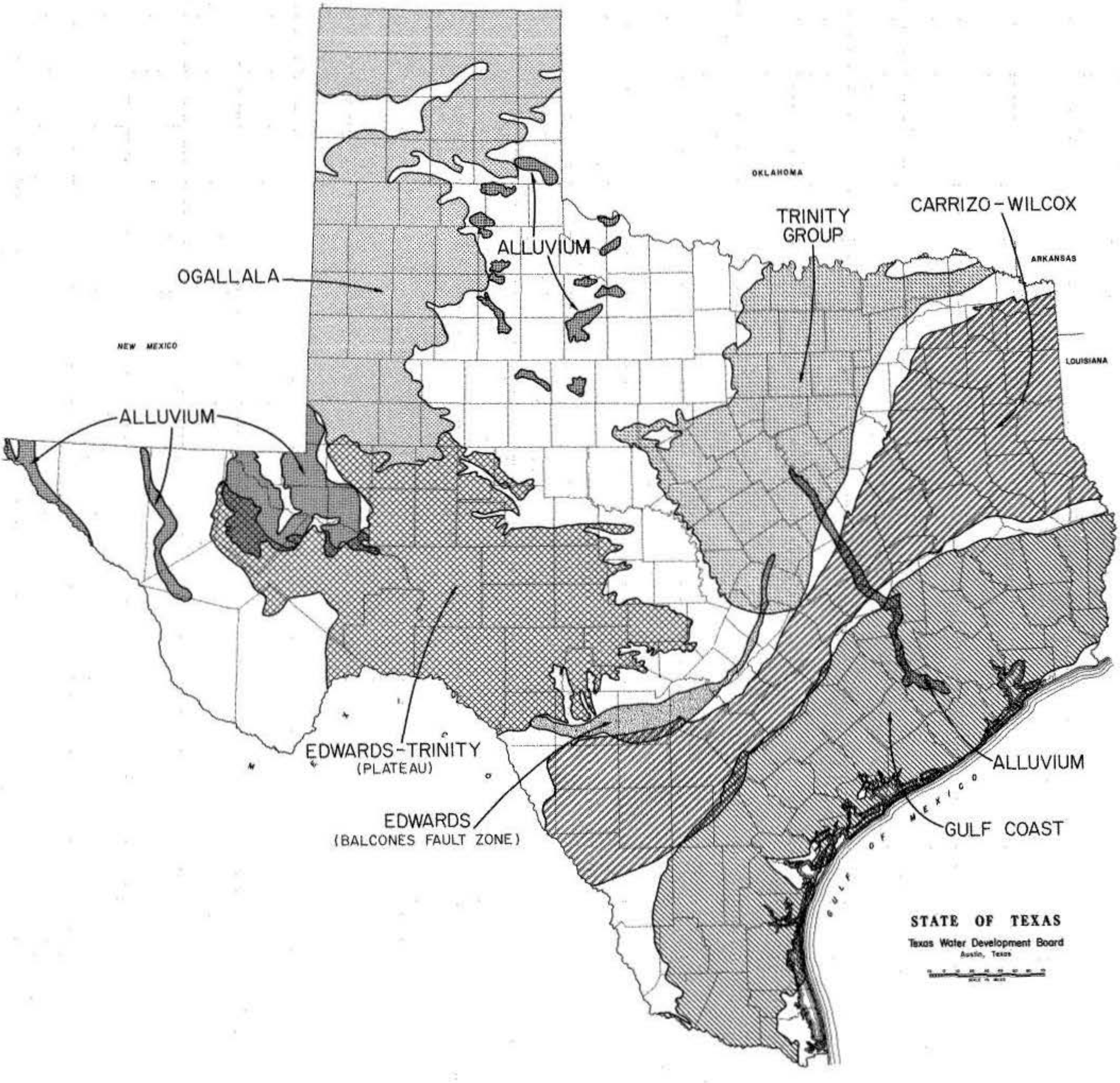

Figure 2. Major aquifers of Texas.

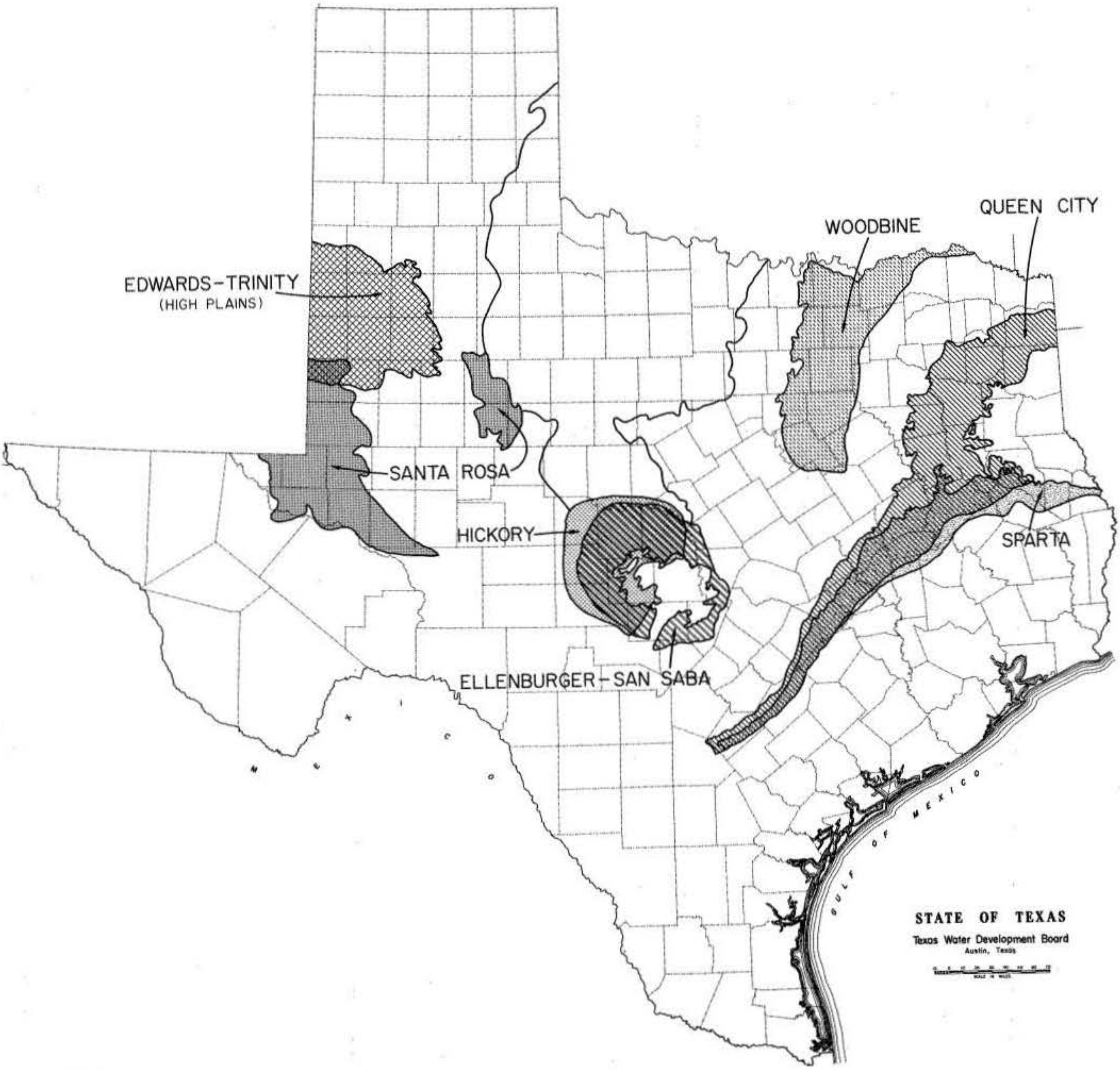

Figure 3. Minor aquifers of Texas.

SUMMARY

Availability of water may be the factor which limits lignite development in Texas. Large amounts of water will be needed for cooling, processing, mining, domestic, and other purposes including the population increases in the area induced by construction and operation of these lignite utilization and conversion facilities. Such facilities include steam-electric powerplants and lignite liquification and gasification plants. Consumptive water requirements for a facility using 25,000 tons of lignite per day (equivalent to a 2,000 MW powerplant, or a 250 million standard ft^3 per day high-Btu gasification plant, or a 50,000 barrel per day liquification plant) could range from 1,000 to 25,000 acre-ft per year, depending on the type of process and cooling system used. Intake requirements could be substantially greater. Maximum water conservation and efficiency can be achieved by using air-cooling wherever feasible or once-through wet-cooling systems located directly on multipurpose reservoirs or estuaries where air-cooling systems are not feasible.

If present trends in lignite utilization and steam-electric powerplant expansion continue, Texas could be mining more than 130 million tons of lignite per year by the year 2000. If it is assumed that most of this lignite is used for producing electricity, water consumption rates could foreseeably exceed 300,000 acre-ft annually by the year 2000. This amount is enough water to supply the consumptive municipal needs of 3.5 million people.

The lignite deposits of Texas occur in the Wilcox Group, Yegua Formation, and Jackson Group of the Texas Coastal Plain; therefore, they stretch from the high rainfall areas of East Texas to the arid regions of South Texas. Surface water, in varying quantities, is generally available in East and Central Texas, but must be acquired from existing water rights permit holders in many cases. In South Texas, surface water is not readily available in some cases and even where available usually must be acquired from existing permit holders.

Ground water is also available for lignite development needs on a site specific basis throughout East and Central Texas and in the northern parts of South Texas, but in the Winter Garden area of the Nueces River basin in South Texas ground-water withdrawal rates from the Carrizo-Wilcox aquifer already exceed natural recharge rates.

Recent and current trends in development and utilization of lignite and construction of lignite-fueled steam-electric powerplants in Texas will continue to have significant impact upon statewide water resource planning by the Texas Water Development Board. The Board's staff is currently assessing the full impact of energy development in Texas as an integral part of updating and revising the 1968 Texas Water Plan.

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IMPEDIMENTS TO THE UTILIZATION OF FLUE-GAS DESULFURIZATION SYSTEMS

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ABSTRACT

The combustion of Gulf Coast lignite will require the utilization of sulfur dioxide emissions-control technology. Given the present status of technology, flue-gas desulfurization is virtually the only viable approach for meeting this requirement. The controversy surrounding this technology is well known, and this paper is devoted to an examination of the principal issues in this controversy. The spectacular early failures are reviewed as are such topics as the chemical nature of this technology in an industry not geared to chemical technology, the uncertainty surrounding the need for implementation of flue-gas-cleaning processes in terms of demonstrable adverse health effects, and the question of system reliability. Specifically with respect to reliability, data are presented which contrast the early experience with this technology with more recent experience. A summary of the present technical and political aspects of flue-gas cleaning is presented.

INTRODUCTION

The combination of the relatively high sulfur content and the relatively low heating value of Gulf Coast lignite virtually assures the need for flue-gas desulfurization (FGD) technology if this lignite is to be used in combustion applications. However, flue-gas desulfurization (FGD) technology has been the focal point for one of the most turbulent experiences in the history of technological development. This paper explores the reasons for this turbulence and examines those factors which continue to contribute to the resistance to the utilization of FGD technology. There are many causes for the present conditions surrounding the utilization of flue-gas cleaning systems. As with all matters of controversy, there are facts available to support all sides of the argument, and the final conclusion is judgmental rather than absolute.

The issue of implementation of FGD technology has been divided into six subtopics in this paper: (1) historical background, (2) nonproductive capital costs, (3) chemical processes, (4) the need for emission control, (5) recent reliability data, and (6) sludge disposal.

A brief presentation of FGD technology, including a discussion of the process chemistry of calcium-based systems, will be given first. This discussion will provide the groundwork on which further discussion can be based.

AN OVERVIEW OF FGD TECHNOLOGY

A discussion of commercially available FGD technology usually centers around four processes: (1) lime/limestone, (2) double alkali, (3) magnesium oxide, and (4) Wellman-Lord. These are generally considered to be the most advanced desulfurization systems since all of them have been, to some extent, successfully demonstrated on full-scale units. There are several new FGD systems which are still in various developmental stages. Some of these systems are the catalytic oxidation (cat-ox) process, the Shell process, and the Foster Wheeler-Bergbau Forschung process (all dry-adsorption processes), as well as the Citrate, the Phosphate, and the Chiyoda processes (wet-scrubbing processes). However, this discussion will be limited to technology which has been well established on a commercial basis in the United States.

Of the aforementioned processes, the four that have been proved are wet-scrubbing systems. The lime/limestone and double alkali are throw-

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[1] Radian Corporation; Austin, Texas 78766.

away processes which produce a solid-waste product containing calcium sulfite and calcium sulfate. The Wellman-Lord and the magnesium-oxide processes are regenerable processes which can generate either concentrated sulfuric acid or an elemental sulfur product. Of these, the Wellman-Lord process is the only one which has not been demonstrated at an electric powerplant in the United States. However, this process has been employed successfully at oil-fired power stations in Japan and in certain refinery applications in the United States. A Wellman-Lord system is scheduled for initiation this year at the Mitchell Station of Northern Indiana Public Service.

The majority of the demonstration units built to date have been lime or limestone systems, as the summary of operational FGD systems shown in table 1 will document. Further discussion of FGD technology, then, will concentrate on lime/limestone systems.

This presentation of lime/limestone FGD technology includes a brief presentation of the overall process chemistry. A presentation of a typical process flow diagram and an explanation of the function of the major equipment is furnished. Also presented is a brief review of some of the problems which have been encountered.

The basis for lime/limestone wet scrubbing is the reaction of an alkaline scrubbing liquor with sulfur dioxide in the flue gas to produce an insoluble waste product. The overall reactions of lime (CaO) and limestone (CaCO) with gaseous sulfur dioxide (SO) to form calcium sulfite are indicated in equations 1 and 2.

$$SO_2(g) + CaO(s) + \tfrac{1}{2}H_2O \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O(s) \qquad (1)$$

$$SO_2(g) + CaCO_3 + \tfrac{1}{2}H_2O \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O(s) + CO_2(g) \qquad (2)$$

Sulfite oxidation results in formation of solid calcium sulfate as shown in equations 3 and 4.

$$SO_2 + \tfrac{1}{2}O_2(g) + CaO(s) + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O(s) \qquad (3)$$

$$SO_2 + \tfrac{1}{2}O_2(g) + CaCO_3(s) + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O(s) + CO_2(g) \qquad (4)$$

Because the calcium sulfite and sulfate salts that are formed are highly insoluble in the aqueous scrubbing liquor, sulfur may be removed from the system using conventional solid-liquid separation technology. Furthermore, since limestone is an inexpensive additive, the economics of the process indicate that this solid product can be discarded. Although lime is somewhat more expensive than limestone, better additive utilization can be achieved with it than with limestone. The process chemistries of lime and limestone systems are very similar, and each system has advantages.

A simplified flow diagram for a typical lime/limestone system is shown in fig. 1. The first step in the process is vapor-liquid mass transfer which occurs in the scrubber. The scrubber provides the means of contacting the SO_2 rich gas with the alkaline scrubbing medium. The function of the hold tank is to provide adequate residence time for additive dissolution and for the precipitation of calcium sulfite and sulfate solids. The clarifier/filter serves as a solid-liquid separation device so that a high-solids-concentration waste stream can be produced. The overflow from the clarifier is recycled to minimize makeup water requirements.

Of all the problems which have been identified during operation of these systems, demister plugging and stack-gas reheat are perhaps the two most frequently mentioned. Work has been performed in these areas, and operation of this equipment is far more reliable now than it was 5 to 6 years ago. Two additional problems which still present operational difficulties in some systems are chemical scaling in the scrubber and sludge quality. Ongoing research in these areas, however, has led to a much better understanding of these problems.

Table 1. Summary of operational FGD systems[1].

Process	Number of units	Megawatts (MW)
Limestone	5	1,189
Lime	5	1,409
Lime or limestone	2	20
Limestone injection	4	765
Double alkali	2	52
Magnesium oxide	1	120
Other	4	293
TOTAL	23	3,848

[1] From PEDCo-Environmental Specialists, Inc., 1976.

HISTORICAL BACKGROUND

The first scrubber installed on an operational system was in England in the 1920's. That system worked because the Thames River was pumped through a scrubber, thereby precluding any problems with solids buildup. The system, however, was abandoned. More recent experience began with the Union Electric Meramac Station. This technology involved the injection of limestone into the boiler and the collection of the calcium-containing species and the fly ash in a wet scrubber.

Most manufacturers are aware of the unsatisfactory, in fact disastrous, performance of the Meramac unit. We know now that the contacting of lime formed in the boiler with water in the wet scrubber produced a high pH, a condition tailor made for $CaSO_3$ scaling. Photographs of the Union Electric completely scaled scrubber were available at various technical presentations. It is probably true that this catastrophic initial failure did as much as any single incident to produce concern about this technology in the minds of those utility plant managers responsible for the continuous operation of electric generating stations.

