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TECHNOLOGY AND USE OF LIGNITE

Proceedings: Bureau of Mines-
University of North Dakota Symposium,
Grand Forks, N. Dak., May 1-2, 1969

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

1970

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Compiled by James L. Elder and Wayne R. Kube

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This publication has been cataloged as follows:

Elder, James L comp.

Technology and use of lignite. Proceedings: Bureau of Mines-University of North Dakota Symposium, Grand Forks, N. Dak., May 1-2, 1969, compiled by James L. Elder and Wayne R. Kube. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1970]

174 p. illus., tables. (U.S. Bureau of Mines. Information circular 8471)

1. Lignite—Congresses. I. Bureau of Mines-University of North Dakota Symposium, Grand Forks, N. Dak., 1969. II. Kube, Wayne R., jt. comp. III. Title. (Series)

TN23.U71 no. 8471 622.06173

U.S. Dept. of the Int. Library

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $1.75

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TECHNOLOGY AND USE OF LIGNITE

Proceedings: Bureau of Mines-University of North Dakota Symposium, Grand Forks, N. Dak., May 1-2, 1969

Compiled by

James L. Elder[1] and Wayne R. Kube[2]

INTRODUCTION

The 1969 Lignite Symposium was held at Grand Forks, N. Dak., on May 1-2, 1969. Cosponsored by the University of North Dakota and the Department of the Interior, Bureau of Mines, the meeting was the fifth in this series. Registrants from many States and Canadian Provinces attended the meeting representing many segments of energy-oriented companies, State and Federal Government, and universities. At 2-year intervals, these symposia provide a common meeting place where recent research and developments in technology and utilization of energy resources with emphasis on solid fuels (lignite) are presented. Proceedings[3] of the previous symposia including a Forum held in 1958 have been published.[4]

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[3]Company and trade names are used throughout these Proceedings for clarity and identification purposes only, and their use does not imply endorsement or recommendation by either the Bureau of Mines or the University of North Dakota.

[4]Kube, Wayne R., and James L. Elder (compilers). Technology and Use of Lignite. Proceedings: Bureau of Mines-University of North Dakota Symposium, Grand Forks, N. Dak., April 27-28, 1967. BuMines Inf. Circ. 8376, 1968, 201 pp.

Elder, James L., and Wayne R. Kube (compilers). Technology and Use of Lignite. Proceedings: Bureau of Mines-University of North Dakota Symposium, Bismarck, N. Dak., April 29-30, 1965. BuMines Inf. Circ. 8304, 1966, 124 pp.

Kube, Wayne R., and James L. Elder (compilers). Technology and Use of Lignite. Proceedings: Bureau of Mines-University of North Dakota Symposium, Grand Forks, N. Dak., April-May 1963. BuMines Inf. Circ. 8234, 1964, 128 pp.

Elder, James L., and Wayne R. Kube (compilers). Technology and Use of Lignite. Proceedings: Bureau of Mines-University of North Dakota Symposium, Grand Forks, N. Dak., April 1961. BuMines Inf. Circ. 8164, 1963, 113 pp.

North Dakota Economic Development Commission. North Dakota Lignite Forum, Speech Summaries. Bismarck, N. Dak., 1958, 49 pp.

Fifteen technical presentations were made including papers on electrical power generation, combustion, lignite ash deposition, handling, utilization and analysis, mining, spoil bank rehabilitation, carbonization, oil shale, and relationship of coal, gas, and oil to the total energy concept.

Presiding at the various sessions were: W. L. Crentz, Acting Assistant Director--Energy, Bureau of Mines, Washington, D.C.; Duane R. Skidmore, Acting Dean of Engineering, University of North Dakota; A. M. Cooley, Chairman, Department of Chemical Engineering, University of North Dakota; Sidney L. Groff, Chief, Ground Water and Fuels Division, Montana Bureau of Mines and Geology; and John Lemish, Professor of Geology, Iowa State University of Science and Technology.

George W. Starcher, President of the University of North Dakota, representing the University, opened the Symposium with the following remarks:

> I have a few minutes to assure you that we at the University are very interested in the subject matter of this Symposium, and have been for many years starting with Dean Babcock in 1889. Babcock succeeded in establishing the School of Mines, but, of course, there was no money for it. This situation isn't entirely strange even today as the Federal government, the State government, and others often establish institutes or schools with everything available except funds. However, without funds, Dean Babcock was able to do some of the first work on lignite in North Dakota. He also studied prairie grasses and sugar beets and he anticipated much of the progress that we take for granted today. I am not going to mention the others who, throughout the history of the University of North Dakota, have been intensely interested in research on lignite. The University should always have people engaging in research seeking new knowledge and new uses for old knowledge and old products. Thus, we have long been interested in the many problems that you will be discussing today and tomorrow.
>
> For this Symposium, we have had two very energetic planners, Mr. Kube and Mr. Elder who, incidentally, first discussed this Symposium with me over a year ago. It has been constantly on their minds and I would like to commend them on the fine job they have done all year planning a meaningful and useful program. Therefore, I want to pay tribute to them while welcoming you, then explain that they made a serious error when they said the Symposium series started in 1961. I know that I welcomed some of you, and others who are not here today, for the first Lignite Forum in 1958. This Forum, a 1-day meeting, was sponsored by the Bureau of Mines, the University of North Dakota, the Greater North Dakota Association, and the North Dakota Economic Development Commission. I thought it was just sophistication in calling subsequent meetings a "Symposium" rather than a "Forum," however, there seems to be more than just the name involved and this really is the fifth Lignite Symposium. The Forum in 1958 was in connection with the 75th Anniversary of the University and it doesn't count. But it may have helped to inspire the increasingly significant series of symposia--if so, we are glad.

In any event, we cordially welcome you to the University campus. I hope you will find time to see all of the campus while you are here, although I know you are going to be quite busy with the program that has been planned. We are generally interested in the subjects of your discussions today and we are interested in all of the kinds of things you do. Of course, we are interested in the education and training that will provide for replacement of skilled scientists and businessmen to carry on the lignite industry which is going to last a long, long time. They will be needed to carry on in your footsteps. And so with this thought, and because the papers coming up are more important than anything I might say, I will close by saying again, on behalf of all of us at the University, welcome to the 1969 Lignite Symposium.

Thank you very much.

Hollis M. Dole, Assistant Secretary of the Interior for Mineral Resources, U.S. Department of the Interior, representing the Department, responded as follows:

It is with pleasure that I am here to attend the 1969 Lignite Symposium and wish to convey to you best wishes from Secretary Hickel. Unfortunately, the Secretary could not be here to meet with you personally as he left the country recently on a special mission to Micronesia at the request of President Nixon.

Despite the benefits that the mining industry provides in supplying the materials that we associate with everyday life, the industry does not have a good public image and must take strong steps to improve the situation. I am pleased, therefore, to observe on your program such topics as the effects of surface mining on the environment and what industry is doing to overcome the problem. This is the type of story that must be told so that the public becomes aware of the efforts of the minerals industry to become a good neighbor.

We must continue to have a viable mineral resource industry if future generations are to have available the raw material sources that produce the essentials of what we consider to be the "good life." The mineral industry has become a "social" problem in that it is not geared to produce the quantity of minerals that are needed by the people of this country as our economy expands.

Lately, we have had some good fortune in the discovery of oil in Alaska. It has given our energy situation a new and improved look. A few days ago, Mr. Tom Kelly, Commissioner of Mines in Alaska, in a meeting in Washington, D.C., estimated that the total oil reserves along the North Slope may be 100 to 150 billion barrels. If true, this find will be one of the largest discoveries of petroleum in the history of mankind.