Other failures followed. In particular, the Lawrence Station of Kansas Power and Light (KP&L) experienced substantial scaling problems. The Lawrence Station also used a limestone-injection process, and this failure together with the Union Electric experience led to the abandonment of the dry limestone-injection approach.

The major problems which were originally anticipated with FGD technology were perceived to be mechanical in nature. For example, great emphasis was placed on systems that would allow good contact between the gas and liquid. The problems at Union Electric and KP&L, however, began to underscore the fact that scrubber technology was a chemical process and that the problems of scaling, corrosion, and overall system performance could be solved only through a sound fundamental knowledge of the chemical principles involved. It has been the concentration on that facet of the problem which has resulted in the significant increases in scrubber reliability which have been observed more recently.

Another aspect of scrubber technology which has caused considerable concern is associated with the solid-waste disposal problem. Calcium-based scrubbers have received the most attention and appear to be the most advanced. But, calcium-based systems produce a sludge which must be disposed of in some environmentally satisfactory fashion. The Commonwealth Edison scrubber at the Will County Generating Station produced a sludge which exhibited singularly undesirable characteristics, and the term "toothpaste" became synonymous with scrubber sludge. Again, photographs were available showing mechanical equipment attempting to move this material to no avail. These pictures along with the advertising campaign of American Electric Power convinced many people that even if scrubbers did work, the world would be up to its neck in "oozy gook," as the ad termed the sludge.

In summary, the early years of development of flue-gas cleaning technology produced several failures, many of which were spectacular. The information regarding these failures was widely disseminated, and they clearly created a deep-seated concern in the electric utility industry.

NONPRODUCTIVE CAPITAL COSTS

Flue-gas cleaning systems do not produce electricity. Although efforts are underway to develop flue-gas cleaning systems which produce a salable by-product, in general these efforts are not so far developed as those involving throwaway systems. Even these processes, however, will produce a product which is outside the mainstream of most business entities requiring flue-gas cleaning technology.

Flue-gas cleaning systems are expensive capital investments. Although cost figures cover an extremely broad spectrum, numbers between $50 and $120 kilowatt are good estimates for just the capital expenditures associated with flue-gas cleaning systems. For a capital-short industry going through what 2 years ago was a financial crisis, the thought of spending an additional 20 to 30 percent of the cost of an electric generating station on nonproductive equipment was difficult to accept. In many instances management was forced into a position of resisting the implementation of flue-gas cleaning equipment on the basis of cost alone. Irrespective of whatever environmental benefit might be derived from the technology, cost continues to be a major area of concern *for an industry which is only moderately* healthier than it was 2 years ago.

CHEMICAL PROCESSES

The purpose of an electric utility is to generate, transmit, distribute, and market electric power. Although electric utilities are not the only users of FGD systems, clearly they are among the most likely. An electric utility is staffed to meet the needs of its business. It uses mechanical equipment to generate electric power and accordingly, its engineering activities are predominantly mechanical and electrical. Further, plant operators are trained to operate mechanical and electrical equipment. Flue-gas desulfurization processes are chemical processes, and if the capital costs associated with the scrubbing system for a major electric generating station were compared to the cost of the typical petrochemical plant, the cost of the scrubbing system would be of the same order of magnitude as many large petrochemical facilities. A completely different technological focus is required to operate and maintain an FGD system. Operators must be retrained; chemical engineers must be included in the engineering staff; different types of process-control equipment must be purchased and maintained.

An important facet of the problem is the inevitable resistance to radical change. The electric utility industry has a proud tradition of high system reliability and relatively low costs. This FGD technology, because it is totally outside the mainstream of electric utility operations, raises substantial concern in the minds of those charged with the continuation of that tradition.

NEED FOR EMISSION CONTROL

Some of the most vigorous resistance to FGD technology has been instigated primarily because the utility management could not be convinced of the need for this type of technology. The electric utility industry has a record of willing compliance with environmental initiatives which offer a favorable cost/benefit ratio. The controversy surrounding health effects of SO_2, sulfates, nondeterioration of air quality, and so forth has created in the minds of many legitimate concern regarding the need for implementing expensive technology where the benefit has appeared incremental. This concern particularly has been true when electric generating stations have been sited deliberately in remote locations to minimize their environmental impact on population centers. The concept of the intermittent control system which focuses on the ambient air quality standard is a product of precisely that situation. It has been difficult for many to understand the need for meeting new source performance standards when ambient concentrations have been a minor fraction of the ambient standards and when the impact of a new facility of that low ambient level would be small.

RECENT RELIABILITY DATA

Recently major strides have been made in the direction of achieving a better understanding of the process chemistry involved in lime/limestone systems. Some of this increased understanding is reflected in the improved system performance data, which have been published recently. Four parameters that are frequently used to measure system performance are shown in table 2. Some understanding of the basis of these parameters is essential to properly interpret FGD systems performance data. No one parameter appears to adequately document system performance. Some combination which supplies a measure of FGD system responsiveness as well as a measure of the stress applied to the system would be ideal. PEDCo recommends combining operability and utilization. Unfortunately, the data needed to calculate these parameters are not available for all systems.

Table 3 presents data tabulated for the Electric Power Research Institute by Battelle. These data are for systems brought on-line prior to 1975. Comparable data collected by PEDCo for the Environmental Protection Agency (EPA) are shown in table 4. Several comments are noteworthy. First, Lawrence 4 and 5 reliabilities are essentially 100 percent, but this level is achieved by cleaning each scrubber once a week and by washing the mist eliminators and reheaters nightly. This approach is possible at Lawrence because the unit load swings allow sufficient time for cleaning.

Table 2. FGD system performance parameters (definitions).

$$\text{Availability } (\%) = \frac{\text{Hours FGD system was available for operation}}{\text{Hours in time period}} \times 100$$

$$\text{Reliability } (\%) = \frac{\text{Hours FGD system was operated}}{\text{Hours FGD system was called upon to operate}} \times 100$$

$$\text{Operability } (\%) = \frac{\text{Hours FGD system was operated}}{\text{Hours boiler operated}} \times 100$$

$$\text{Utilization } (\%) = \frac{\text{Hours FGD system was operated}}{\text{Total hours in time period}} \times 100$$

Experience with more recently designed lime and limestone tailend scrubbers is more encouraging. The Will County No. 1 Unit, for instance, has shown vast improvement in performance. Module B was closed in May 1973 to concentrate efforts on solving the problems in Module A. The average operability of Module A for 1974 was 67 percent. However, if a slightly different time period is chosen, system performance can be viewed quite differently. Module A operability for 1 year beginning April 1974 was 89.9 percent. This very respectable performance was in part caused by a redesign of the demister wash loop. Fresh water is now used for washing, and the mist eliminator wash effluent is discharged from the system. Module A, which has been off-line since July 1975, is awaiting the arrival of new reheaters. Also, the boiler, turbine, and other scrubbing system components have undergone modifications which began in October 1975. Both modules were scheduled to be restarted in March 1976. Certainly, Will County cannot be considered to be a completely successful demonstration. However, many problem areas have been identified in this system, and solutions are being sought.

Present procedures at Ly Cygne call for cleaning one module each night on a rotational basis while keeping all modules available during daytime peak hours, and this means that each scrubber gets cleaned once every 7 to 10 days. If the average availability can be maintained at 86 percent or higher using this procedure, the boiler can remain at full load 100 percent of the time. Although this procedure is not the optimal method of operating a unit, the PEDCo data indicate that the system is functioning adequately under these conditions. Battelle's comments run contrary to this. Their reported availabilities are somewhat lower, and Battelle indicates that Kansas City Power and Light is contemplating building an eighth scrubber module to maintain plant operation. In any case, a large portion of Ly Cygne's operating problems are acknowledged by the utility to be caused by the high fly ash concentrations in the recirculating slurry. These high fly ash slurry concentrations are caused by the lack of primary particulate controls at Ly Cygne (PEDCo-Environmental Specialists, 1976).

Both Cholla and Paddy's Run No. 6 are documented successes; however, both operate under conditions which are not universally applicable. The Paddy's Run unit operates with a carbide lime additive. It also is a peaking unit and as such does not have a heavy load factor. Although the unit has been operated primarily for test purposes, it has run as many as 45 days continuously with no process problems. The upcoming EPA test program, which is scheduled at Paddy's Run later this year, hopefully will provide a basis for extrapolating the Louisville Gas and Electric success to other units.

Cholla No. 1, which employs limestone as its alkaline additive, also has operated for 45 days continuously. However, two operational procedures cloud this success somewhat. First, the sulfur concentration in the coal is low—in the 0.4 to 1 percent range. Secondly, the system presently operates in an "open loop" mode with no clarified liquor return from the pond. Open loop operation is possible with this system because of the high pond-evaporation rates obtained at the plant site. Open-loop operation may not be possible when Cholla No. 2 comes on-line, an event scheduled for mid-1977.

Although these data do not indicate that scrubber success now can be guaranteed, a trend of improving scrubber reliability is clearly evident. Additional research prompted by early failures has led to improved designs. An understanding of the reasons for some of the early failures

Table 3. Battelle's availability data for FGD demonstration plants.[a]

Utility and Plant	Capacity, MW	Process Type	Initiation (month/year)	Annual Availability, percent 1972	1973	1974
Kansas Power and Light						
Lawrence 4	125	Limestone injection/ wet scrubbing	10/68			
Lawrence 5	400	Limestone injection/ wet scrubbing	9/71			
Kansas City Power and Light						
Hawthorn 3	125	Limestone injection/ wet scrubbing	11/72	DNA[b]	40	40
Hawthorn 4	140	Tail-end limestone scrubbing	8/72	DNA	40	40
Ly Cygne	820	Tail-end limestone scrubbing	6/73	—	45	45
Commonwealth Edison						
Will County No. 1	165	Tail-end limestone scrubbing	2/72	29.5	27.1	69.0
Arizona Public Service						
Cholla[c]	125	Tail-end limestone scrubbing	12/73	—	—	91.5
Louisville Gas and Electric						
Paddy's Run No. 6	70	Lime scrubbing	4/73	—	90	100
Duquesne Light						
Phillips	387	Lime scrubbing	8/73	—	low	<50
Southern California Edison						
Mohave 2[c]	790	Lime scrubbing	11/73	—	—	85.4

[a] From Rosenberg and others, 1975.
[b] Data not available.
[c] Low-sulfur coal.

Table 4. Data for FGD demonstration plants.[a]

Utility and Plant	Initiation (month/year) Start-up Date	Annual Availability, percent 1972	1973	1974	1975
Kansas Power and Light					
Lawrence 4	12/68	Not reported by utility			
Lawrence 5	11/71	Not reported by utility			
Kansas City Power and Light					
Hawthorn 3	11/72	—	—	—	23[b]
Hawthorn 4	8/72	—	—	—	34[b]
Ly Cygne No. 1	2/73	—	—	76[c]	84
Commonwealth Edison					
Will County No. 1	2/72	23[c,e]	22[c,e]	67[c,e]	40[c,e]
Arizona Public Service					
Cholla	12/73	—	—	91[d]	88[d]
Louisville Gas and Electric					
Paddy's Run No. 6	4/73	—	67[e,g]	98[e]	100[e]
Duquesne Light					
Phillips	8/73	—	—	—	57[b]
Southern California Edison					
Mohave 2	11/74	—	—	61[f]	—

[a] From PEDCo - Environmental Specialists, 1976.
[b] Last half of 1975.
[c] 'A' module only.
[d] Reliability rather than availability.
[e] Operability rather than availability.
[f] Four months testing.
[g] Last 5 months of 1973.

has furnished the scrubber industry with the necessary background to design successful scrubbing systems. It is therefore reasonable to expect that future systems should have higher reliabilities than those units operating today.

SLUDGE DISPOSAL

Disposal of the solid waste produced by throwaway systems has been an area of major concern. The first problem encountered was one of producing a solid which could be disposed of in ponds. Some sludges tend to be thixotropic and will not support much weight. However, several fixation methods are available which improve this situation significantly. An example is the sludge at Will County No. 1 where the addition of lime and fly ash has solidified the solid waste and made the sludge manageable.

Another area of concern has been the possibility of ground-water contamination by hazardous material such as trace metals which may be leached from sludges in unlined ponds. The Radian Corporation has completed a study of the environmental effects of trace metals in the disposal of ash and FGD sludge (Holland and others, 1975). The conclusions of this study indicate that trace-metal leaching from sludge is not a major source of ground-water pollution. Most soils provide sufficient absorption of trace metals to insure that proposed EPA regulations for public waters supply intake are met. Although increases in total dissolved solids may still be a potential problem, location of disposal ponds away from local water supply sources will minimize the danger.

CONCLUSIONS

Calcium-based FGD systems can be designed to be operated reliably in an electric utility generating station. Certainly not every scrubber system has been so designed in the past, and it is not certain that all future systems will be so designed. But, in terms of technological capability, sufficient information is known regarding the chemistry of these systems to achieve reliabilities comparable to those obtained with other electric utility industry equipment. It must be recognized, however, that to achieve this level of reliability, cost cannot be cut to the absolute minimum. It was demonstrated recently that cost cutting in the electrostatic precipitator industry (an established technology) produced some rather spectacular failures in precipitator performance. The same could occur with FGD systems. Margins for error must be included in the process and equipment designs if scrubber reliability is to be maintained.

Technology is available to render the disposal of scrubber sludges environmentally acceptable. Recent information indicates that surface disposal of scrubber sludges is an environmentally acceptable option. Fixation processes also can be used if required.

Flue-gas desulfurization systems are expensive. Although the construction costs of FGD systems have been reduced somewhat over the past several years, to retrofit the old systems continues to be expensive. If it is desirable to use high-sulfur coal or oil and if new source performance standards continue to be enforced, FGD technology is the only near-term option which will permit the utilization of high-sulfur coal. Even if gasification or liquefaction technology were available on a commercial scale, the cost apparently would be substantially higher than FGD system cost.

Once the reliability of FGD systems is accepted, several key questions remain to be answered: (1) Should this technology be installed? (2) Should FGD systems be required in areas where ambient air-quality standards already are met? (3) Should intermittent control systems be permitted in such circumstances? and (4) Is nondeterioration a desirable aspect of environmental control? These are political questions and outside the scope of this presentation, but these issues are realistic impediments to the implementation of FGD technology, and it is these judgmental issues which now must be addressed. System reliability and control of sludge quality no longer appear to be the major impediments to the utilization of FGD technology.

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SUITABILITY AND AVAILABILITY OF TEXAS LIMESTONE FOR FLUE-GAS DESULFURIZATION

T. J. Evans[1] **and M. G. Moseley**[1]

ABSTRACT

The proposed use of limestone-based wet scrubbers to control sulfur dioxide emissions from large powerplants in Texas focuses attention on the relative suitability and availability of Texas limestone for such use. Flue-gas desulfurization systems are being constructed or planned for six generators at three locations—Martin Lake units, 1, 2, 3, and 4; Monticello unit 3; and San Miguel unit 1. The generation capacity of each of these units is 750 megawatts, with the exception of the 400-megawatt unit at San Miguel.

Review of basic chemical reactions and the results of testing and analyses reported in the literature indicate that the dissolution rate of limestone particles is an important parameter affecting scrubber behavior. Several Texas limestones were collected for this study with most coming from quarries currently operating. Evaluation of these samples included spectrographic analysis, wet-chemical determination of CaO and MgO, particle-size analysis, determination of dissolution rate at constant pH in H_2SO_3, and mineral analysis from thin-section examination. Texas limestones display a wide range of dissolution rates. Factors controlling dissolution rate are related to particle surface area, as reflected by average particle size.

Limestone consumption in the six Texas generators scheduled for operation with flue-gas desulfurization equipment by early 1981 is estimated to be less than 1 million tons per year. This annual requirement is only about 2 percent of the annual crushed limestone production in the State and is an insignificant part of the total estimated limestone resources (6 trillion tons) in the vicinity of the lignite-fueled powerplants.

A variety of supply modes and adequate railway and highway networks insure strong competition among suppliers of limestone for flue-gas desulfurization systems. Estimated total cost per ton of limestone at the generation site ranges from $4 to $13, depending on haul distance and mode of supply.

INTRODUCTION

Flue-gas desulfurization (FGD) systems constitute one strategy for compliance with Federal and State air-quality regulations restricting sulfur dioxide (SO_2) emissions from fossil-fuel-fired steam-electric powerplants. Steam-electric generators receiving permits in Texas after 1971 must comply with the Federal new-source performance standards of 1.2 lbs SO_2 emissions per million Btu input.

In the United States, 20,000 megawatts (MW) of generating capacity will have some type of FGD system in the near future (table 1). These FGD systems encompass a wide range of processes and additives, but limestone-based systems are the principal type of scrubber being considered. Based on generating capacity, limestone-based scrubbers comprise 64 percent of all operational FGD units and 51 percent of those units under construction or in the active planning stage.