Our energy needs of the future are so great, however, that as large as this oil find is it must be augmented by other forms of energy, such as coal. Coal research is necessary and must receive funding support from Government. It is necessary, also, for Government to encourage symposia such as this one, so that news of the total research effort receives wide dissemination.

Unfortunately, Federal funding of research is difficult to obtain. Within the Department of the Interior, we have comparative ease in securing increased appropriations for mine inspection or oil-well inspection.

An increasing percentage of our funds is going into our regulatory functions and away from the frontier of our research. This unfortunate and unhealthy trend stems from the fact that research per se does not seem to have a sufficiently attractive sales value to those responsible for allocation of funds.

The reason for this was the subject of a recent dialogue I had with an important congressional committee. I was asked why research does not have the appeal to the public that it should. Although I am not sure that I answered that question with certainty, I am convinced that unless research is given more attention and increased funding, it is likely that our future needs for minerals and energy will be in jeopardy.

In conclusion, the progress of this symposium has the best wishes of the Department. We urge you to continue and to expand the valuable research efforts that will be discussed here and make your contributions known to the general public by meetings of this kind. I am looking forward, with interest, to the technical papers that follow.

Abstracts of the papers presented at the 1969 Lignite Symposium follow:

ABSTRACTS OF PAPERS

LIGNITE AND THE TOTAL ENERGY CONCEPT

By C. H. Hardesty, Jr., Senior Vice President,
Continental Oil Co., New York, N.Y.

Prospects for increased utilization of lignite were discussed in terms of generation of electrical power, production of pipeline gas, and liquid hydrocarbons. The effect of prime interest rate, depletion allowances, and oil import controls were considered.

PROJECT BRONCO--A STATUS REPORT

By J. Wade Watkins, Director of Petroleum Research,
Bureau of Mines, Washington, D.C.

Project Bronco is a proposed Government-industry, nuclear-explosive fracturing, in situ retorting experiment in Green River oil shale; this project was originally conceived in 1958. Negotiations for a contract between Government and industry to conduct the experiment are in progress. Data applicable to the experiment have been and are being obtained from the Atomic Energy Commission's underground nuclear-testing program and the Bureau of Mines batch-retorting research. Prospects for a successful experiment appear favorable, and the final design of early phases of the experiment should be available in the near future.

ESTEVAN LIGNITE: MINING AND MARKETING

By R. W. Zeindler, P. E., Manager, Mining Division,
Luscar Ltd., Edmonton, Alberta, Canada

Operations of the three open-pit mines producing over 2 million tons per year from the Saskatchewan lignite field were described, and the local geology was discussed. Present and possible markets seem to concentrate in electrical generation and industrial applications other than heating. The low-temperature carbonization plant at Bienfait, Saskatchewan, produces lignite char for briquetting and other industrial uses.

EFFECTS OF SURFACE MINING ON ENVIRONMENT

By Thomas A. Gwynn, Company Geologist, Montana-Dakota
Utilities Co., and Manager, Reclamation &
Conservation, Knife River Coal Mining
Co., Bismarck, N. Dak.

Progress in reclaiming surface-mined lands in the north-central area was discussed. Special soil and climate conditions and population density present different problems than those encountered in the Eastern States. Recent developments in reclamation laws in North Dakota, Montana, and Wyoming were compared.

THE IMPORTANCE OF ASH IN THE COMBUSTION OF COAL

By William T. Reid, Senior Fellow, Columbus Laboratories,
Battelle Memorial Institute, Columbus, Ohio

The occurrence of inorganic matter (ash) in coal and its behavior on heating was reviewed. Fusibility of coal ash, viscosity of coal-ash slags, and temperature relationships for Newtonian and non-Newtonian cases were presented. The influence of coal-ash composition on viscosity was given graphically and in the form of empirical equations. Attention was given to the special case of ash from lignite. Fireside fouling of boiler tubes was

discussed and explanations of the mechanism by which ash constituents, especially the alkalies and sulfur, lead to external corrosion of superheaters and reheaters were offered.

180-MW J. E. CORETTE PLANT BURNS MONTANA SUBBITUMINOUS COAL

By R. J. Labrie, Asst. Chief Engineer--Generation, Montana Power Co., Butte, Montana, and H. E. Burbach, Supervisor, Proposition Engineering Dept., Combustion Engineering, Inc., Windsor, Conn.

Design, construction, and operational details of the Montana Power Company's J. E. Corette Plant were presented. The 180-mw plant has been in satisfactory operation since July 1968, firing pulverized subbituminous coal from the Colstrip pit. Reviewed were special design considerations and coal and ash handling facilities, as influenced by local conditions and fuel characteristics.

ASH FOULING AND AIR POLLUTION STUDIES USING A PILOT-PLANT TEST FURNACE

By G. H. Gronhovd, Project Coordinator, A. E. Harak, Chemical Research Engineer, and P. H. Tufte, Chemical Engineer, Grand Forks Coal Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.

Results from a 19-month test program using a 75 lb/hr pulverized-coal-fired furnace were summarized. Test probes inserted into the gas stream simulated boiler tubes, and deposit weights were measured after a standard period of operation. Fouling increased with the sodium oxide concentration in the ash up to 8 to 10 percent. Flue-gas temperature in the deposition area influenced deposition rate. High calcium concentration in the ash gave reduced fouling at similar sodium levels. No measurable SO_3 was found in the flue gas from burning North Dakota lignite, although SO_2 levels at 1,400 ppm were determined.

EXAMINATION OF COAL AND COAL ASH BY X-RAY TECHNIQUES

By W. Beckering, Research Chemist, Grand Forks Coal Research Laboratory, H. L. Haight, Associate Professor of Chemistry, Ohio Northern University, Ada, Ohio, and W. W. Fowkes, Project Coordinator, Grand Forks Coal Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.

The capability of an electron microprobe to analyze particles 1 or 2 square microns in area makes it useful in the study of minerals in lignite or in boiler deposits. In conjunction with X-ray diffraction and X-ray fluorescence, relatively complete information concerning elemental composition can be obtained. Electron microprobe examination of lignite indicates that much of the mineral matter exists as salts of humic acids and is uniformly distributed.

Examination of fireside ash deposits from a test furnace indicated the presence of three layers: The inner white layer is rich in sodium sulfate and completely surrounds the tube; the adjacent layer consists of discrete particles loosely bonded to each other; the outer layer consists of ash particles embedded in a matrix of lower melting point sodium silicates.

ASH DEPOSITION RESEARCH ON CANADIAN LIGNITES

By A. D. Winship, Manager, Design and Performance Department, and F. Bender, Research Engineer, Combustion Engineering-Superheater Ltd., Montreal, P.Q.

Basic deposition mechanisms involve thermal and eddy diffusion, condensation of vaporized material, and inertial impaction. Deposits form in three stages with the last or massive deposition stage being most important with regard to design purposes. Reduction in gas temperature, metal surface temperature, and gas velocity lowered the deposition rate, as did increasing the fineness of lignite pulverization. The lower the sulfur content, the lower the deposition in stage 2. Sodium content of the ash, as well as the sulfur, effects the deposition rate at the start of stage 3. In the massive deposit stage, all ash particles impinging on the surface adhered, and the deposition rate was influenced by the size, density, and the quantity of ash.

OPERATIONAL EXPERIENCE WITH LIGNITE AT THE UNITED POWER ASSOCIATION PLANT

By Charles McQuarrie, Manager of Power Production, UPA, Rural Cooperative Power Association, Elk River, Minn., and Justin P. Winkin, Director of Engineering, Equipment Division, Foster Wheeler Corp., Livingston, N.J.

Experience with burning lignite in the United Power Association boiler has shown that when the sodium content is high, the slag develops a very tenacious deposit on the furnace walls and on the convection surfaces. The wide tube spacing originally designed into the unit, together with the techniques described, permit the unit to operate at high loads under difficult conditions.

The low heating value, high moisture content, and potentially difficult slagging characteristics of lignite require special consideration in the design of the boiler and the pulverizing equipment. It also calls for extra attention during operation.

The United Power Association installation has demonstrated that lignite fuel may be used for the generation of electricity on a large scale and has paved the way for larger units now being projected.

U.S. GAS DEMAND AND SUPPLY

By Henry R. Linden, Director,
Institute of Gas Technology,
Chicago, Ill.

The demand for natural gas continues to increase at higher than anticipated rates because of its increasing value in relation to most other fossil fuels when the cost of air pollution control is included. However, there are clear indications that natural gas supply from the contiguous 48 States and the continental shelves will not indefinitely keep up with this rapid growth in demand. An empirical model of natural gas discovery and production in the United States which expresses the overall effect of the various technologic, geologic, and economic factors is used as the basis for forecasting the extent of potential deficiencies in gas supply from the 1970's to the year 2000. Other forecasts of gas supply are compared and selections from the various estimates of future gas demand are made to arrive at a conservative forecast of supplemental gas requirements. Among the sources of supplemental gas are (1) imported pipeline natural gas from Canada and Mexico, (2) tanker importation of liquefied natural gas, and (3) synthetic pipeline gas from coal. By far the most abundant, at potentially competitive costs, is pipeline gas from coal.

LIGNITE FLY ASH UTILIZATION

By Oscar E. Manz, Assoc. Prof. of Civil Engineering,
University of North Dakota, Grand Forks, N. Dak.

This report discusses recent research at the University of North Dakota on the use of lignite ash additions in lightweight concrete, structural concrete, soil stabilization, and bricks or other structural products. Both fired and unfired pressed brick containing only lignite fly ash have been made that comply with ASTM specifications. Minimal shrinkage and warpage was obtained. Use of as much as 50 percent fly ash in mixtures involving granular material have produced 90-day strengths of 2,100 psi. The feasibility of using lignite fly ash as filler in asphaltic concrete has been confirmed.

THE USE OF LIGNITE PRODUCTS AS PLANT GROWTH STIMULANTS

By Philip G. Freeman, Research Chemist, Grand Forks Coal
Research Laboratory, Bureau of Mines,
Grand Forks, N. Dak.

Limited field tests using leonardite applications to potatoes and soybeans indicated a significant increase in yield with no sacrifice of quality over control plots. The increase in yield appeared related to observed increased pigmentation and apparent vigor of the plants. Laboratory tests using radioactive Fe^{59} with chlorella cultures and hydroponic grown soybeans in the presence of leonardite showed an increased uptake and translocation of iron.

LEONARDITE IN FERTILIZER

By A. M. Cooley, Professor and Chairman, Dept. of Chemical Engineering, University of North Dakota, Grand Forks, N. Dak., Gary Douglas, Plant Agronomist, W. H. Rasmussen, President, J. J. Rasmussen, Vice President, and J. Theis, Plant Manager; the last four authors are from Northland Chemical Co., East Grand Forks, Minn.

Manufacture of a pelletized leonardite-base fertilizer marketed under the name of Natro-gro was described. Having an analysis of 10-10-5, the product was designed for use in gardens or on lawns. Concentration of fertilizer components can be adjusted to give any desired analysis. Test plots of barley, potatoes, and sugar beets indicated a beneficial effect of the leonardite in excess of actual nutrient value in 1 year of testing.

THE USE OF CHAR TO IMPROVE THE PHYSICAL QUALITY OF COKE

By Charles C. Boley, Project Coordinator, and M. Merle Fegley, Chemical Engineer, Grand Forks Coal Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.

Char, of various volatile matter content produced by entrainment carbonization, was blended in a two-component blend with a bituminous coal having limited coking characteristics. A 500-lb-capacity movable-wall slot oven was used for coking the blends. Any blend with char concentrations of 10 to 15 percent tested improved coke quality as measured by the coke physical index. The best coke produced from the char-coal blend compared favorably with coke from blends of coals that are now used commercially in the West. A blend of lignite char and the bituminous coal resulted in a coke superior to that from the unblended coal.

LIGNITE AND THE TOTAL ENERGY CONCEPT

By C. Howard Hardesty, Jr.[1]

Introduction

As far back as I can remember, people with furrowed brows and gloomy hearts have been predicting personal catastrophes and universal cataclysms. Whether it is the cancer you are going to get if you eat too many maraschino cherries or the Antarctic polar cap that is sliding into the sea, if the viewpoint is startling enough and the facts plausible enough, the prediction will be good for a feature story in a newspaper or for a raconteur in an after-dinner story fest.

I might as well tell you right from the start I am basically on the optimistic side, so you might want to discount some of the good things I am going to say about lignite. However, I have two reasons to think my optimism is well-grounded. First, it has been my experience that a great many predictions of dire things to come are scare tactics designed to produce a certain effect or achieve a certain immediate goal; in other words, they smell slightly of the fraudulent. Second, and perhaps more important, I have enormous confidence in man's capabilities as a problem-solver. If someone tells me the sun's losing its power, I secretly say to myself: "That's okay; we will find a substitute."

Our own business, the energy business, has not been exempt from soothsayers. Depending on whom you listen to, we might drown in oil or see the end of the gasoline engine or become extinct in a wave of SO_2. However, I must rapidly add that some very responsible people have been looking into our future and have come up with rather interesting figures. Based on a report, "Outlook for Energy in the United States," prepared by the Chase Manhattan Bank,[2] we learn that oil and gas, which today supply three-fourths of our energy needs, will still be in first place in 1980, even though by then their share of the energy market will have dropped to two-thirds.

Coal's Future in the Energy Picture

Coal is the third major source of energy, and it, too, will grow, although somewhat less than proportionately. While these projections are interesting, the estimates are only indicative of a direction and an order of magnitude, and with good reason. I can cite at least three reasons for possible variations from the statistical outcome as foreseen today:

First, because one can have sure knowledge only of that which has already happened, future predictions tend often to be simple extrapolations of the past.

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[1] Senior vice president, Continental Oil Co., New York, N.Y.

[2] Chase Manhattan Bank. Outlook for Energy in the United States. New York, 1968, 60 pp.

Second, technological advances are among the pleasant surprises of life, and are just as unpredictable. We never know when a breakthrough might come. What is more, in very practical terms, the amount of government money allocated for coal research has never amounted to more than a twentieth of that given for research on nuclear power generation. So that, too, might change.

Third, interrelated political and economic factors will play a large role in encouraging or discouraging coal research, investment in new processes, plant expansion, and other management decisions. I am referring, of course, to things like import control, coal lease royalties, tax treatment, interest rates, and so forth.

Given the uncertain nature of soothsaying, I think I would prefer to take a narrower look at what is in store for us. Here I might start with two rather extreme figures: one so small it does not even make the statistical abstracts, the other so large it looms as unique. The first, the small one, is the amount of lignite that is mined each year. Industry figures indicate that 14.25 million tons of anthracite and 545 million tons of bituminous coals were produced last year. Buried somewhere in the bituminous figure is the amount of lignite mined. Since lignite has not been separated from bituminous production, I think we must conclude that it has a long way to go before it becomes a major factor in supplying energy for our ever-expanding needs.