FGD systems will be installed on at least six generators at three locations in Texas (fig. 1). All six generators will be outfitted with limestone-based nonregenerative (throw-away) units. Martin Lake, which will be one of the largest coal-fired powerplants in the country, will use Research-Cottrell scrubbers on each of the 750 MW generators. Another 750 MW generator, Monticello 3, will be outfitted with scrubbers marketed by Chemico. San Miguel 1, a 400 MW unit, will probably use the FGD unit vended by Babcock and Wilcox. Installation of scrubbers on the Monticello 3 generator, at an estimated cost of $36 million ($48 per kilowatt of installed capacity), is pres-

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ently in litigation regarding the validity of State regulations requiring the use of present FGD technology. The outcome of this suit will have a profound effect on the future use of FGD systems in Texas.

Table 1. Flue-gas desulfurization systems in the United States: generating capacity (number of units shown in parentheses. From Slack, 1975).

Status	Additive Limestone, MW	 Other (lime, etc.), MW	Total
Operational	2,154(11)	1,208(10)	3,362(21)
Under construction	2,390(16)	5,140(16)	7,530(32)
Planned[a]	5,927(13)	2,895(8)	8,822(21)
Total	10,471(40)	9,243(34)	19,714(74)

[a] Planned includes units for which contracts have been awarded or for which letters of intent have been signed.

LIMESTONE SCRUBBERS: GENERAL PRINCIPLES

The principle upon which limestone-based FGD systems operate can be generalized in the following reaction:

$$2CaCO_3 + 2SO_2 + 2\tfrac{1}{2}H_2O + \tfrac{1}{2}O_2 \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O + CaSO_4 \cdot 2H_2O + 2CO_2 \quad (1)$$

A slurry of limestone and water is brought into contact with a flue gas containing SO_2 reacting to produce calcium sulfite and calcium sulfate.

In actual practice, however, a more complex series of reactions is involved (table 2). According to Nannen and others (1974), gas-phase diffusion (items 1 and 2, table 2) and limestone dissolution (item 5, table 2) are the important reactions affecting SO_2 removal in this type of scrubber.

A typical limestone-based scrubber, such as that which will be used in Texas, comprises several elements (fig. 2). Flue gas from the lignite-fired boiler is passed through a high-efficiency electrostatic precipitator for particulate removal. Removal efficiencies ranging from 99.1 to 99.8 percent will be required for the typical lignites that will be burned at the Texas powerplants mentioned previously. The flue gas is next brought into contact with a limestone slurry containing about 5- to 15-percent solids. The slurry, supersaturated with respect to calcium sulfite and sulfate, is routed to an absorber tank where adequate time is provided to complete the formation of the reaction products, precipitate these solids, and introduce the required "makeup" limestone. A waste sludge, containing calcium sulfite, calcium sulfate, and unreacted limestone, is removed from the system and transported to a disposal site. Texas powerplants will use large sedimentation ponds for sludge disposal. Clarified water can be returned from these ponds for use in the slurry.

Commercially available scrubbers differ mainly in their method of maximizing the additive surface area available for reaction with SO_2. Adjustment of liquid-to-gas ratios (generally about 50 to 65 gal of slurry per 1,000 ft^3 of flue gas) and the use of "packing" are two common approaches to this problem. The Research-Cottrell unit shown in figure 2 uses both schemes in its three-stage absorption tower. Additional techniques for maximizing additive surface area per unit of SO_2 input include grinding limestone to finer particle sizes and using limestone in quantities exceeding stoichiometric requirements. Other approaches center around the use of additional chemicals to enhance $CaCO_3$ dissolution, such as benzoic acid or magnesium sulfate (Kim and others, 1975; Cronkright and Leddy, 1976).

Limestone dissolution rates can be a significant factor in the scrubber operation, with scrubber efficiency enhanced by higher dissolution rates. Higher rates of dissolution allow greater additive surface area to be exposed to the incoming SO_2; thus, with all other factors being equal, limestone that dissolves most rapidly in the scrubber liquor is the most desirable stone among other similarly available limestones.

TEXAS LIMESTONE: SUITABILITY

The purpose of this study is to measure relative rates of dissolution of Texas limestones. Relative dissolution rates are believed to be a useful guide to evaluating relative suitability of these materials for use in limestone-based FGD systems.

The scope of this study includes sampling a broad range of carbonate materials within a reasonable distance (about 200 miles) of the major lignite deposits. Sixty-six samples were collected from 28 localities (fig. 3). Samples included dolomite, dolomitic limestone, coarse- and fine-crystal-

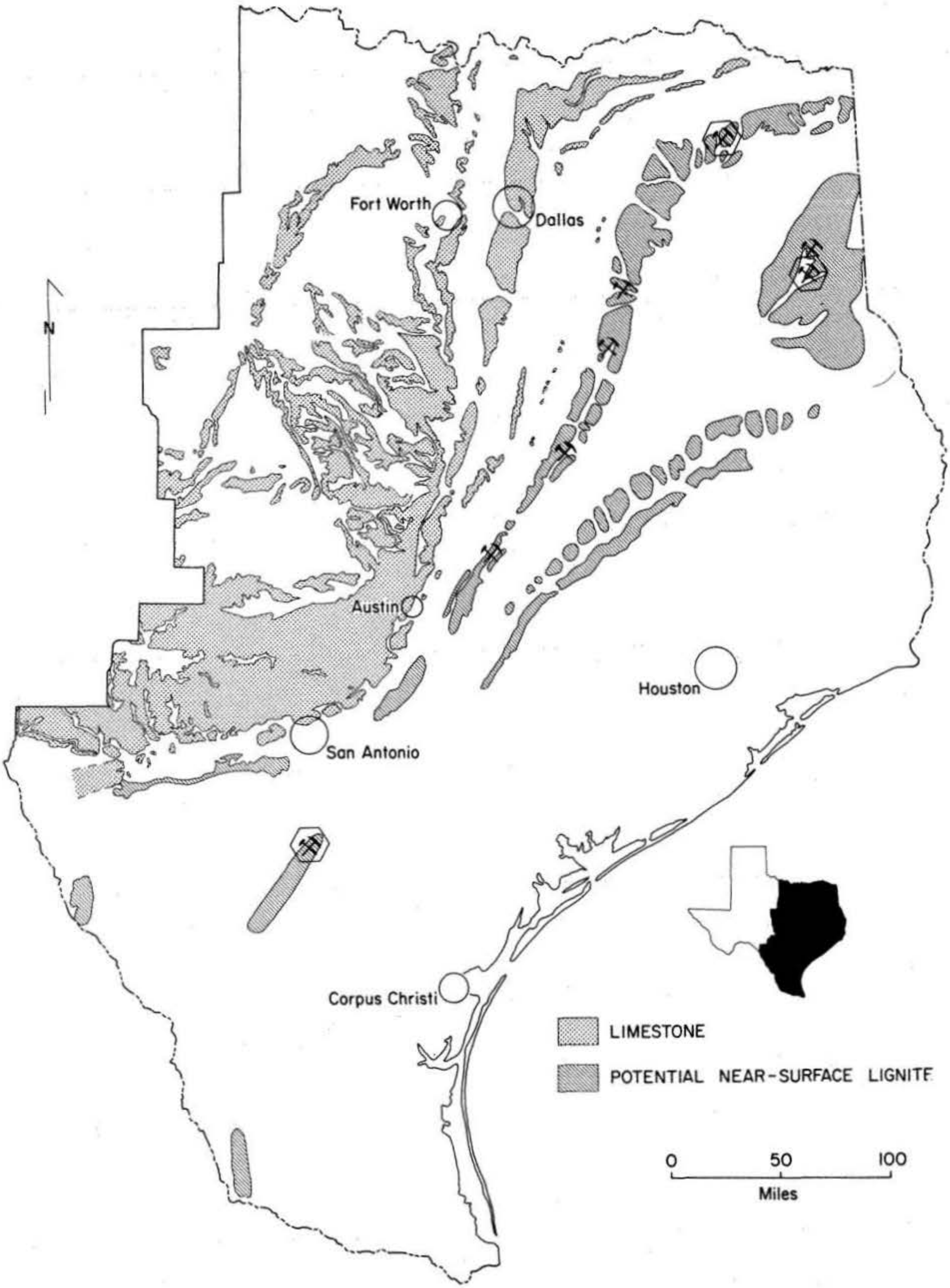

Figure 1. Distribution of limestone outcrop, near-surface lignite, active and proposed lignite mines, and locations of plants planning to use FGD systems. Limestone outcrop from available geologic mapping and near-surface lignite deposits from W. R. Kaiser (personal communication, 1976).

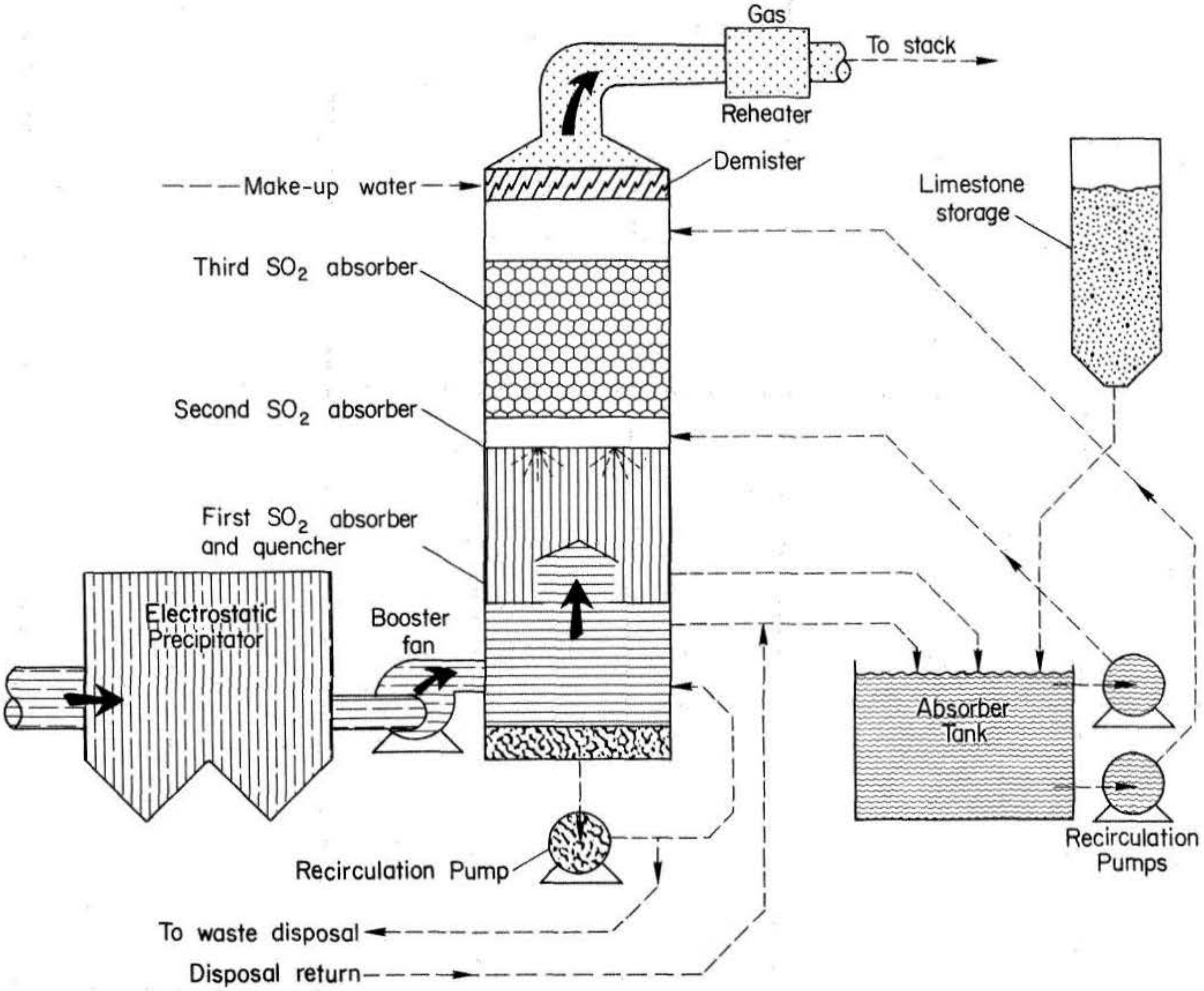

Figure 2. Research-Cottrell limestone-based FGD system similar to those to be used at Martin Lake Steam-Electric Station, Texas. After Slack (1976) and Chemical and Engineering News (1975).

line limestone, oyster shell, caliche, pulverulent limestone, and a calcitic sludge. Mostly operating crushed stone quarries were selected for sampling so that the results would reflect materials actually available; however, outcrop samples and other kinds of samples were collected to insure a broad range of stone types and a broad geographic distribution. At active production sites, only processed stone was sampled, including coarse aggregate (4- to 6-inch stone), smallest sized commercial aggregate, and the "unders" or "fines" which are commonly stored in large waste ponds or piles. The geologic age of the limestone units ranges from Ordovician to Eocene; Recent caliche and oyster shell samples were also collected.

TESTING PROCEDURE

Two kinds of samples—massive and particulate—were processed through a series of physical and chemical tests. Massive samples, principally

Table 2. Principal chemical reactions and diffusion steps in a limestone-based FGD unit (from Nannen and others, 1974).

1. Diffusion of SO_2 to and through the gas-liquid film
2. SO_2 (gas) $\rightleftarrows$ SO_2 (aqueous)
3. SO_2 (aqueous) + $HO_2 \rightleftarrows H_2SO_3 \rightleftarrows H^+ + HSO_3^-$
4. $HSO_3^- \rightleftarrows H^+ + SO_3^=$
5. $CaCO_3$ (Solid) $\rightleftarrows$ $CaCO_3$ (aqueous) $\rightleftarrows Ca^{2+} + CO_3^{2-}$
6. Diffusion of H_2SO_3 and ions through the liquid film and into the region of dissolved limestone (Ca^{++})
7. $Ca^{2+} + SO_3^= + \frac{1}{2}H_2O \rightleftarrows CaSO_3 \cdot \frac{1}{2}H_2O$ (solid)
8. $CaSO_3 \cdot \frac{1}{2}H_2O + \frac{1}{2}O_2 + 1\frac{1}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O$ (solid)

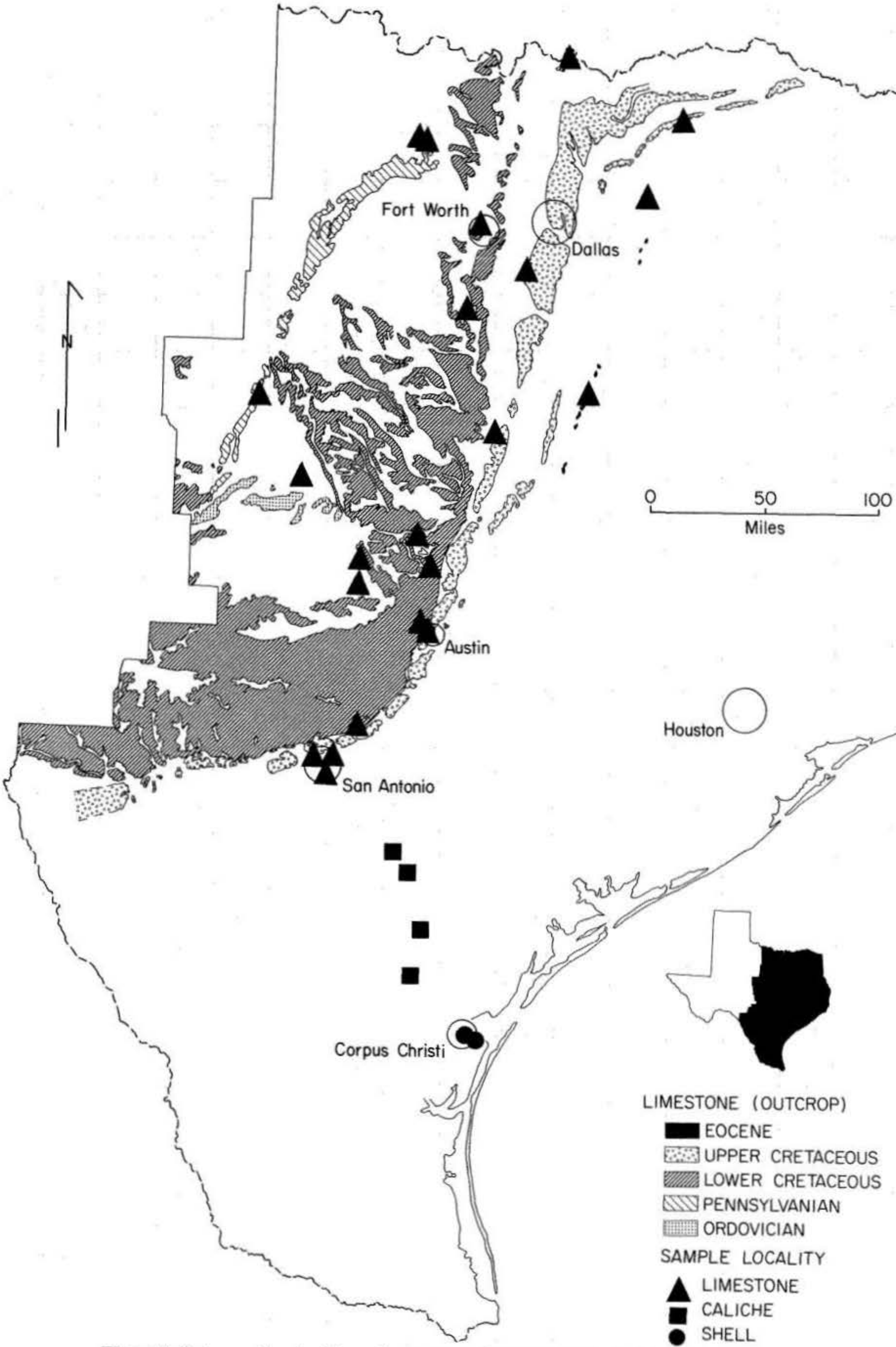

Figure 3. Outcrop of major Texas limestone units near the lignite belt and sampling locations for limestone suitability/availability study.

coarse aggregate or hand-sized specimens, were thin sectioned for mineral identification. Particulate samples (fine aggregate) were tested as received for rate of dissolution, particle-size distribution, and specific surface area. Splits from all samples were crushed to 100 percent minus 200 mesh (100 percent less than 74 microns) and tested in the following manner: emission spectographic analysis for oxides content, EDTA titration for determination of weight-percent CaO and MgO, particle-size distribution by hydrometer and sieve, and specific surface area.

The dissolution rate of the limestone samples was determined by titrating 0.5 N sulfurous acid (H_2SO_3) into a limestone slurry at a constant pH. The slurry was prepared by adding 1 g of the limestone to 200 ml of distilled water. A continuous-reading pH meter was used to monitor slurry-acid pH; H_2SO_3 consumed at 1-minute intervals for 10 minutes was recorded. As the limestone dissolves in the water, acid must be added to maintain the low pH; thus, the more rapid the rate of dissolution, the more milliliters of H_2SO_3 that must be added to the slurry. All testing was completed under standard temperature and pressure conditions in the Mineral Studies Laboratory at The University of Texas at Austin.

Dissolution rates determined in this study can be considered only as approximations of real dissolution rates and have significance only in relation to other samples tested in a similar manner. Since operating conditions in a limestone-based scrubber are different from these laboratory conditions, such laboratory tests should be considered as only a preliminary step to more complete stone characterization. More sophisticated laboratory-scale testing (Ottmers and others, 1973; Kim and others, 1975; Harvey and others, 1974; Drehmel, 1972) encompassing a broad range of variables, such as temperature, partial pressure of oxygen, limestone particle size, slurry pH, and so on, is the next logical step for stone evaluation. Studies to date have focused primarily on laboratory processes and variations among the many variables involved; however, these studies have used a limited range of limestone types. Beyond laboratory testing, a pilot plant is the next relevant step to stone evaluation. Pilot plant scrubbers have been installed on two powerplants in Texas for additive testing, as well as for adapting the scrubber to the particular fuel characteristics at that site. Pilot-plant-scale testing should constitute part of the basis for stone selection. In the context of the nature of the testing completed for this study, the dissolution rates determined are believed to reflect relative limestone suitability; these simple and inexpensive tests, therefore, can constitute an initial step for selecting a limestone for use in an FGD system.

RESULTS OF TESTING

Figure 4 shows dissolution rates for some limestone samples, which were selected to illustrate the range in rates of dissolution observed in the course of this study. It is clear that Texas limestones display a wide range of dissolution rates as determined by H_2SO_3 titration at constant pH. Since the rate of dissolution declines rapidly after the first minute of testing, the 1-minute reading for H_2SO_3 consumption is chosen for comparison purposes throughout the study.

Effects of Particle Size

For samples differing only in the average size of particles, the split with the smaller average particle size shows a faster dissolution rate. Fig-

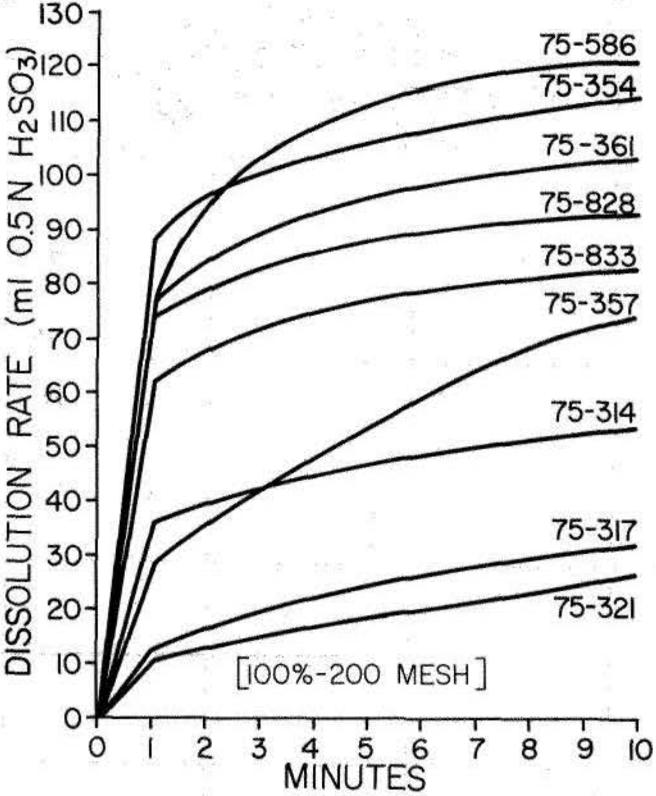

Figure 4. General results of dissolution rate testing for a selected group of samples. Samples included display a range of dissolution rates typical of that observed for all samples crushed to about the same size (100 percent minus 200 mesh).

ure 5 illustrates the variation in dissolution rates between as-received particulate samples and their splits crushed to 100 percent minus 200 mesh. Dissolution of limestone in aqueous media is primarily a function of surface area, and smaller particles have a greater surface area relative to their volume than larger particles. The relationship of increasing dissolution rate with decreasing particle size is expected and has been demonstrated by many other workers (Harvey and others, 1974; Kim and others, 1975; Drehmel, 1972).

Similarly, the determination of specific surface area (surface per unit weight) should also be inversely related to rates of dissolution for crushed limestone samples of generally similar size. Differences in surface area among these samples would be related to differences in particle shape, roughness, porosity, and so forth, since average particle sizes are generally similar. All splits crushed to 100 percent minus 200 mesh were evaluated for specific surface area using the Blaine air-permeability apparatus (American Society for Testing and Materials, 1975). This testing method measures the external surface area of a group of particles relative to a known or standard sample. Air permeability methods should yield surface areas that are a realistic approximation of true external surface areas; however, as figure 6 shows, results of the Blaine test do not correlate with dissolution rates. Two reasons for this lack of correlation are suggested. (1) The Blaine test is empirical, sensitive to operator error, and designed for testing cement fineness; therefore, results for limestone particulate samples may not accurately reflect surface areas. More sophisticated methods, such as gas absorption, are probably necessary. (2) In the small particle-size ranges (100 percent minus 200 mesh) other factors such as stone purity may be important and thus affect the expected inverse relationship between specific surface area and dissolution rate.

Effects of CaO Content

CaO and MgO content for all samples were determined by standard EDTA titration techniques. Figure 7 illustrates the relationship of dissolution rates for the minus 200 mesh splits with CaO and MgO content expressed in weight percent. A general correlation of higher dissolution rates with increasing CaO content is clearly discernible; an inverse relationship with MgO content is less clearly suggested. Thus, stone purity as reflected by CaO content can be an indicator of relative suitability for use in FGD systems for limestone samples crushed to about the same average particle size (100 percent minus 200 mesh).

Rock-type identification from hand-specimen and thin-section examination shows some correlation with dissolution rate because dolomite exhibits consistently low dissolution rates. Figure 8 shows rock types for CaO versus dissolution rate comparisons. The low CaO stones, such as dolomite and some caliche and dolomitic limestone, fall toward the lower end of the range of dissolution rates observed among stones crushed to about the same size. However, among limestones (both coarse and fine crystalline), pulverulent limestones, chalks, shell, and some caliches and dolomitic limestone the rock type alone does not distinguish samples with high rates of dissolution from samples with low rates. Therefore, determination of CaO content for a group of uniformly small-sized samples may be a useful guide to predicting relative dissolution rates, but rock-type distinctions do not appear similarly useful.

SUMMARY

The results of testing a variety of Texas limestones and other carbonate materials lead to two conclusions: (1) Particle size of crushed limestone is a primary factor affecting rates of dissolution; and (2) stone purity, as reflected in weight-percent CaO, is an indicator of relative dissolution rates among particle samples all crushed to about the same size. The importance of particle size is related to the surface area of limestone particles exposed to the SO_2; however, lack of correlation of specific surface area with dissolution rates among similar-sized samples (100 percent minus 200 mesh) suggests that at these small sizes other factors may become important. The general correlation of CaO with dissolution rates for these samples less than 74 microns in size indicates that stone purity is one of these factors and should be considered when choosing a limestone additive for an FGD unit.

Determination of dissolution rates by the titration technique described must be considered only as an indicator of relative suitability for use in a limestone-based FGD system. Further testing, preferably at a pilot plant, is necessary prior to stone selection.

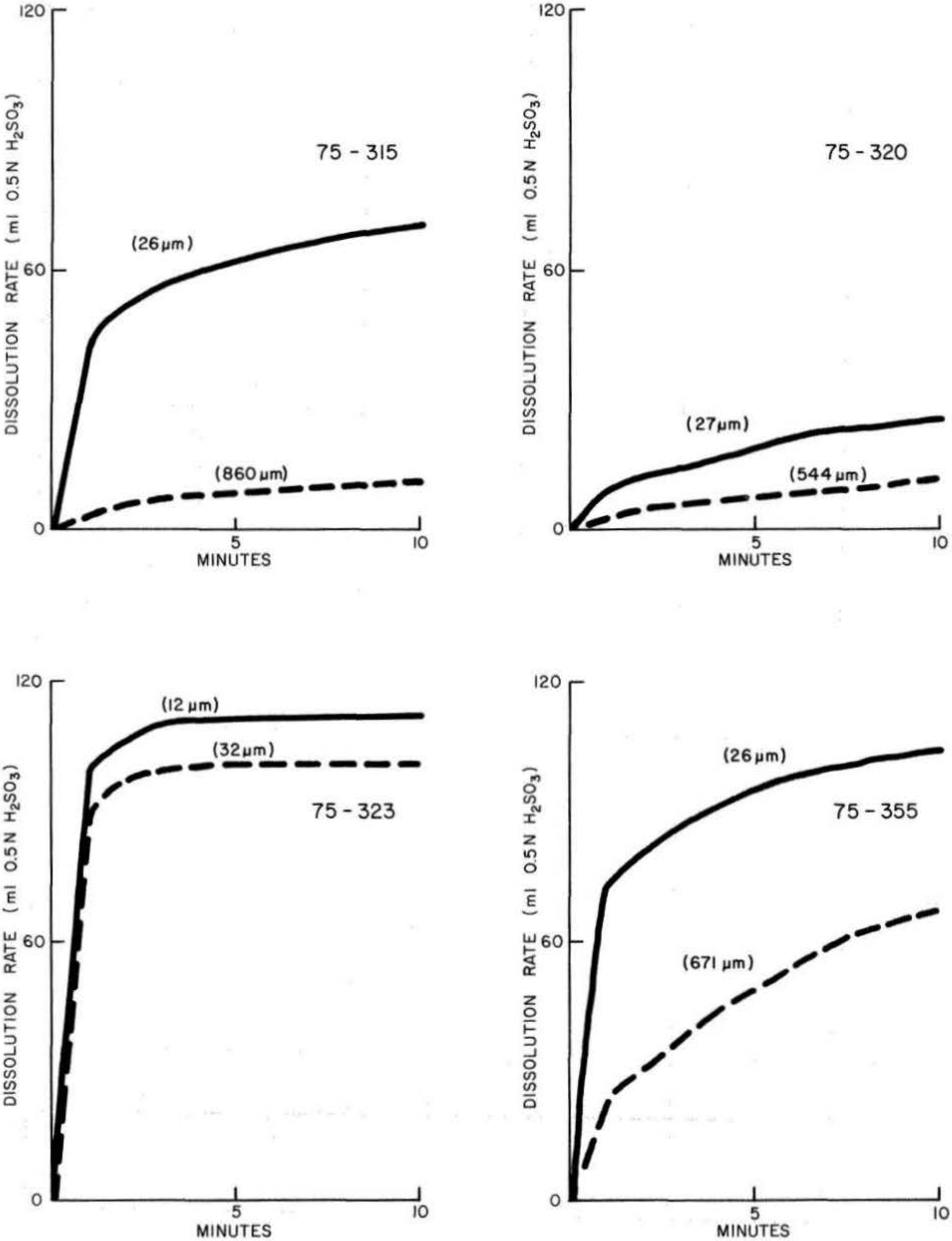

Figure 5. Comparison of changes in dissolution rates for as-received particulate samples and pits crushed to 100 percent minus 200 mesh. Average particle size shown in microns. Samples chosen illustrate range of results typical of all similar samples. 75–315 and 75–355 are coarsely crystalline limestones; 75–320 is a dolmite; 75–323 is a finely crystalline limestone commercially available in a very small average particle size.

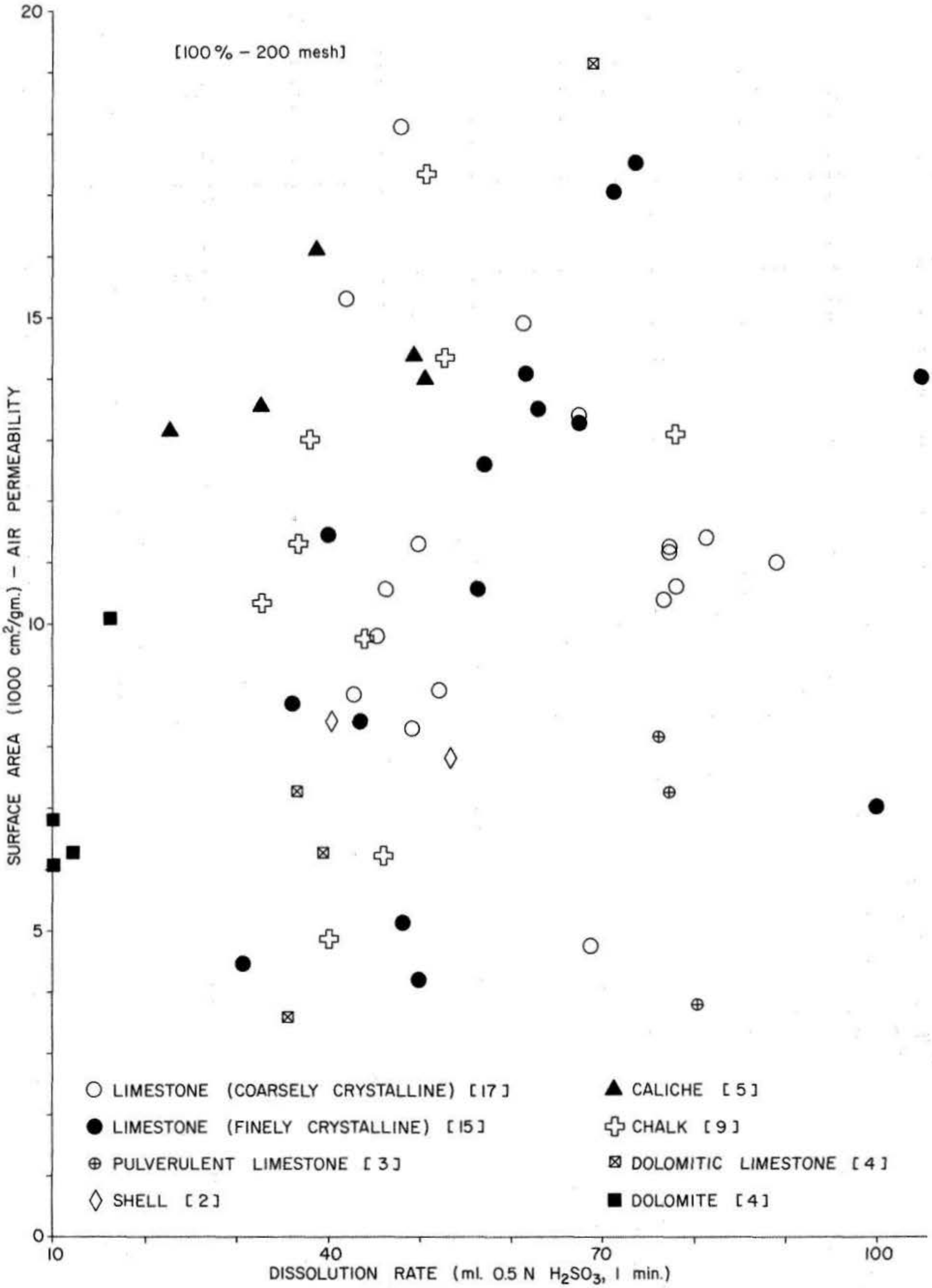

Figure 6. Dissolution rates versus surface area determined by air-permeability apparatus. Samples distinguished by rock type; all samples 100 percent minus 200 mesh.