The second figure refers to the 350-billion-ton lignite reserves in North Dakota. It is my contention that this source of energy is too enormous to be ignored. This is the reason it makes sense to look at lignite's potential, to investigate and experiment, do bench studies, and build pilot plants. My company, Continental Oil and its subsidiary, Consolidation Coal Company, has been in the forefront of such research because we have long been interested in all sources of energy. The interchangeable nature of the forms of energy is fascinating even as an idea. Put into practice, it can also make money for companies that are innovative, experimental, flexible, and more importantly, that promote sound conservation of fuels by maximizing use of those fuels in abundant supply.

Possibilities for Large Tonnage Uses of Lignite

I would like to point out three important mutations to which lignite as well as all coals are susceptible: electricity, liquid hydrocarbons, and pipeline-quality gas.

Let's look at the lignite-electricity mutation first. As we all know, it is not economically feasible to transport lignite over long distances. Its high moisture content and relatively low thermal value per pound do not warrant high transportation costs. Fortunately, transportation is not always necessary. Powerplants can be located near reserves and the short haul can easily be managed by truck. In other cases, mine-mouth operations convert the coal to electricity on the spot and EHV transmission takes it economically to distant markets.

Today, Consol and others supply the electricity utilities in North Dakota with large amounts of low-cost fuel. Basin Electric, United Power, and Minnkota are, or soon will be, operating a total electric generating capacity of about 1 million kilowatts. By 1974, Consol alone will be furnishing almost as much lignite as all the principal producers today. Four million tons of Consol lignite will fuel the boilers of the high-voltage transmission systems operating at the mine mouth.

Another encouraging sign of progress is the decision to tie the Bonneville area to the extra high-voltage transmission grid that links the southwest. I understand that DC and AC links have been established. Even the broader concept of a coast-to-coast tie has taken firmer hold in the minds of many people. As interconnecting ties are made, computers will figure out which plants can most efficiently and most economically supply electrical energy even to faraway points. In the not too distant future, consumers in New York might well be using electricity from lignite produced in North Dakota. What I am saying, of course, is that as the grid develops, lignite will come into greater use as a low-cost energy source, as it will be electricity, not coal, that will be moved.

What about lignite as a source of liquid hydrocarbons? As you know, our company has been in the forefront of liquefaction research. But most of it has been with Eastern coals, not lignite or subbituminous coals. However, we also have a bench-scale operation at our research headquarters which is concentrating on conversion of these Western coals. We hope that our Project Gasoline at Cresap, W. Va., funded by the Office of Coal Research, will be authorized to test subbituminous coal as a part of its research effort. It is too early to report on these investigations, but there are elements, especially economic and political ones, that are relevant whether you start with Eastern coal or with lignite as the conversion source.

Two of the most important factors affecting the prospects for synthetic hydrocarbons are the outlook for future oil and gas exploration in this country and Federal policy on petroleum imports. Recent trends in the exploration environment do not encourage the belief that domestic supplies will keep pace with demand. As costs per barrel of oil produced have gone up, the number of completed wells has gone down. Right now, it looks as though there will be a shortage of domestic crude oil capacity in the late 1970's.

As I said, import policy will also significantly affect the development of synthetic crudes. As an infant industry, these synthetics need protection, not from domestic production, but from an influx of foreign crude oil. Despite this need and despite a well-founded national security rationale, the oil import control program has been under frequent attack. The resulting uncertainties have had an inhibiting effect on the development of synthetic hydrocarbons--as well they might in a situation which calls for tremendous outlays of capital to even get off the ground. Just look at the figures:

Estimated capital requirements for a conventional shale oil operation are immense, about $3,000 per daily barrel of plant output, or $300 million for a 100,000-barrel-per-day facility. The Great Canadian Oil Sands plant, which is

the only one now using tar sands in commercial production, is reported to have cost about $5,000 per daily barrel. These figures relate to barrels of crude, or "synthetic" crude. For coal liquefaction, the capital investment may be about $3,500 per daily barrel of finished product, over and above the coal mining investment which may range anywhere from $500 to $1,500 per daily barrel.

With the prime interest rate now set at 7-1/2 percent and the abolition of the investment credit, a strong probability, a company would have to reflect long and hard before spending between $300 and $400 million for a liquefaction plant. One encouraging development in our company has come from the incessant refinements we bring to the process of liquefaction with a view toward reducing costs. A possibility we are working on now is the use of new catalysts to effect the direct conversion of coal to high-octane gasoline without going through the crude oil stage.

I have presented the factors relevant to the production of synthetic hydrocarbons because this is the situation lignite would be facing if it enters the field. It is the opinion of our Research Division that there is no clear-cut, favorite raw material source in the race for synthetic liquid hydrocarbons. It is in the best interests of the United States to keep all options open. It is this same reasoning which has led us to our research efforts with lignite as another potential source of raw material.

Fortunately some of the very characteristics that operate against lignite under certain circumstances act as a strong supportive element when it comes to gasification. For instance, lignite's low rank and high moisture content make it very reactive at low temperatures and, therefore, highly desirable for this process. With 350 billion tons of lignite reserves in North Dakota, even if one assumes a 50-percent loss in mining, there is a potential for producing the equivalent of 175 billion tons in pipeline gas. Pipeline gas, as does electricity, overcomes lignite's transportation barrier.

Because my company has been so active in coal gasification, I am going to make an extra effort at objectivity by quoting an authority outside the corporate family. In a paper presented at the Industrial Fuels Conference, Martin Elliott, corporate scientific advisor to the Texas Eastern Transmission Corporation, had this to say:[3]

> The recent progress that has been made in coal gasification technology is indicated...by the reduction in estimated cost from about $1.10 per MM Btu to about $.50 per MM Btu in the past eight to ten years. There is an excellent possibility that we may soon be in the range of estimated cost of 40¢ to 45¢ per MM Btu. The progress to date has been so encouraging that it is not unrealistic to have as our objective the development of a coal gasification process that will produce a gas completely interchangeable with natural gas at a price that is competitive with or lower than natural gas delivered to or produced in the area in which the coal gasification plant is situated.

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[3]Elliott, Martin. Gas in the Changing Energy Picture. Pres. at the Industrial Fuels Conference, St. Louis, Mo., Feb. 11, 1969, 10 pp.

The supply and demand picture of natural gas also is favorable to the prospect of gasification of lignite. Natural gas reserves are down; we now have only a 14- to 16-year supply. As oil exploration becomes less attractive in the United States, the chances of finding natural gas become more problematical. I turn again to Mr. Elliott; this is what he says:[4]

> ...we will see history repeat itself as manufactured gas again becomes a significant source of gas energy. Basically, this means the transition from a gas energy system based on the fluid fossil fuel, natural gas, to a system eventually based on the solid fossil fuel, coal, which will be converted to gas. As we meet the future demands for gas, the center of gas production will move from the center of natural gas production in northeastern Texas, probably first in the direction of the center of bituminous coal reserves and eventually in the direction of the center of all coal reserves... that is, in the Dakotas, Montana, and Wyoming. The fact that we will eventually draw heavily on our resources of solid fuels, most of which are remote from present markets, does not imply that it will be necessary to transport solid fuels to center of consumption. On the contrary, the end use market has already expressed its preferance for fluid fuels and this preference will be met by mine-mouth conversion of coal and oil shale to liquids and gases to take advantage of the favorable economics of transporting fluids instead of solids.