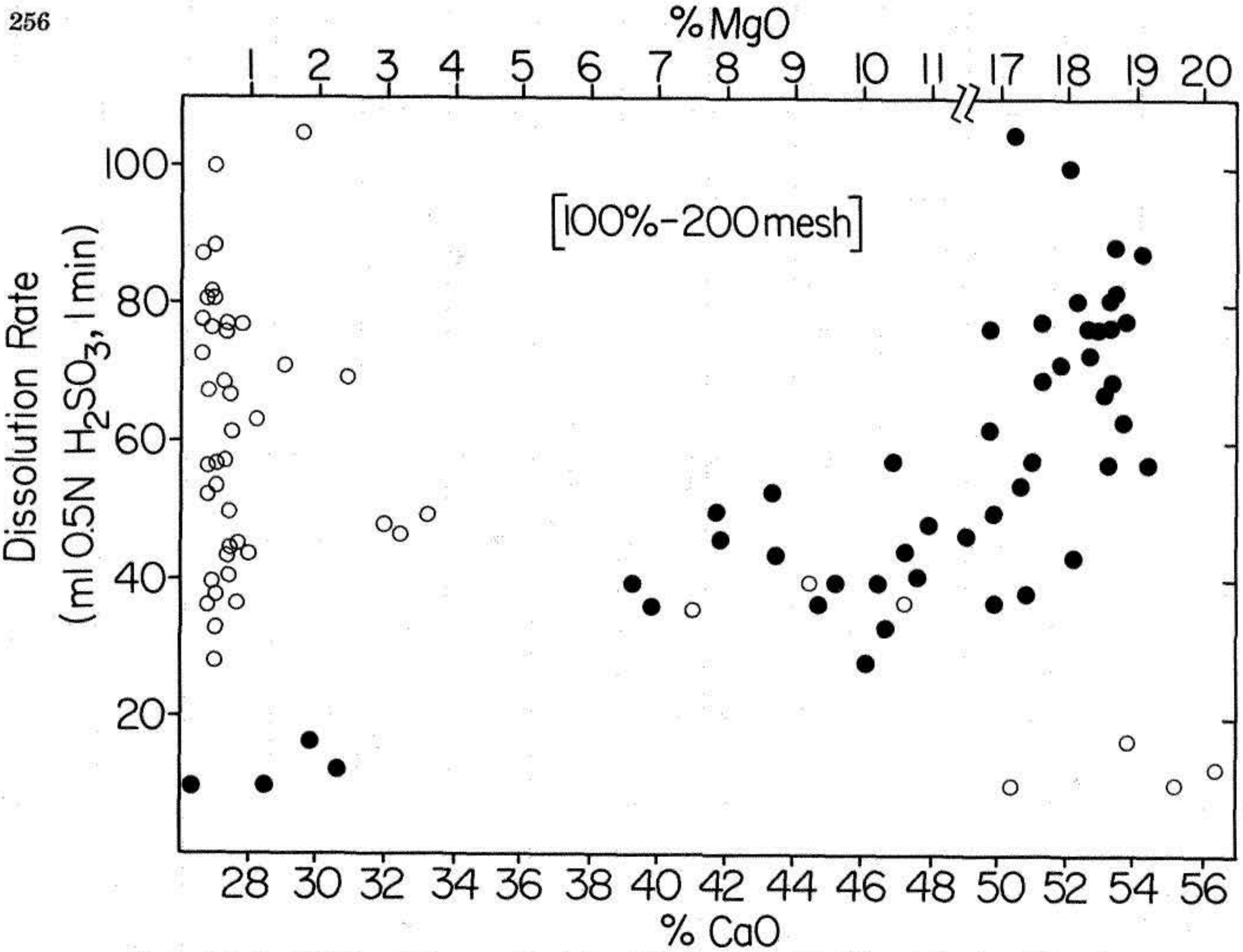

Figure 7. CaO and MgO content versus dissolution rates for all samples 100 percent minus 200 mesh.

TEXAS LIMESTONES: AVAILABILITY

Expected annual consumption of limestone for FGD systems now planned for three Texas powerplants (fig. 1) is summarized in table 3. Limestone consumption is a function of heating value and sulfur content of the fuel (lignite), plant capacity, and operating characteristics of the FGD system. Based on typical lignites available at three mine-mouth powerplants, SO_2 removal efficiencies required to meet Federal and State air-quality standards are just under 60 percent for the Martin Lake and Monticello facilities and about 80 percent for the San Miguel generator. Eighty-percent removal efficiency is attainable by commercially available limestone-based scrubbers. For purposes of the limestone-consumption calculation, annual average load for the generating plant was assumed to be 80-percent capacity (7,008 hr/yr) with 100-percent availability of the FGD system. Limestone purity was assumed to be 95-percent $CaCO_3$. Scrubbers were assumed to be operated using limestone at a rate equivalent to 1.2 stoichiometry (1.2 moles $CaCO_3$ for each mole of SO_2).

Based on the previous assumptions and the general fuel characteristics listed in table 3, limestone requirements for FGD systems in Texas will amount to less than 1 million tons annually. At current levels of annual crushed limestone production, the FGD market will increase production by only about 2 percent (fig. 9). Limestone used for FGD units will most likely be on the order of at least 70 percent minus 200 mesh—essentially a fine-grind limestone. Fine-grind limestone production in Texas would be expanded by about 200 percent over current production levels (fig. 9), if FGD needs were met solely by this material. Production of fine-grind limestone for commercial distribution is expensive because of the high cost of size reduction and grading (Hukki, 1975).

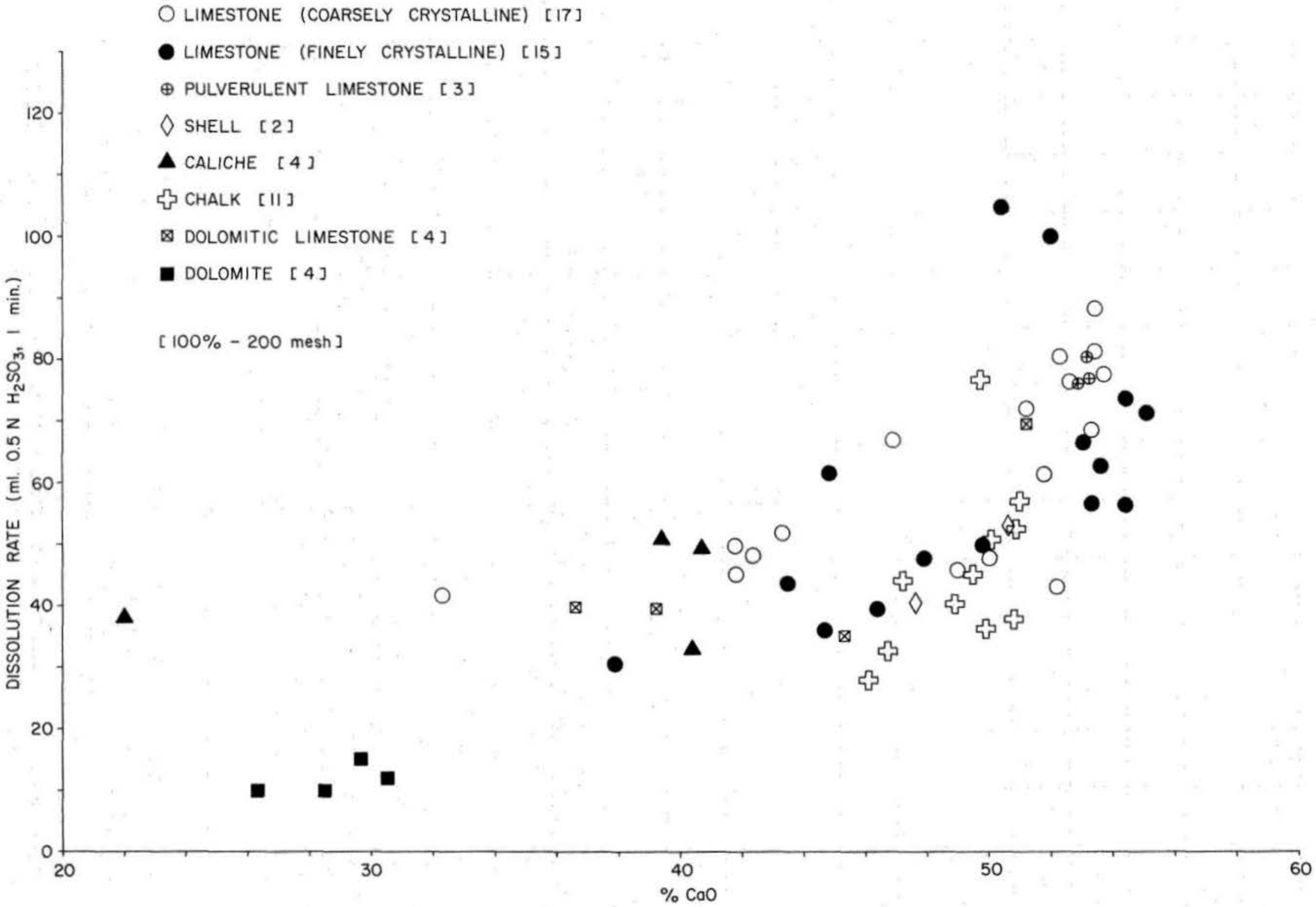

Figure 8. CaO content of different rock types compared to dissolution rate. All samples 100 percent minus 200 mesh.

Table 3. Expected annual limestone requirements for FGD systems scheduled for use on major Texas powerplants.

Plant/Generator (Date in service)	Limestone, tons tons/yr	Cumulative total, tons/yr
Martin Lake 1 (March 1977)	102,000	102,000
Martin Lake 2 (February 1978)	102,000	204,000
Monticello 3 (March 1978)	116,000	320,000
Martin Lake 3 (February 1979)	102,000	422,000
San Miguel 1 (December 1979)	189,000	611,000
Martin Lake 4 (February 1981)	102,000	713,000

Martin Lake: 750 megawatts; 1.00% sulfur; 7,200 Btu/lb
Monticello: 750 megawatts; 1.00% sulfur; 6,700 Btu/lb
San Miguel: 400 megawatts; 1.67% sulfur; 5,000 Btu/lb

Limestone resources in the vicinity of the Texas lignite belt (fig. 3) are large. Using the method for limestone resource estimation employed by Rodda and others (1966), total limestone resources in the area indicated in figure 3 are estimated at over 6 trillion tons. Reserves suitable for use in scrubbers probably are at least on the order of billions of tons; therefore, the resource base available for limestone-based FGD systems is not a limiting factor in the use of these systems in Texas.

COST ESTIMATES: QUARRY

Major Texas producers of crushed limestone (annual production more than 500,000 tons) are shown in figure 10. Costs of crushed limestone from these sources will vary depending on the mode of supply selected by the FGD operator and vendor. Basically, three supply modes are possible —each with its own advantages and expected cost range (table 4).

Mode 1 is the direct supply of fine-grind limestone to the powerplant site. The advantage of this mode is that the limestone would be ready for immediate use without further processing and with a minimum of handling. Most crushed-limestone producers do not market a commercial product in this size range; however, three companies in Texas do currently produce fine-grind limestone in sizes 70 percent minus 200 mesh and finer. This material is used principally as a filler and extender, or as whiting. Annual production of fine-grind limestone is modest compared to estimated annual requirements of FGD systems (fig. 9, table 3), suggesting that significant expansion of these production facilities would be required to meet the FGD demand. The estimated cost of fine-grind limestone at the quarry ranges from \$4 to \$9 per ton.

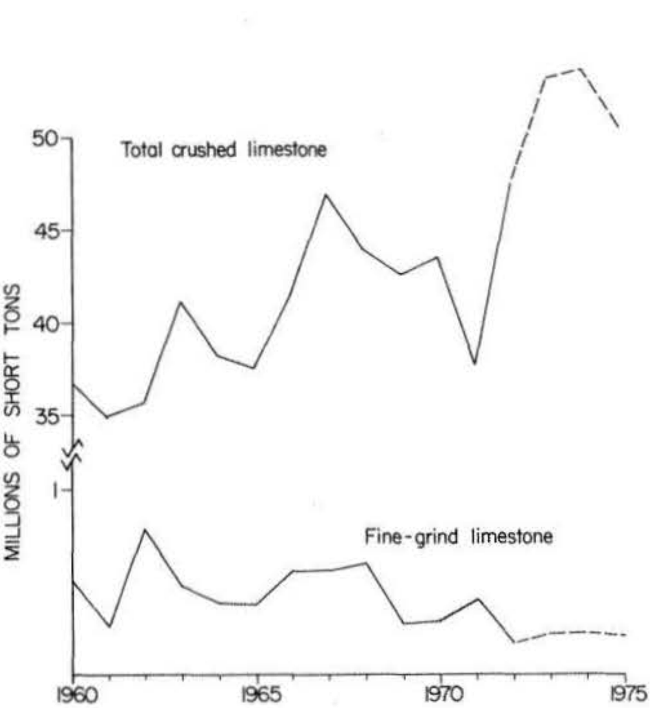

Figure 9. Annual crushed-limestone production in Texas, 1960–1975, including fine-grind limestone. Production for 1973 through 1975 estimated from historic percentages (85 percent of crushed stone produced is limestone; 0.4 percent of crushed limestone produced is a fine-grind material).

Mode 2 represents the purchase of ½- to 1-inch stone by the scrubber operator (at an estimated cost of \$1.50 to \$2.50 per ton), hauling the stone to the scrubber site, and crushing the limestone at the powerplant in a crushing/sizing plant operated by the utility. Capital costs and operating costs for a crushing/sizing plant are not available, but the cost of on-site stone processing is not likely to add significantly (about \$1 per ton maximum) to the overall stone cost. Operators of powerplants would need to consider these additional costs for a stone-processing plant.

Mode 3 incorporates the use of the large volume of waste material commonly stockpiled at a quarry. These "unders" or "fines" from the screening plant generally are considered a noncommercial product. These are generally moved to large holding ponds in a water slurry. The cost

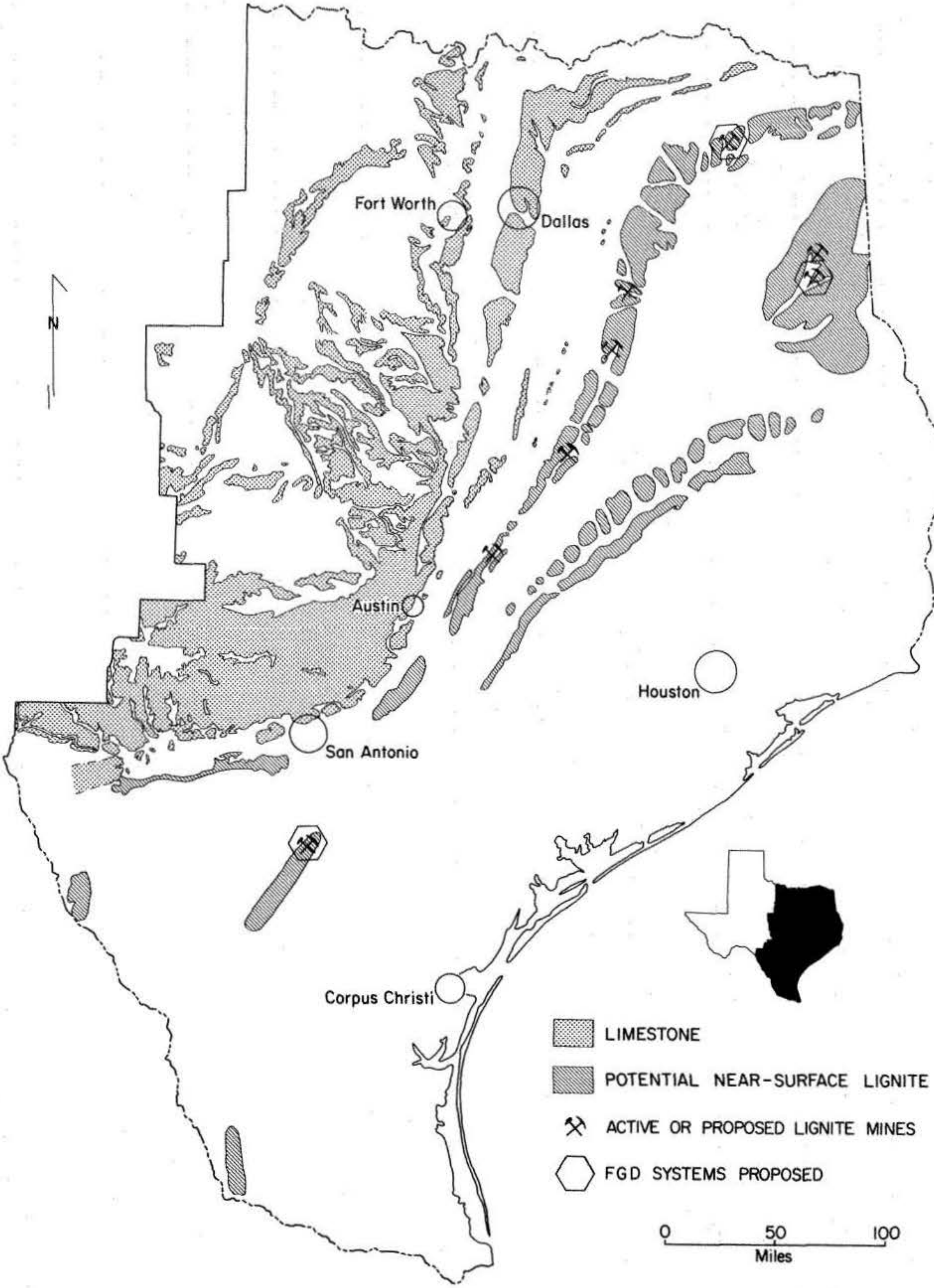

Figure 10. Major Texas producers of crushed limestone.

of supplying these minute waste materials is unknown and subject to the consideration of many factors, including accessibility of stockpiles, size ranges present in the waste materials, current physical state (wet or dry), and so forth. It is likely that some additional equipment would be needed to size the waste materials to meet the FGD operator's specifications. Since these waste products would probably be low in cost, such materials are a potentially significant source of limestone for scrubber systems in Texas. The estimated cost of these materials might range from \$1 to \$2 per ton. Their availability depends on rate of production during the course of quarry operation and the amount initially available from existing stockpiles.