At the present time, one major plant for gasification using the electrothermal process is under construction in Chicago. It is being built by the Office of Coal Research in cooperation with the Institute of Gas Technology at a cost of between $14 and $15 million.

In April, our own CO_2 acceptor process for the conversion of lignite to pipeline quality gas was given an assist when the Office of Coal Research announced that it was ready to let the contracts for the construction of a pilot plant. This project is based on the use of Northwestern lignite and subbituminous coals as the primary carbon source; hence, the choice of Rapid City, S. Dak., in the heart of lignite country as the plantsite.

The principal feature of this process is that it does not require large amounts of oxygen. It uses dolomite as the heat-transfer medium and also to separate carbon dioxide from the salable product gas. Results from laboratory and bench-scale work have been most encouraging. Incidentally, significant improvements in the cost of synthetic gas is not easy; this process is a far step out from conventional technology. It involves the flow of two different solids through three different reactors at high pressure and temperature, something which has never been done before. No doubt this type of development will not be easy and we must be prepared for a real battle with nature before the operation is well in hand.

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[4]Work cited in footnote 3, p. 7.

After studying a sample area which included the Dakotas, Minnesota, Nebraska, and Iowa, it was estimated that a potential commercial-industrial market existed for 1 trillion cubic feet of gas per year. A commercial lignite-to-gas plant could meet part of that demand with gas delivered to the city gate at about $0.45 to $0.50 per million Btu.

Although I have talked about lignite principally in its relationship to electricity, liquid hydrocarbons and pipeline gas, this does not exhaust lignite's potential. Right now, for example, Consol and others are engaged in exploratory work on a deashing process in which lignite is dissolved and most of the ash is filtered out. Since lignite is high both in moisture and in ash content, this process raises the Btu per pound from 7,500 to about 15,000. The extract can then be used in the following two ways: As a high melt extract, it can be pipelined in water as a slurry and fed directly to a utility plant; if it is made into a low melt extract and can be used as if it were a heavy oil.

No discussion of the future development and use of Western coals would be complete, much less accurate, if mention were not made of several very important questions now pending before Congress and the new administration in Washington. Legislative or administrative action taken with regard to depletion allowances and the oil import program will have a most material effect on the timing and availability of synthetic crudes and gases.

It is difficult to conceive that the very substantial capital investments needed to develop and produce synthetic sources of fuels from coal will be available if unlimited amounts of lower cost foreign crude are allowed to be imported into this country. Many people believe that a lowering of percentage depletion on oil and gas could also affect the amount of percentage depletion on coal. Thus, those who are interested in the expanding markets for coal afforded by its conversion into liquids and gases must also resolve themselves in a wise resolution of the Mandatory Oil Import Program and allowances for percentage depletion.

I hope you believed me when I intimated earlier that I am not trying to be an oracle somewhat biased by his own naturally optimistic state. In fact, I can see lots of pitfalls and lots of "ifs" in lignite's future. We do not know what actions Government might take in incentives to the oil industry, import quotas, taxation, mineral rights, research funds--all of which can affect lignite's place in the total energy picture. Nor do we know what research might uncover or how soon it will be able to solve the technological problems before us.

The coal industry is one of the oldest of our industrial era. Its long survival through many peculiar cycles has required stamina and ingenuity. We at Continental Oil are happy to have Consolidation Coal as a focal point of our multienergy orientation, and proud to be active in the research which gives our industry its vitality.

PROJECT BRONCO--A STATUS REPORT

By J. Wade Watkins[1]

Introduction and Background Information

Project Bronco is a proposed in situ retorting experiment using nuclear-explosive fracturing in Green River oil shale. The experiment originally was conceived and discussed with technical personnel of the Atomic Energy Commission in mid-1958, following announcement of the Ranier event, which was the first contained nuclear explosive (September 19, 1957). Data from the Ranier experiment were evidence that nuclear explosives, yielding tremendous energy in a small physical package, should be applicable to breaking rock in many hydrocarbon- and minerals-extraction operations. Oil shale, which was considered originally because of the tremendous resource potential, is essentially impermeable, has a very low heat conductivity, and occurs at depths and thicknesses adequate to contain a nuclear explosion.

In situ retorting, if technically and economically feasible, has several potential advantages over conventional aboveground retorting. The costs of in situ shale-oil production may be less, because the costs of mining, crushing, and conveying would be eliminated. Furthermore, it is reasonable to assume that nuclear-explosive methods of fracturing the shale in place may be developed that are cheaper than mining and crushing costs. It also may be possible to recover a higher percentage of shale oil than with conventional methods. Room-and-pillar mining, for example, yields a maximum of about 75 percent of the in place rock. This yield can be expected to decrease when deeper and thicker deposits are developed with this technique. In addition, some losses occur in the crushing and retorting steps. For deep, thick beds, recovery may be as low as 50 percent by conventional mining methods. The cost of disposing of spent shale also would be eliminated in a successful in situ process. Also important from a social-benefit standpoint and not insignificant with regard to costs, potential pollution of air and water and disfiguration of the earth's surface would be minimized by an in situ process. Some evidence is available that a higher grade oil may be produced in situ, depending upon the method of retorting. For these reasons, in situ retorting appears attractive enough to warrant a substantial research effort.

A meeting of Government and industry officials, scientists, and engineers was held at Dallas on January 6-7, 1959, to discuss the concept. Recognized limitations were that data on nuclear-explosive phenomenology were available for only one rock type, and no data were available on retorting random-sized blocks and particles of oil shale in place.

Despite these limitations, there was some interest expressed by industry in a Government-industry experiment. Through the auspices of the American Petroleum Institute, a committee was formed to investigate the feasibility of a Government-industry experiment on nuclear-explosive fracturing, in situ retorting of oil shale. The voluntary cessation of nuclear-explosive testing

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[1]Director of Petroleum Research, Bureau of Mines, Washington, D.C.

in 1959 precluded further action at that time. Underground nuclear-explosive testing subsequently was resumed by the United States in 1961, after the Soviet Union had resumed nuclear-explosive testing.

Our researchers continued to look at the feasibility of utilizing nuclear explosives in hydrocarbon production. Those efforts culminated in Project Gasbuggy, the first Government-industry Plowshare experiment. Gasbuggy was designed to determine the efficiency of stimulating natural gas production from relatively impermeable (less than 1 millidarcy), deep, thick gas-bearing formations. The 26-kiloton thermonuclear explosive was detonated December 10, 1967, at a depth of 4,240 ft in a tight gas sand in northwestern New Mexico. Production testing and analysis still are underway; preliminary results indicate a successful experiment.

In 1965, CER Geonuclear Corporation was formed to offer consulting and other services in peaceful uses of nuclear explosives. Shortly after incorporation, CER personnel contacted numerous oil companies, the Department of the Interior, and the Atomic Energy Commission concerning the possibility of a Government-industry nuclear-explosive fracturing, in situ, oil-shale retorting experiment named Project Bronco. Some 18 companies authorized CER to complete a feasibility study and to negotiate a contract for the experiment with the Federal Government.

Negotiations were begun in December 1967 and a compromise contract was drafted in July 1968 after several lengthy and complicated negotiation sessions. This draft and a draft operating agreement between industry and CER subsequently were reviewed by the Government agencies concerned and by the companies contacted by CER. The contract was not attractive enough to the prospective industrial participants for any of them to accede to it. A modified contract (or contracts) is now being considered.