COST ESTIMATES: TRANSPORTATION

A significant part of the total cost of low-value commodities such as crushed limestone is transportation. Estimating transportation costs, however, is very difficult, as a wide range of factors influence these costs on a case-by-case basis. Among the variable factors is the adequacy of transportation networks. Texas has an excellent railway network crossing the lignite outcrop belts and extending into the limestone-producing areas (fig. 11). The highway system in Texas is also excellent and includes not only the Federal and State highways shown on figure 12, but also an extensive system of farm-to-market roads. Selection of a transportation mode is another factor affecting estimation of transportation costs. Truck and rail hauls of crushed limestone will range from distances of 50 to 200 miles or more. In general, rail is the preferred transportation mode at distances exceeding 100 miles, but other considerations besides distance affect the final selection of a transport mode. Trucks offer maximum flexibility in terms of delivery schedules, load capacities, and route selection, but are constrained by traffic and road conditions, limited maximum load capacity, and generally higher costs per ton-mile (fig. 13). The high costs for truck hauls reflect the supplementary charges added to the basic motor-carrier tariff, including detention, diversion, tarping, toll, and other charges.

Distance is major consideration for selecting rail as a transportation mode as cost per ton-mile is generally low (fig. 13). However, other factors need to be considered, including inflexibility of delivery schedules and terminal locations, and the need for truck hauls between unloading tipples and the site of consumption (Schenck and Torries, 1975). These disadvantages are modified when stone producers have easy access to the railroads or have their own railroad cars and lines.

Figure 13 illustrates the range of transportation costs for both truck and railway modes. Basic motor-carrier and railroad tariffs approximate the minimum costs; the upper range is extrapolated from national data (O'Donnell and Sliger, 1972). Information on the upper range of truck hauling costs for distances exceeding 100 miles is not available, but probably ranges from \$.05 to \$.06 per ton-mile. Though truck hauls can be more expensive than rail hauls, as shown in figure 13 and table 5, the other factors of flexibility and convenience may dictate the selection of the truck mode instead of the rail mode. With long distances, however, these factors play a less significant role, and rail is the preferred transportation mode.

Table 4. Estimated cost per ton of limestone for FGD systems, excluding cost of transportation. (See accompanying text for explanation of supply modes.)

Supply	Range of Cost	Additional Cost at Plant Site[a]
Mode 1	\$4 to \$9	Minimal
Mode 2	\$1.50 to \$2.50	About \$1
Mode 3	\$1 to \$2	Minimal

[a] Additional costs include those incurred from handling and processing limestone prior to use in the FGD units at the powerplant site. Mode 2 additional costs reflect construction, operation, and maintenance of an on-site crushing/sizing facility.

Table 5. Estimated transportation costs per ton for crushed limestone hauls by truck and by rail (single line) in Texas. Costs shown based on costs in cents per ton-mile using median values determined in figure 13, except as noted.

Distance, miles	Truck, \$/ton	Rail, \$/ton
50	3.50	2.35
100	5.10	3.30
150	5.40[a]	4.05
200	6.80[a]	4.20

[a] Costs for truck hauls shown in parentheses (150 and 200 miles) are the basic motor-carrier tariff only. Actual haul costs would be larger because of supplementary charges. Truck hauls at these large distances are not common.

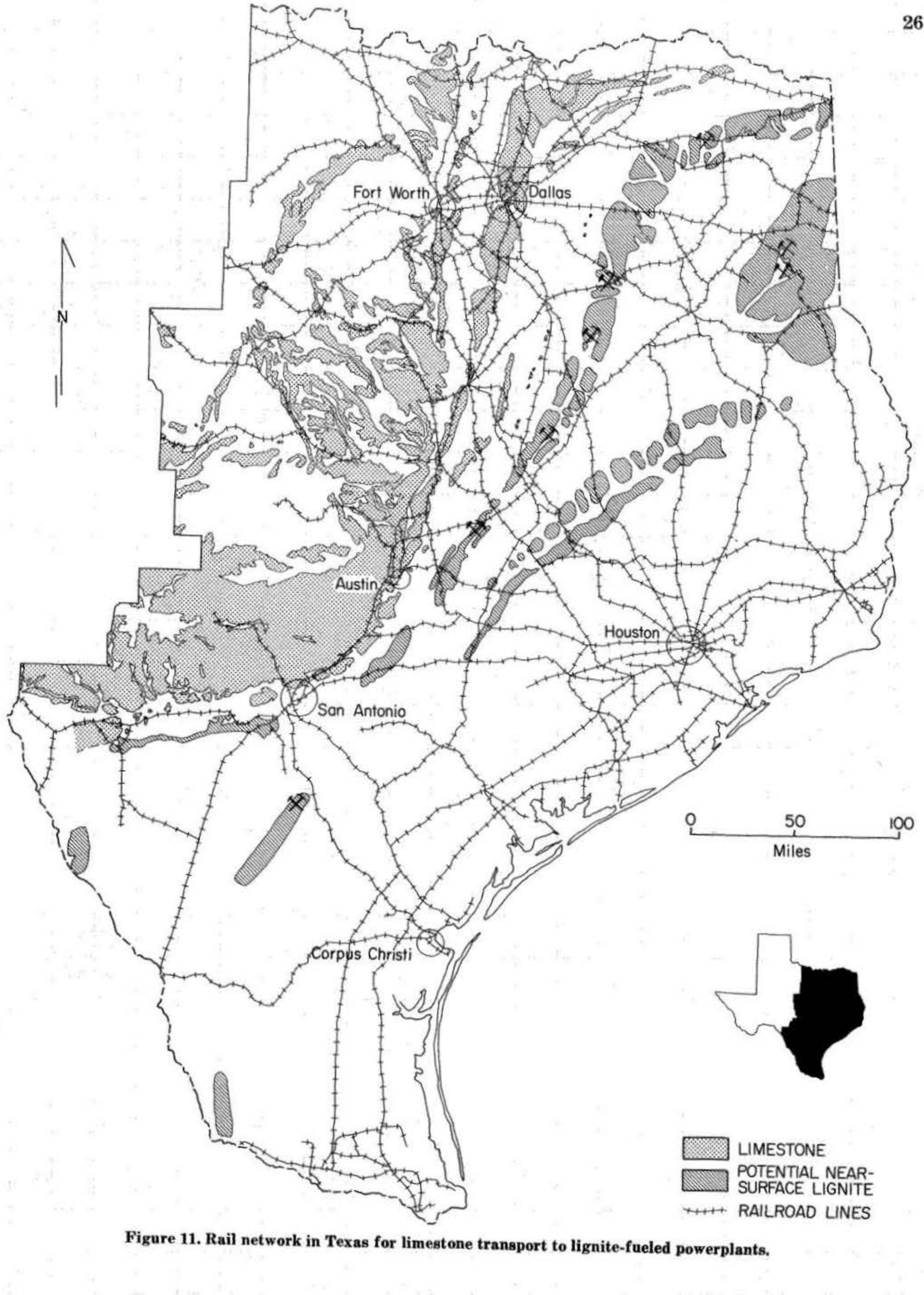

Figure 11. Rail network in Texas for limestone transport to lignite-fueled powerplants.

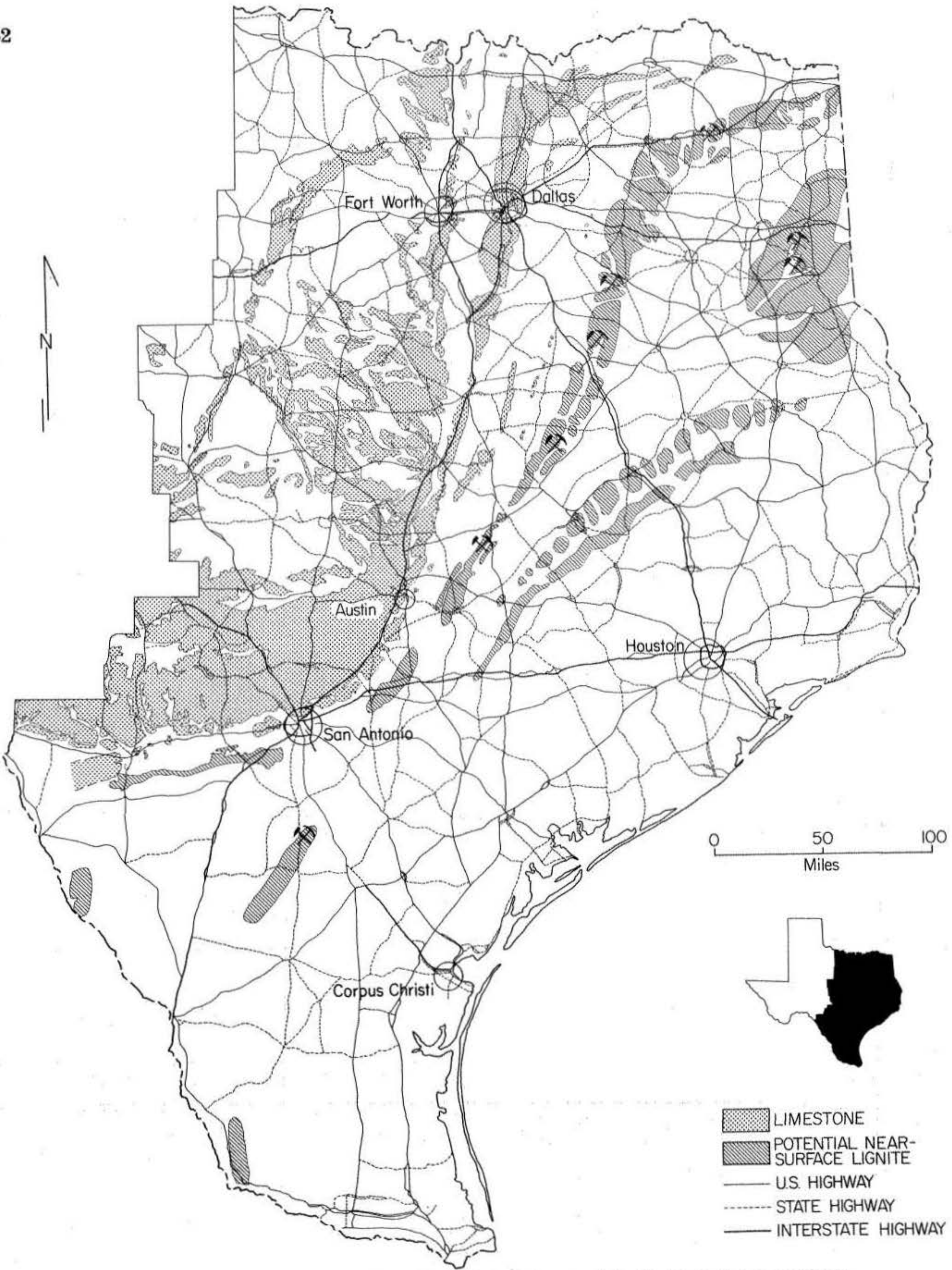

Figure 12. Highway network in Texas for limestone transport to lignite-fueled powerplants. Only Federal and State highways are shown.

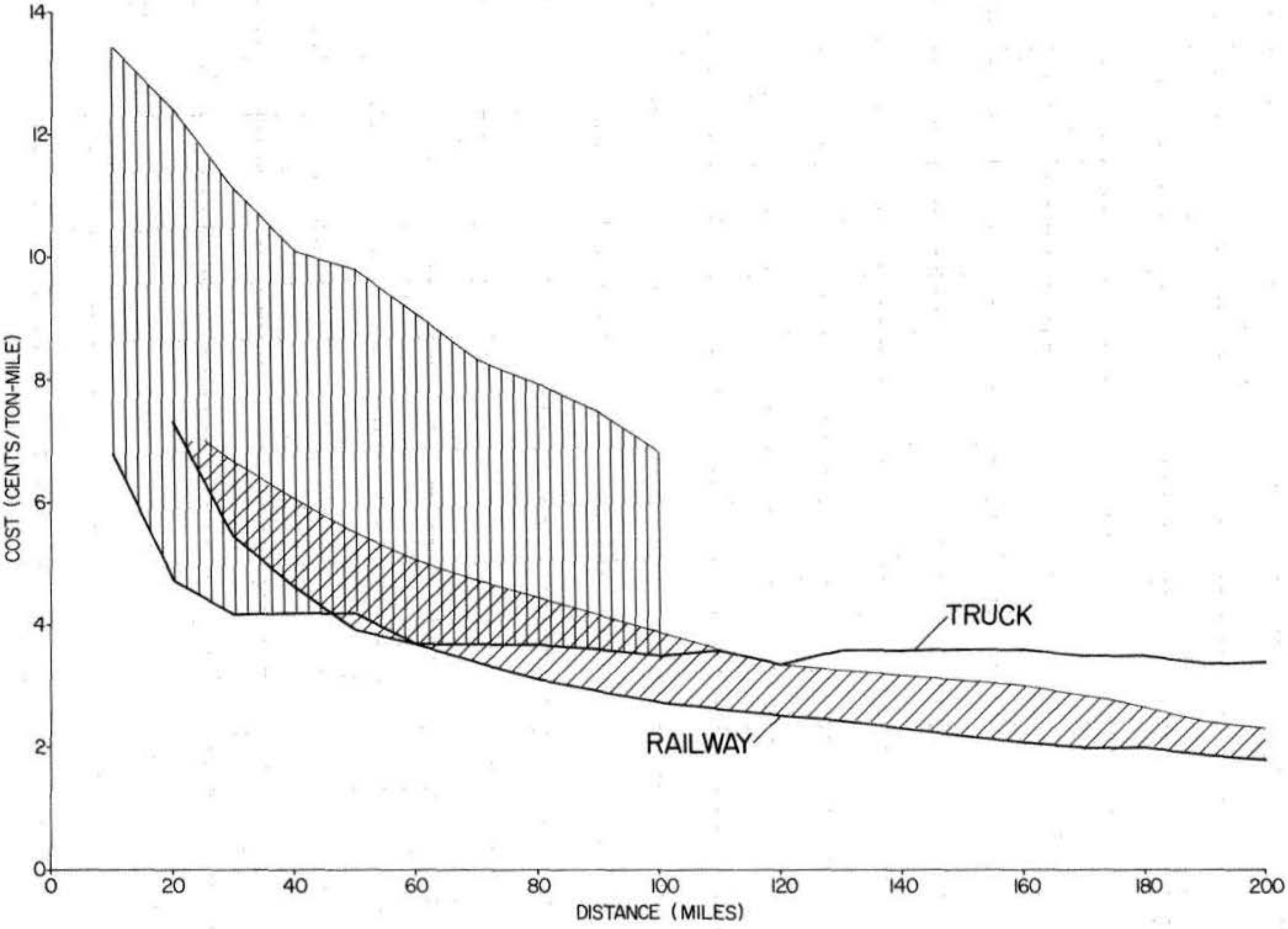

Figure 13. Comparison of truck and railway (single line) costs in cents per ton. Values shown represent minimal costs and do not include supplementary charges that can only be evaluated on an individual basis.

SUMMARY

Available reserves of limestone in Texas for flue-gas desulfurization are adequate to meet potential demand. Annual expected consumption is less than 1 million tons for FGD units scheduled for use by the early 1980's. This expected annual consumption is a minor part of yearly crushed limestone output in Texas, but represents a significant expansion of current fine-grind limestone production.

Cost to scrubber operators will vary according to mode of supply and distance of the powerplant from the limestone supplier (table 6). Each consuming site will need to evaluate the options of supply and transportation modes. For example, sites of production of fine-grind limestone may be so far away from the FGD unit location that the high cost per ton dictates that the scrubber operator construct and operate an on-site processing plant for the limestone additive. Conversely, the high unit cost of fine-grind limestone may be competitive with other supply modes when located near the point of stone consumption. Costs shown in table 6 are estimates; actual costs, at the quarry and for transportation, should be determined on a competitive basis for each potential supplier for each FGD system.

Table 6. Estimated total limestone cost for FGD operators in Texas.

Mode of Supply	Cost at Quarry	Haul Cost, 50 miles/200 miles Truck/Rail	Total Cost
Fine-grind limestone	\$4.00–\$9.00	\$3.50/\$4.20	\$7.50–\$13.20
Limestone aggregate crushed at powerplant site	\$1.50–\$2.50	\$3.50/\$4.20	\$6.00–\$7.70[a]
Stockpiled "fines"	\$1.00–\$2.00	\$3.50/\$4.20	\$4.50–\$6.20

[a] \$1.00 per ton costs for capital expenditures and continuing operation of an onsite crushing and sizing facility are included in these totals.

CONCLUSIONS

Texas limestones vary in suitability for use in limestone-based flue-gas desulfurization systems. An inexpensive, simple battery of tests can be used to differentiate among various commercial stones, and comparably suitable limestones can then be selected for more sophisticated laboratory and pilot plant testing. Availability of Texas limestone for FGD systems is generally excellent, with a variety of supply modes and more-than-adequate transportation networks.

Testing of competitive limestones should precede stone selection for each FGD unit or plant site, because the dissolution rate of Texas limestones varies widely and is not generally predictable on the basis of gross lithology (rock type). Smaller particle sizes favor more rapid rates of dissolution, and stone purity, as expressed in weight-percent CaO, seems to be an additional indicator of relative suitability among stones all crushed to about the same average particle size.

Suitability of limestones is naturally considered within the context of availability—quantity and cost. Expected annual requirements for FGD systems are modest, and existing production capacity is probably adequate, except for the case (mode 1) in which limestone supplied would be of the fine-grind variety. Estimated limestone resources are so large as to pose no constraint on the additional crushed limestone production required for the FGD market. Cost for limestone starts at about \$3 per ton and is dependent on transportation costs and mode of limestone supply. As a result of the many possible combinations of supply and transportation modes, the FGD limestone market in Texas is likely to be very competitive.

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COAL PREPARATION VERSUS STACK-GAS SCRUBBING TO MEET SO_2 EMISSION REGULATIONS

S. C. Schaeffer[1]

ABSTRACT

Sulfur dioxide emission control has received extensive attention as a research subject by the coal industry and governmental regulating agencies. Several approaches have been proposed to meet emission control; however, only two are currently feasible on a commercial scale for the hundreds of coal-fired powerplants in operation or under design: (1) coal preparation to reduce pyritic sulfur and (2) desulfurization of powerplant flue gases.

Which of these two approaches, when exposed to an engineering economic analysis, will result in the lower owning and operating cost per ton of coal burned? What effect will variables such as coal seam, percentage of pyrite removed, new versus existing powerplant design, or type of scrubber system employed have on the analysis? These are questions this paper will answer. The study will also explore the combined use of both methods to evaluate costs and environmental problems.

Pennsylvania was used as the area of in-depth investigation to make possible a detailed study of coal reserves and the electric generation market for these reserves. United States Environmental Protection Agency air standards were compared to Commonwealth standards to measure the impact each approach has on air-quality regulation and coal reserve utilization.

The last section of the paper will be a discussion of environmental regulation constraints on the utilization of Gulf Coast lignites. Additional research needs will also be addressed in this section.

INTRODUCTION

A number of approaches have been proposed to meet emission-control regulations imposed by Federal, state, or local agencies; however, only two approaches are currently commercially feasible for the hundreds of eastern coal-fired powerplants in operation or being designed. These approaches are (1) coal preparation to reduce pyritic sulfur and (2) desulfurization of powerplant flue gases. Which of these two approaches will result in the lower owning and operating cost per kilowatt hour (kWh) of electricity generated? What effect will either new or existing powerplant design or type of scrubber system employed have on the analysis? To answer these questions on a national level would require a series of studies to compensate for regional variations in coal characteristics and state emission regulations. Therefore, only Pennsylvania was used as the area of investigation for this paper to make possible a detailed study of coal reserves and the electric generation market for these reserves. The U. S. Environmental Protection Agency (EPA) air standards are compared to the Commonwealth of Pennsylvania standards to measure the impact each approach has on air-quality regulation and coal-reserve utilization.

The reserve base of coal in Pennsylvania is 31 billion tons. Approximately 7 billion tons of these reserves are anthracite; the remaining 24 billion tons are of bituminous rank. The statistical method used to derive the figures for sulfur content was weighted values based on reserve size. Raw data were bituminous reserves and average sulfur content by county and seam in Pennsylvania.

Sulfur in coal occurs in three forms: organic, sulfate, and pyritic. However, sulfur reduction by physical separation is restricted to the pyrite content. The pyrite content of coals in the United States varies from 30 to 70 percent of total sulfur, but Pennsylvania coals, in general, contain about

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67 percent pyritic sulfur. In addition, Pennsylvania coals contain large pyrite particles averaging 156 microns in size (McCartney and others, 1969). These two factors make Pennsylvania coals generally amenable to significant sulfur reduction by coal washing. In 1965, a study of 121 coal samples was initiated by the U. S. Bureau of Mines (Deurbrouck, 1976). These samples were evaluated by crushing and analyzing their washability to show the effect of stage crushing on the pyrite content of the coals.

Although greater pyrite reduction was possible with 50-percent yield of combustible unrejected coal, the incremental benefit was marginal; therefore, 80-percent yield was selected for detailed study in this paper at ⅜-inch top or maximum size.[2]

Results of this investigation showed an average total sulfur reduction of approximately 40 percent at ⅜-inch top size crushing and 80-percent yield. Unfortunately, washability results showed great variability with some coals exhibiting sulfur-reduction potential far above and some far below this average.

Before an evaluation is made of coal washing versus stack-gas scrubbing, the emission regulations of Pennsylvania were reviewed.

EMISSION REGULATIONS

The Clean Air Act Amendments of 1970 require each state to develop an implementation plan to meet ambient air standards. The plan developed and implemented by Pennsylvania includes a three-class emission standard for sulfur oxides. Because of either proximity to high-population areas or meteorological inversions, four air-quality basins have the most stringent controls. Eight other basins have a second level of requirements. Separate EPA regulations apply to emissions from all new powerplants constructed. Table 1 summarizes requirements of the state and Federal regulations for electric powerplant installations.

To understand how these regulations affect the utilization of Pennsylvania's coal-reserve base for electrical power generation, assume 40-percent average sulfur reduction by coal washing. The preparation will allow an increase in coal heating value from 12,000 to 14,000 Btu/lb for the washed coal.

Despite coal washing at this level, the vast majority of reserves when washed cannot meet the State or Federal regulations in the four stringent air-quality-controlled basins and in all new plants proposed or under construction. The impact of this observation is placed in better perspective when the Pennsylvania electric utility industry is examined.

PENNSYLVANIA ELECTRIC UTILITY INDUSTRY

There are 16 independent, investor-owned electric companies supplying 96 percent of the power for Pennsylvania; 8 of the independent companies account for 100 percent of the generating capacity.

Interviews were held with operating executives of the eight Pennsylvania utilities owning generating facilities. In addition, statistical data were supplied by the Pennsylvania Utility Commission on dollar value of capital projects for environmental quality. Information secured through the interviews revealed four significant points:

1. Fuel problems related to the utilization of coal stem from air-pollution regulations causing the use of oil for generating fuel to increase sharply during the past 2 years to meet these standards.
2. Pennsylvania utilities plan to invest more than $600 million in stack-gas scrubbing by 1981 with no assurance of solving the problems of scrubber technology or waste disposal.
3. The eight generating utilities in Pennsylvania had 20,600 megawatts (MW) of capacity in 1973 with a planned increase to

Table 1. Pennsylvania SO_2 emission regulations.

Area	Allowed $SO_2/10^6$ Btu, lbs.	Sulfur content of coal, percent[a]
Stringent air basins	0.6	0.4
Remaining air basins	1.8	1.1
Rest of state	4.0	2.4
All new powerplants	1.2	0.7

[a] Assumes 12,000 Btu/lb of coal.

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[2] Total Btu of coal - Btu of coal rejected with pyrite/Total Btu of coal.

37,200 MW by 1981. Delays on nuclear projects and difficulty in raising capital for construction has forced a postponement in retiring several older coal-fired plants. The revised coal-fired capacity is approximately 16,000 MW. This reduction is part of a retarded system capacity of approximately 22,000 MW compared to the predicted 25,700 MW.

4. The 16,000 MW of coal-fired generation are located as follows.

Four critical air basins	3,500 MW	(22%)
Eight remaining air basins	900 MW	(6%)
Rest of state	11,700 MW	(72%)

Coal washing alone can be utilized for about 12,000 MW of existing generating capacity; therefore an examination of stack-gas scrubbing versus coal preparation should be made to compare the economics of each approach.

STACK-GAS SCRUBBING

Two major areas of controversy exist with the use of stack-gas scrubbers: first, the expense of the equipment to install and operate, and, second, the reliability of the systems once they become operational. Vast differences of opinion are expressed by the interest groups involved. Electric utility spokesmen have claimed the technology is totally unreliable with installation costs running above $100 per kilowatt (kW) of station capacity. A different opinion is shared by representatives of equipment manufacturers and certain governmental agencies. This group considers stack-gas scrubbing a proven technology with installed costs running about $50/kW. After interviews with people from all three sectors, the reasons for the cost differences became apparent. Several major reasons were:

1. Comparing regenerable systems with once-through throw-away equipment. Regenerable systems are approximately 35-percent more expensive than the lime/limestone systems.
2. Using different base dates for cost adjustments. Inflation can change identical comparisons by 20 percent in a 1-year construction delay.
3. Different definitions of a complete system. Items such as waste disposal or reprocessing plants will significantly affect capital costs.
4. Sulfur content of coal fired in the plant. Western plants utilizing low-sulfur coal will have lower cost per kilowatt than an eastern counterpart.

A national survey was conducted by a private consulting firm to resolve the cost conflict. Thirty utilities were surveyed in detail to ascertain capital costs. The survey covered 32 plants and 68 boilers for a total generating capacity of 32,120 MW (PEDCo, 1975a). Table 2 shows the range of costs reported for flue-gas desulfurization (FGD) systems in dollars per kilowatt of capacity.

The second area of controversy is the reliability of stack-gas scrubbing systems. Proponents of scrubbing report over a hundred systems installed or under design or construction. A June 1975 progress report submitted to the EPA com-

Table 2. Range of costs reported for FGD systems.

FGD Process	Manufacturers		Utilities		Adjusted by Consulting Firm[a]	
	New	Retrofit	New	Retrofit	New	Retrofit
Regenerable	—	—	107	33 to 197	95[b]	115 to 205
Nonregenerable (lime/limestone)	33 to 74	42 to 78	33 to 129	40 to 115	50 to 81	59 to 87

[a] Does not include waste facilities and acid-processing plants.

[b] Only one plant reported in this category.

prises table 3 (PEDCo, 1975b). A point of major interest is the fact that only 10 of these systems, with a total rating of 1952 MW, were operational during the month of June. These statistics would indicate that stack-gas scrubbing is not yet a proven reliable technology.

Stack-gas scrubbing systems in Pennsylvania include one system with operating experience, two once-through systems, and one regenerable magnesium-oxide system under construction, and another throw-away system is under design. Land use problems for sludge disposal were a major consideration in the selection of the magnesium-oxide regenerable plant. Every system under design or construction was estimated by utility spokesmen to cost more than \$100/kW.

Table 3. Number and total MW of FGD systems.

Status	No. of units	Capacity, MW
Operational	21	3,344
Under construction	23	7,550
Planning		
Contract awarded	9	3,841
Letter of intent	11	4,711
Requesting/evaluating bids	8	3,877
Considering only FGD systems	45	23,307
Total	117	46,620

COAL PREPARATION

Coal preparation can be separated into three general stages of cleaning and unit operations (Skelly and Loy, 1975).

STAGE 1: CRUSHING AND SIZING — BASIC CLEANING

This stage of coal cleaning involves only crushing and sizing. The two major objectives in stage 1 preparation are (1) a reduction of raw coal to uniform market sizes and (2) segregation of refuse material which usually appears as reject from the first screening. Since these goals are accomplished with removal of only large refuse material, stage 1 cleaning plants achieve maximum calorific recovery but minimal improvement in ash and sulfur reduction.

Flow paths of coal and refuse within a typical stage 1 preparation plant are shown in figure 1. A water circuit is not included in plant design because stage 1 preparation is usually a dry process.

STAGE 2: HYDRAULIC SEPARATION — STANDARD CLEANING

Stage 2 coal preparation is a standard system that has provided a clean coal product ideal for the utility coal market. A primary objective of stage 2 preparation is removal of liberated mineral matter by cleaning at high gravity. This cleaning provides a uniform product with reduced ash and sulfur content. Coal-preparation plants employing this system accrue a high calorific recovery with some inherent loss of combustible material (85-percent clean coal recovery). Mechanical drying with a centrifuge is usually required with wet cleaning of fine coal. Thermal dryers are used for fine clean coal only when necessary.

STAGE 3: DENSE MEDIUM SEPARATION — COMPLETE CLEANING

Coal preparation plants grouped in stage 3 provide complete and sophisticated coal cleaning. Sized raw coal is cleaned in a stage 3 preparation plant by heavy media separation and froth flotation. Magnetite is the most common dense medium employed for cleaning coal, although sand is still used occasionally.

These three stages are predicted on a size reduction to attain the maximum freeing of particles that can be economically justified.

PREPARATION PLANT COSTS

Coal preparation is an established reliable technology with capital construction costs less controversial than those of stack-gas scrubbing. Capital costs for coarse-coal-cleaning plants are approximately \$10,000 when expressed in terms of ton-hour capacity. The figures increase to \$25,000 per ton-hour for stage 3 plants with thermal drying and heavy media separation or froth flotation, or both.

Plant type and capacity are the major factors determining the capital and operating costs associated with coal cleaning. Results of a survey that included more than preparation facilities indicate initial plant costs can range from $300,000 to 25 million dollars—capacities varied from 50 to 1,500 tons per hour.

COAL-CLEANING VERSUS STACK-GAS SCRUBBING COSTS

Assume a generation plant heat rate of 10,500 Btu/kWh and raw coal with a calorific value of 12,000 Btu/lb. Based on capital costs, the preparation plant cost for cleaning would be equivalent to $4/kW for coarse coal cleaning and $10/kW for advanced technology. These figures represent only capital costs, but illustrate the fact that equipment for stack-gas scrubbing requires 10 to 25 times the capital investment. A complete analysis must include factors such as preparation-plant operating costs, transportation cost adjustments (coal cleaning means more Btu's per pound), grinding costs at the powerplant, and ash disposal. When these items are factored into the study, the cost difference between burning raw coal and stage 2 prepared coal is less than 1 mill/kWh (Lovell, 1975), whereas the owning and operating cost of scrubbers has been estimated at 3 to 6 mills/kWh.

When used in conjunction with scrubber systems, recent studies have shown coal-cleaning costs can be offset by the savings in coal transportation costs and reduced sludge disposal at the powerplant site. The relatively long distance from preparation plant to generating station was the deciding factor in favor of combined coal preparation and gas scrubbing in the study.

Another study illustrates the expense of gas scrubbing sludge-disposal costs. One Pennsylvania utility allotted $84 million in sludge-disposal facilities with operating costs of $17 million per year. Expressed in terms of electric power generated, the disposal cost will be 1.37 mills/kWh.

NEEDED RESEARCH OF TEXAS LIGNITES

The data for this paper have been based on Pennsylvania bituminous-ranked coals. The question we now ask is, "Will any of the findings apply to Texas lignites?" With respect to pyrite reduction, the answer does not appear to be as promising as with Pennsylvania coals.[3] However, there are other benefits from coal preparation.

First, Texas lignites contain significant amounts of ash that can be reduced with preparation. This reduction would be valuable for two reasons:

1. It would reduce the load on electrostatic precipitators installed at the powerplants.
2. Ash reduction would mean a savings in transportation costs where savings are also possible through moisture reduction of the lignites with thermal drying.

The second area of potential benefit with lignite preparation is associated with a growing concern that trace elements in coal may contribute substantial quantities of potentially hazardous materials to the atmosphere. Washability studies conducted by the U. S. Bureau of Mines on eastern coals have resulted in significant reductions of elements such as copper, chromium, nickel, and lead.

How will coal washability reduce trace elements in Texas lignites? Only research holds the answer.