Design of the Bronco Experiment

The design of Bronco, as with any scientific experiment, is flexible and subject to change. The present design calls for the detonation of a nominal 50-kiloton nuclear explosive at a depth of about 3,000 ft in a location where the thickness of continuous oil shale is at least 2,000 ft under about 1,000 ft of overburden. As indicated in figure 1, which is based on calculations, it is expected that a chimney with a radius of about 133 ft and a height of about 665 ft will be created. Fractures are expected to extend radially outward horizontally (excluding the chimney radius) to a radius of about 400 ft and a height of about 930 ft. The chimney should contain about 1.9 million tons of broken oil shale with an equivalent of 1.12 million barrels of oil. The fractured area may contain 30 million tons of oil shale, with an equivalent of about 18 million barrels of oil.

Bronco is divided into four phases: Phase I, site confirmation; Phase II, construction, detonation, and evaluation; Phase III, chimney treatment; and Phase IV, fracture zone treatment.

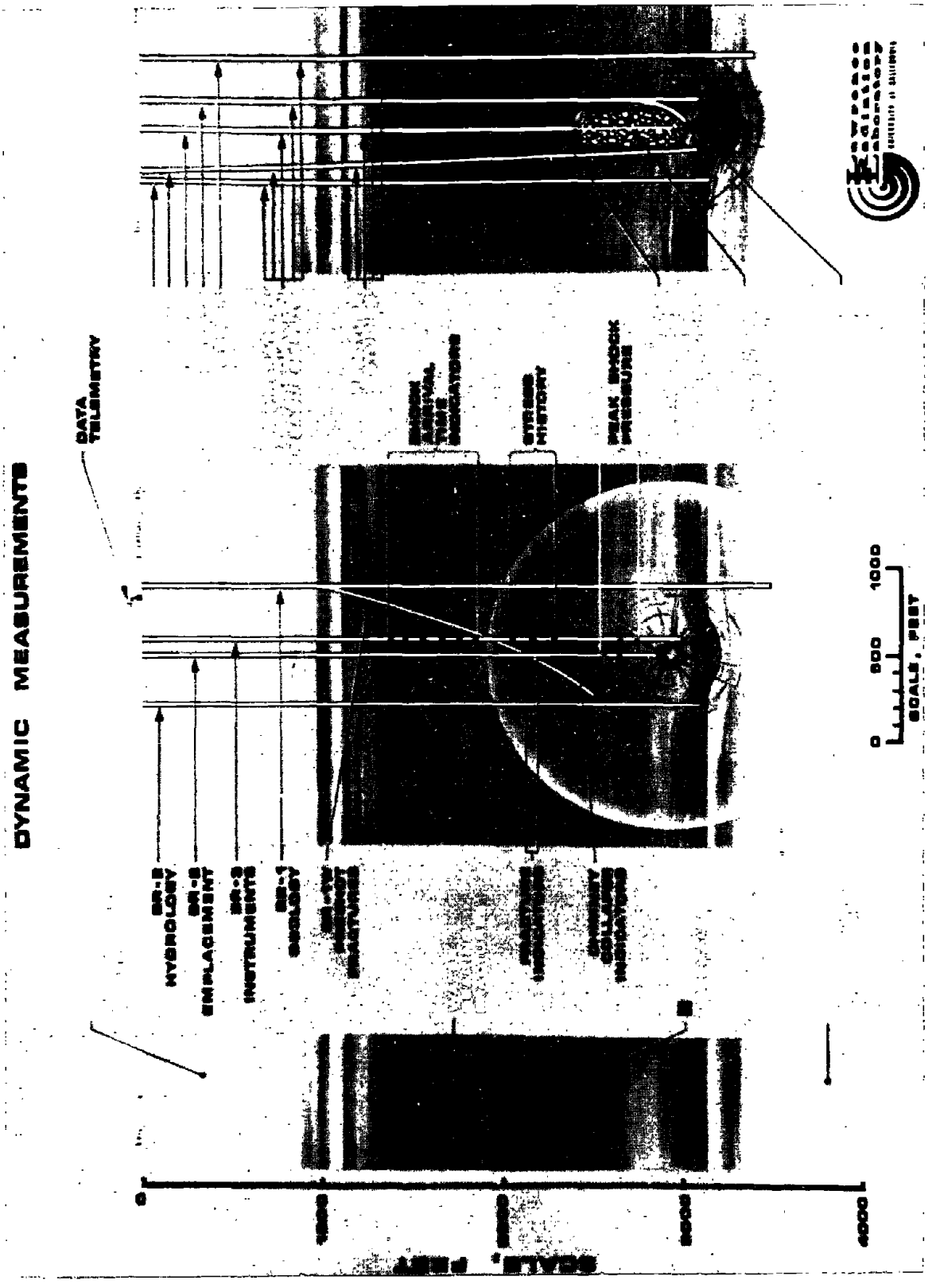

FIGURE 1. - Project Bronco–Explosion Effects.

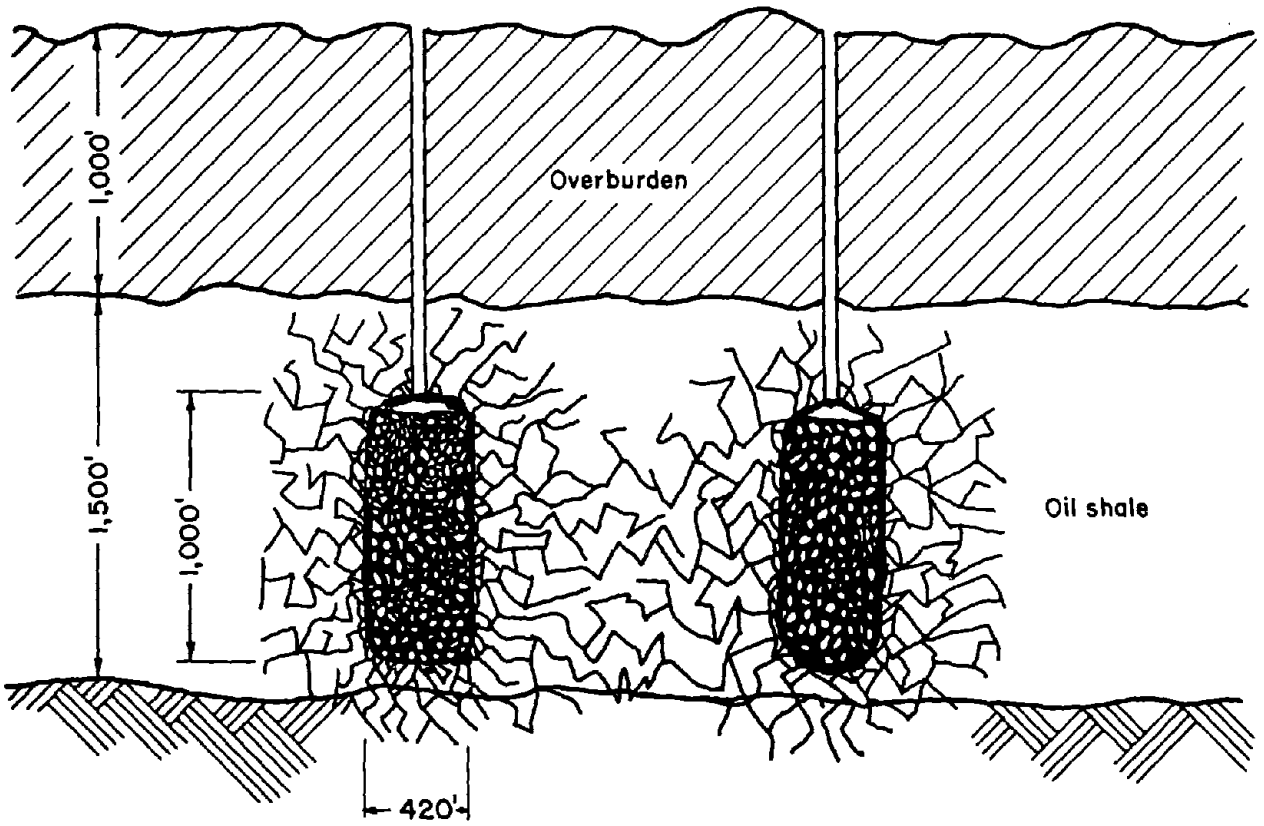

FIGURE 2. - Size of the Nuclear Chimney.

The concept of how multichimney development might be accomplished, if it is proved feasible to retort the fractured zone as well as the chimney, is shown in figure 2. This is conceptual and the resultant chimney measurements are not based on a 50-kiloton device.

Retorting

It is assumed that the retorting method to be used, especially for the chimney, will be combustion. However, there is a possibility that hot methane, hot hydrogen, or superheated steam might be used. It is most probable that the latter three methods of retorting would be more applicable to the fractured zone, if the fractures remain open enough to permit fluid flow, and that combustion retorting would be more applicable to the chimney rock.

Related Retorting Research

To obtain information on optimum retorting parameters for random-sized, random-grade blocks and particles of oil shale, we have been conducting experiments at the Laramie Petroleum Research Center with the batch-type retort shown in figure 3.

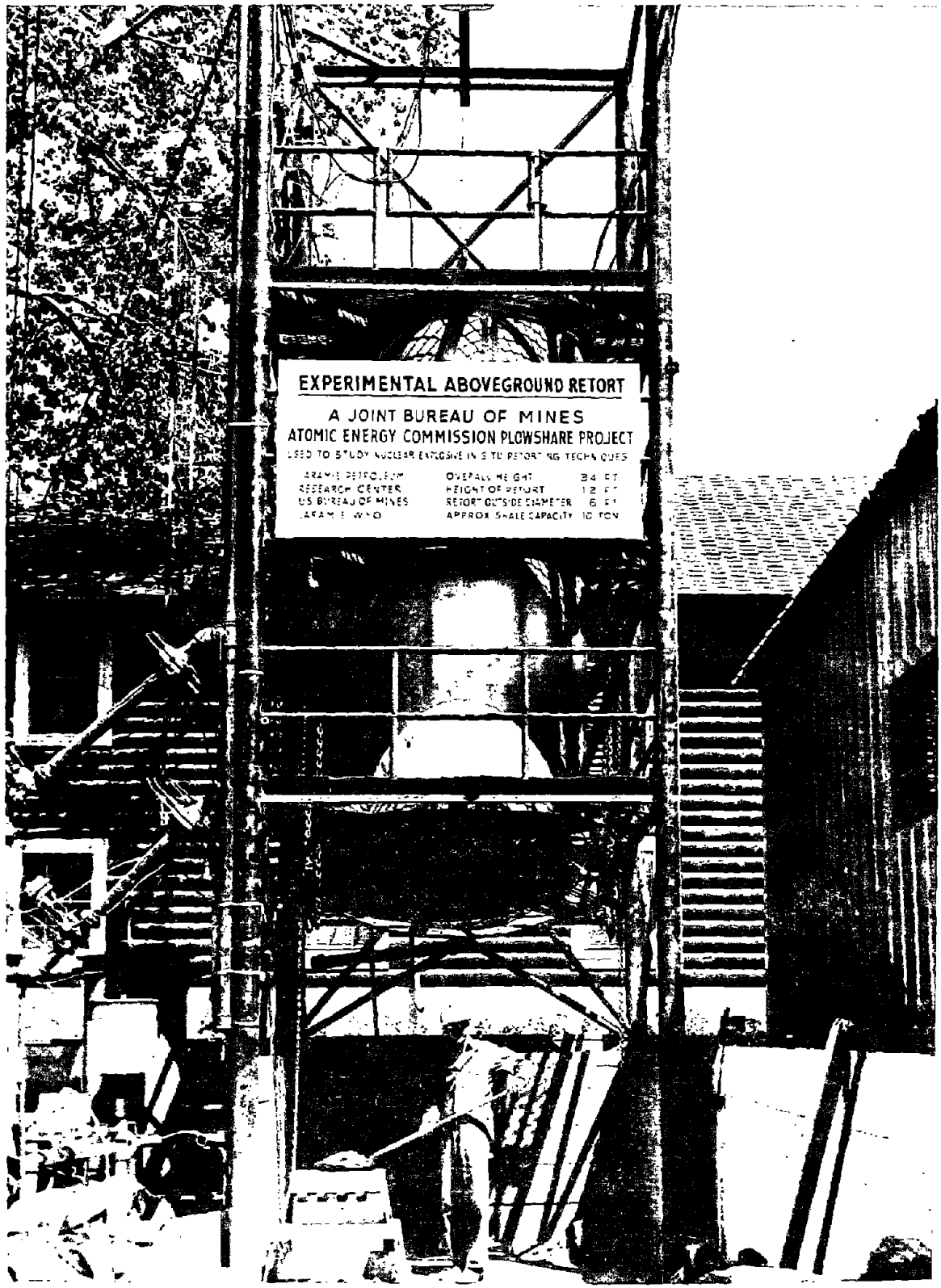

FIGURE 3. - Experimental Aboveground Retort.

Apparatus

The capacity of the retort is about 10 tons; the overall height of the unit is 34 ft. The retort vessel is 6 ft in diameter by 12 ft tall and has a cast refractory lining tapering from a thickness of 8 in at the top to 6 in at the bottom. A simplified schematic diagram (fig. 4) shows the retort vessel and associated equipment. Feed rate is from 1 to 17 pounds per hour of shale. Retorting temperature is 900° F, and oil yield is 28 to 80 percent of the Fischer assay. The shale initially contains 0.6 to 1.0 percent sulfur, 0.4 to 0.6 percent nitrogen, and from 1.5 to 2.3 percent hydrogen.

A natural-gas burner used to preheat the shale charge and initiate combustion is located at the top of the retort vessel. All of the gas supplied to the burner is measured and samples for analysis are taken periodically. Temperatures are measured and recorded by means of thermocouples inside thin-walled stainless steel tubes at 18-in vertical intervals in the shale bed.