SUMMARY

Utilizing stage 2 or 3 coal-preparation technology, large quantities of Pennsylvania's 23 billion tons of bituminous coal can be fired in existing electric generating plants located outside the State's 12 air basins. This figure represents over 10,000/MW of existing coal-fired plants not equipped with stack-gas scrubbers.

Coal preparation requires only a fraction of the capital needed to own and operate stack-gas scrubbing systems. In addition to reduced costs, system reliability is another major advantage of coal preparation. Unfortunately, existing State and Federal emission regulations, as written, eliminate coal preparation as a sole means of compliance for new plants or existing plants located in air basins. Presently, existing plants in air

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[3] Editor's note: Available data indicate majority of sulfur in Texas lignite is organic.

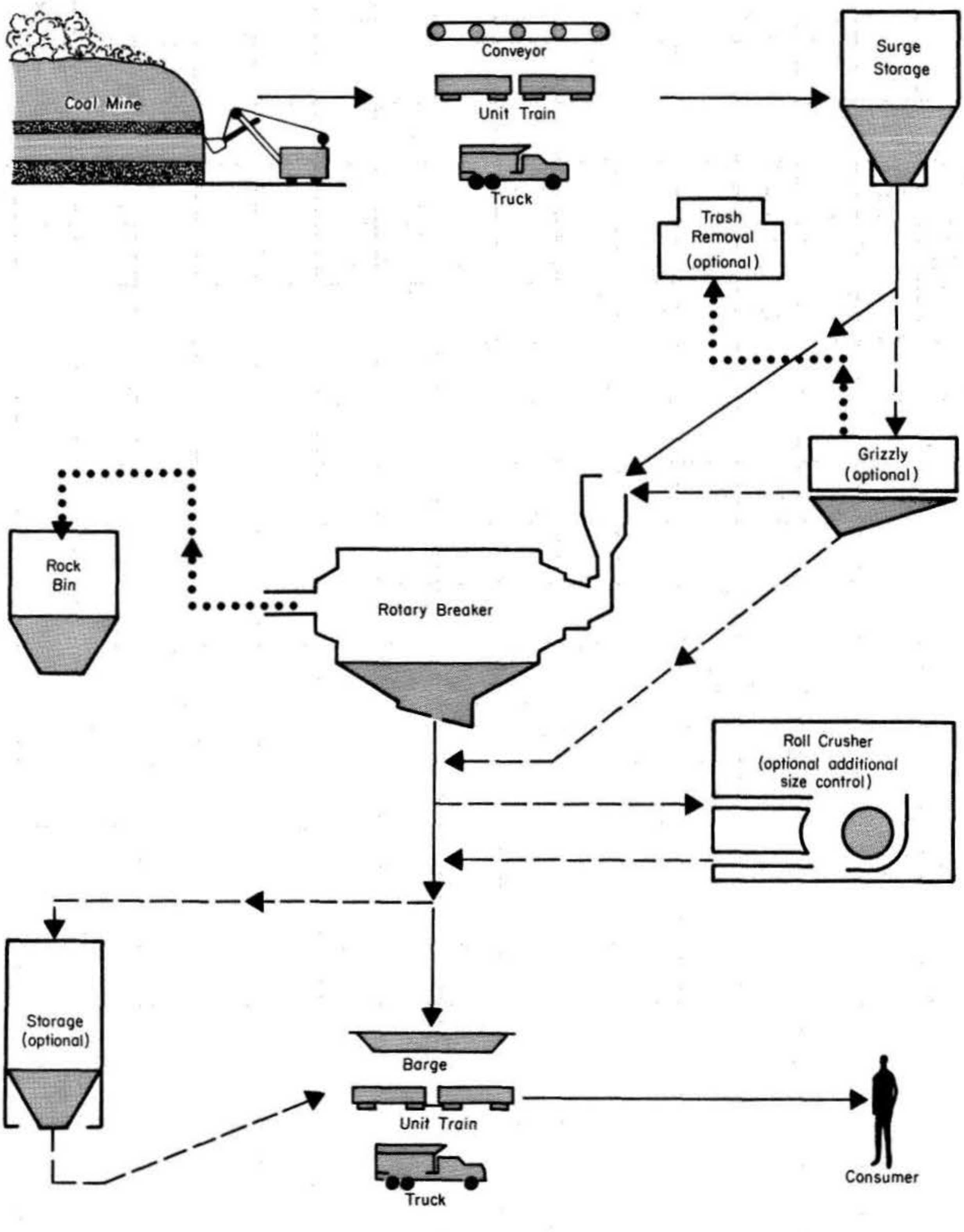

Figure 1. Stage 1 coal-preparation plant.

basins represent only a small fraction of electric power system capacity. However, as new plants are constructed and existing plants retired, scrubber requirements will drastically increase.

Several detailed cost studies have shown coal preparation costs can be justified in conjunction with scrubber systems based on cost savings in coal transportation and a cost reduction in scrubber reagents and sludge disposal.

CONCLUDING REMARKS

As written and enforced, State and Federal emission regulations lack the flexibility needed to cope with today's energy and environmental dilemma. If these regulations were more flexible, the Federal Energy Administration's mission of energy development could be accomplished while minimizing capital expenditures and negative environmental impacts.

The EPA standard for SO_2 emissions from new sources is a rigid 1.2 lbs of SO_2 per million Btu's of coal fired. This regulation does not allow enforcing agencies the use of the incremental cost/benefit analysis approach to emission limitations. Conversely, regulations enacted by the Commonwealth of Pennsylvania allow existing powerplants located outside air basins to emit up to 4 lbs of SO_2 per million Btu's of coal fired. These plants tend to approach the 4 lb level because there is no incentive to apply an incremental cost/benefit philosophy to sulfur reduction through the use of coal preparation.

The goal of good emission regulations should be a maximum reduction in SO_2 with minimum capital requirements. Unfortunately the State or Federal regulations enforced in Pennsylvania do not meet this goal. Older, less efficient plants are retained on-line emitting relatively large amounts of SO_2, whereas new plant construction is delayed because of excessive capital requirements aggravated by scrubbers.

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THE ROLE OF THE UNIVERSITY IN LIGNITE RESEARCH AND DEVELOPMENT

W. R. Kaiser[1]

INTRODUCTION

Geology, utilization, and environmental aspects workshops were held concurrently to help evaluate the university's role in lignite research and development. They will be reviewed in the order listed. Overlap of disciplines occurs and is common between utilization and environmental aspects where separation is especially difficult in the pollution-control area. Research topics are listed in tables 1, 2, and 3. All are topics the university should be involved in, but it is not because of limitations of one kind or another. University capability to do the indicated research was assessed subjectively in the general context of Gulf Coast universities and specifically with respect to Texas universities. Only those topics believed to be within present university capability were ranked; rankings reflect the immediacy of the problem.

GEOLOGY

This workshop was led by W. R. Kaiser and mainly attended by company geologists. The general impression received, based on the response of this group, was that universities have a minor role to play in lignite geologic research and development. Furthermore, industry and academia apparently do not understand each other's capabilities, needs, and goals. Not surprisingly, in that light, there was almost no overlap of topics suggested by industry and university representatives (table 1).

Lignite petrography and palynology were most frequently mentioned by the participants, in the context of lignite behavior in conversion processes and as a tool for correlation or time stratigraphy, respectively. Interestingly enough, topics suggested by industry are the very ones universities are least able to work on. Few participants realized that university research in those areas is severely constrained by data availability, mine access, and facilities. In fact real contradiction exists for the research suggested by industry can go forward only with proprietary industry data such as cores, logs, and analyses. Probably in today's very competitive atmosphere, access to data and mines will be restricted for some time to come.

Regional studies and continuing education, topics of highest rank, were not mentioned by industry (table 1). The neglect of regional studies was disappointing in view of the fact that studies had been presented at the Conference that bore directly on exploration. Kaiser showed in a regional study that knowledge of depositional systems is of more than academic interest and has real utility in an integrated exploration effort. Perhaps some unconsciously prefer that public research be directed away from exploration-related topics and toward peripheral topics like petrography and palynology. One participant later suggested that the companies do not want others to know where lignite is for competitive reasons.

Reflection seismology and geophysical logging, exploration topics, were university suggested. Until now reflection seismology has received little attention as a tool in coal exploration; it is cheaper to drill 200 ft holes on half-mile centers. This will not be the case when exploration turns to deeper

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lignite (500 to 2,000 ft). At some depth point, economics will favor seismic lines over boreholes.

Geophysical logging is absolutely essential to any exploration program. New criteria are needed to make lignite identification on electric and induction logs more certain. Methods of determining ash and moisture content and mechanical properties of overburden directly from geophysical logs need refinement. The relationship between log patterns and the occurrence of lignite is tentative; systematic effort should be made to establish the correlation.

The university researcher makes his most important contribution as synthesizer of data and generator of new ideas. Passing them along to the working geologist is continuing education. Though not stated as such, reference was made to it by the industry-suggested topic, basic sedimentology (table 1). Interest was expressed in the development of models (modern and ancient) of deposition. Field-oriented seminars or short courses emphasizing depositional systems, depositional models, and sedimentary processes and their use as exploration tools might be an appropriate approach to continuing education. After all, the field is the best place to get to know rocks.

UTILIZATION

This workshop was led by T. F. Edgar and attracted the largest attendance. Discussion was spirited, exceeded the allotted time, and elicited excellent response from industry. Numerous research topics were suggested (table 2). The list was compiled and prioritized by Edgar. Kaiser assessed capability and assigned rankings within each priority group rather than to the list as a whole. Higher rankings were given to the immediate problems associated with current utilization in steam-electric plants. The magnitude of funding for university research need not follow the rankings. For example, kinetics of gasification and liquefaction may not be deemed critical in a development sense, but might be an important part of university research. The university researcher probably can best contribute by developing and strengthening the theoretical aspects implicit in the topics listed.

Much discussion centered on particulate removal, desulfurization, *fluidized-bed combustion*, and in situ processing. Currently in Texas three particulate-control strategies are used: electrostatic precipitation, flue-gas conditioning, and baghouses. Needed is an understanding of the theory of collection mechanisms and its relationship to the chemical and physical properties of lignite ash. As expected, desulfurization was a concern of many. A need for the development of simultaneous particulate- and sulfur-removal technology was expressed. Fluidized-bed combustion of lignite was of interest because of high potential for efficient power production and improved desulfurization. In situ processing (gasification, chemical comminution, and liquefaction) received a lot of attention. The energy in vast deep-basin lignite resources, especially in Texas, can only be recovered by in situ technology. At the moment, inter-

Table 1. Geology research topics.

	Industry Suggested	University Suggested	Capability[a]	Rank[b]
Lignite petrography	X		B	
Palynology of lignite	X		B	
Mineral economics	X		B	
Basic sedimentology	X		A	4
Regional studies		X	A	1
Continuing education		X	A	2
Reflection seismology		X	B	
Geophysical logging		X	A	3

[a] A = University presently able to do research.
B = University presently unable to do research but could contribute were it not for limitations of data availability, mine access, personnel, funding, facilities, and equipment.

[b] Only "A" items ranked.

est centers on in situ gasification. Two major university research projects on the engineering, geological, and environmental aspects of in situ coal gasification are in progress at the University of Texas at Austin (Edgar's paper) and the University of Alabama.

Of interest among the topics of intermediate priority are front-end beneficiation, methacoal process for lignite transport, comparison of old and new technology, and gasifiers for small-scale users. Front-end removal of sodium is an obvious need because of boiler fouling. Similar removal of pyritic sulfur is desirable; however, applicability to Texas lignite will be limited as most of the sulfur is organic. Removal of mud and clay will become more important as thinner and poorer grade lignite seams are mined. Lignite is water wettable, thus slurry transport of lignite is not likely. The methacoal process may play a role in short-distance transport, tying together smaller discontinuous deposits and a single large steam-electric plant. This process is under study at The University of Texas at Austin. Do the new gasifiers perform better than existing ones such as the slagging Lurgi? This important question remains unanswered. Small-scale economical gasifiers could be sold today to Texas brick, tile, and cement manufacturers.

Thorough characterization of the structure of lignite is needed for a better understanding of its behavior in conversion processes. Sophisticated study techniques such as C-13 nuclear magnetic resonance, photoelectron spectroscopy, X-ray diffraction, and gas chromatography/mass spectrometry might be appropriate. Thermodynamic properties (critical points, pressure-volume-temperature data, fugacity) of lignite-derived fluids would be helpful in designing conversion systems.

Table 2. Utilization research topics.

	Capability	Rank
High Priority		
Removal of particulates in direct combustion	A?	1
Selective front-end removal of sodium	A	5
In site processing	A	2
Fluidized bed combustion	A?	3
Kinetics of gasification and liquefaction	A	4
Selective mining of thin, multiseam deposits	B	
Intermediate Priority		
Transport and utilization of coal fines	A	4
Spontaneous combustion of lignite storage piles	A	3
Simultaneous particulate and sulfur removal strategies	A?	1
Regenerative FGD processes	B	
Feeding lignite to high pressure gasifiers	B	
Gasifier concepts for small-scale users	A	7
Methacoal process for lignite transport	A	5
Chemical and petrographic composition	B	
Net energy comparison of old and new conversion technology	A	6
Front-end beneficiation	A?	2
Models for design and simulation of slurry, fluidized, entrained, and moving bed reactors	A	8
Construction materials and hardware corrosion	B	
Low Priority		
Automatic subsurface mining techniques	B	
Coal-derived fuels (except low-Btu gas) for combined cycle	A	3
Briquetting lignite	A	4
Thermodynamic properties of lignite derived fluids	A	2
Structure of lignite	A	1

ENVIRONMENTAL ASPECTS

This workshop was held by C. D. Henry. His impressions are incorporated in this review. Several participants stressed assessing the long-term impact of surface mining on the land and water. Obviously, environmental studies must not be limited to the short term. The ultimate success of land reclamation can only be judged against the long-term productivity of the reclaimed land or quality and quantity of ground water. Particular concerns of Henry's center on the restoration of mined land to high productive capacity and avoidance of degradation of ground-water resources.

Regional studies like Henry's provide baseline data on overburden, floodplains, and hydrology. Broad problem areas are identified, but detailed studies from different sectors of the lignite belt are needed to identify specific problems. At Fairfield, Texas, excellent studies by Texas A&M University have been done on restoring agricultural productivity. The applicability of these to other lignite areas is uncertain. For example, in far East Texas growing pine trees is and probably will continue to be the most common land use, and in South Texas lack of rainfall and higher sulfur lignite will make reclamation far more difficult.

The whole question of the impact of mining on ground water has been largely overlooked up to now. Considering the potential for degradation and the dependence of municipalities and agriculture in the lignite belt on ground water, this should have been one of the first concerns. The only study to date on ground-water quality, a University of Texas at Austin M.A. thesis, discussed the scope of potential problems. A graduate student from the same university will investigate the hydrology of reclaimed land at Fairfield, Texas.

The effects of conventional and in situ lignite gasification were not discussed in this workshop, but did come up in the utilization workshop. The potential threat of surface- and ground-water contamination is the environmental aspect of greatest concern. Critical research areas are (1) type and quantity of toxic compounds, (2) stability, solubility, analysis, and health effects of these, (3) velocity of toxic species in simulated aquifers and surface sources, (4) monitoring techniques, (5) restoration and abatement strategies, and (6) fate of pollutants. The ultimate dispersal of pollutants (trace organics and metals) generated by gasification is unknown. Predicting their dispersal and the design of monitoring programs requires an understanding of the relationship between geology, hydrology, and their chemistry. Many of the above questions are also relevant to potential leachates from waste-storage areas.

Air pollutants of prime concern to public health are SO_x, NO_x, soot, and fly ash. Universities may play a role in setting standards by investigating the interrelationship of health effects, existing air quality, stack height, wind patterns, relative humidity, lignite composition, combustion mode, and plant density. An emissions-related problem is the partitioning of trace elements between fly ash, bottom ash, and stack gases. Technologically less significant but relevant is an assessment of the socioeconomic impact of power-plant construction and mining on affected communities. And although not a research topic, an annotated catalog of the permits required by state agencies for lignite development would provide a service appreciated by all potential users of lignite.

As noted earlier, universities are limited by data availability, mine access, and facilities. These limitations are reflected in table 3. Private cooperation is critical to almost all the research topics listed. In view of the emphasis placed on long-term environmental studies, graduate student research will require careful planning. University capability is especially important in lignite composition studies. No university in Texas is equipped to do complete coal analyses, yet many of the problems have geochemical origins. One Texas A&M study will look at selenium, arsenic, and uranium in Texas lignite. Perhaps the university researcher can best serve as an assessor of impact. For example, what is the significance of x parts per million of trace metal in a lignite seam?

Table 3. Environmental research topics.

	Capability	Rank
Regional baseline studies	A	1
Reclamation of mined land	B	
Hydrology of reclaimed land	B	
Chemical composition of lignite	B	
Socio-economic impact of lignite development	A	4
Ground water recharge, quality, and mining	B	
Partitioning of trace elements	B	
Waste disposal and storage strategies	A	2
Impact of lignite gasification	A ?	3
SO_x, NO_x, and particulate emission standards	A	5