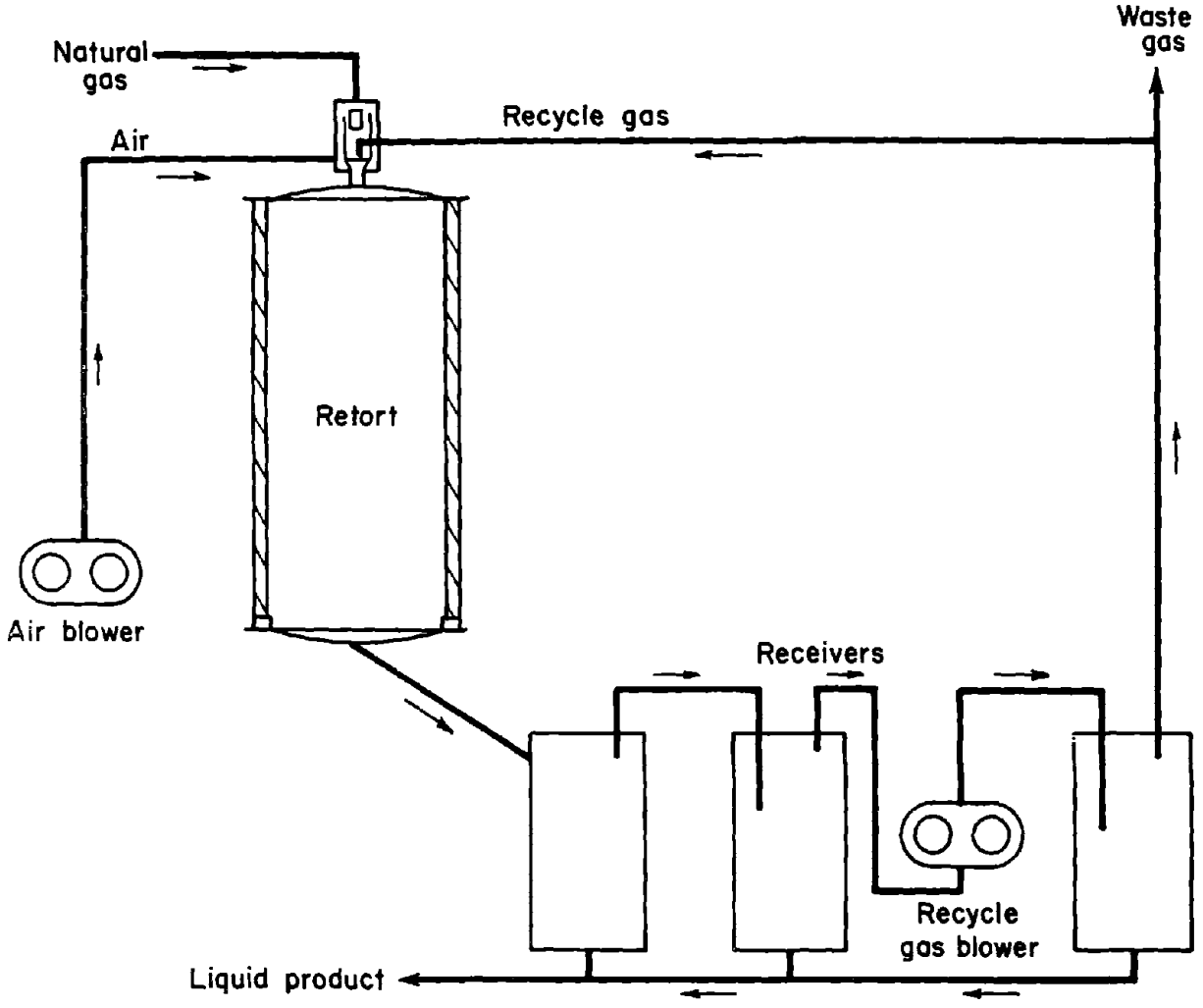

FIGURE 4. - Schematic Diagram of Experimental Aboveground Retort.

Rotary blowers in the first two recovery tanks agglomerate shale-oil mist. The recycle-gas blower, used for the same purpose, recovers oil in the third tank.

Oil-Shale Charge

The oil-shale charge for each experiment is prepared from mine-run shale obtained from the Bureau's Anvil Points Facilities near Rifle, Colo. Oil-shale assays of the charges for these experiments range from 26.0 to 48.0 gallons per ton. Size distribution of each charge as determined by actual measurements ranges from sand-grain size to pieces 20 in in two dimensions. Each new charge is carefully loaded into the retort to avoid further breaking of the pieces, and particles are placed randomly in an attempt to avoid segregation by size.

Retorting Parameters

Retorting of the oil shale is started by heating it with the natural gas burner. The length of time the burner is used varies from a few hours to a few days. The burner is generally not required after the top of the shale bed has been heated to about 350° F. Above this temperature, the system is self-sufficient with regard to heat requirements owing to the combustion of carbonaceous material in the shale.

Control of the retorting operation is based on either bed temperature or oxygen concentration in the stack gas, or both. In some of the experiments, a maximum bed temperature is chosen, and air and recycle gas-flow rates are adjusted to maintain this temperature. In other experiments, the flow rates are adjusted to maintain a minimum oxygen concentration in the stack gas and, in still others, to maintain a chosen oxygen concentration and a chosen temperature. In the series of experiments described here, two were made using air only, with no recycle gas.

Retorting runs are continued until the combustion zone reaches the bottom of the retort. This point is determined from temperature measurements and also from sudden large increases in the oxygen concentration in the stack gas which is attributable to a decrease in the amount of carbonaceous material available for fuel. Retorting is assumed to be complete when the bottom thermocouples are at an average temperature of 900° F. Material balances are calculated over the entire retorting period.

Oil Recovery

Oil yields from 28 to 80 percent of Fischer assay were obtained from 13 runs. Such variations in yield are attributable largely to changes in the measured and controlled operating variables, such as air-flow rate, recycle gas-to-air ratio, and Fischer assay of the oil-shale charge; however, to a lesser extent, the variations are caused by uncontrolled variables, such as shale particle-size distribution and location of the particles in the retort bed. The effects of such uncontrolled variables may be of major importance in the retorting of an actual nuclear chimney in oil shale.

Retorting Rate

Unit retorting rates covered by this study varied, depending on operating conditions, between 1 and 17 pounds of shale per hour per sq ft of retort cross section.

Liquid Product Properties

Oil from the aboveground retort is similar in appearance to oils produced in other internally heated retorts. The oil is black and viscous, has a relatively high pour point, and has a distinctive odor. Table 1 gives a comparison between the properties of the oils from other retorting processes and two of the oils recently produced in the aboveground retort. The oil from the aboveground retort has a somewhat lower specific gravity, lower pour point, and a lower viscosity than the oils obtained from the other retorts. Sulfur and nitrogen contents are essentially the same.

TABLE 1. - Properties of shale oils

Property	Type of retort			LPRC batch run number	
	Gas flow	Gas combustion	N-T-U	14	11
Gravity, API, 60° F/60° F.....	17.3	20.0	22.0	25.2	23.0
Pour point.....° F..	80.0	85.0	90.0	70.0	72.0
Viscosity, SUS, 210° F.....	58.0	50.4	45.8	36.0	38.0
Sulfur.....weight-percent..	0.70	0.63	0.80	0.78	0.77
Nitrogen.....do.....	2.20	2.09	1.90	1.60	1.92
ASTM distillation:					
Initial boiling point.....° F..	225.0	290.0	196.0	122.0	122.0
5 percent.....° F..	463.0	446.0	436.0	348.0	392.0
50 percent.....° F..	641.0	-	662.0	690.0	735.0
Cut point.....° F..	660.0	694.0	680.0	810.0	810.0
Recovery.....percent..	77.0	49.0	71.0	75.0	66.0

Gas Composition

The product gases consist mainly of nitrogen and carbon dioxide and consequently have little fuel value. Small quantities of oxygen, carbon monoxide, methane, and heavier hydrocarbons, including ethane and ethylene, are present. Only trace quantities of propane have been observed.

Energy Considerations

When retorting large particles of oil shale, not all of the carbonaceous material remaining in the spent shale can be used as fuel. Figure 5 shows that a part of this material in the central portion of the larger particles may not be oxidized. Furthermore, the rate of combustion may be too low to produce enough energy because the available fuel is progressively burned from the outside portion of the shale particles. Therefore, under some conditions additional fuel, such as natural gas, may be required.

FIGURE 5. - Block of Retorted Oil Shale Showing Residual Carbon.

To scale up the batch retorting experiments and permit retorting larger blocks of shale, as an intermediate step between the small experiment and retorting in a nuclear chimney, a retort that will have a capacity of about 150 tons now is being constructed.

Conclusions

The potential advantages of nuclear-explosive fracturing followed by in situ retorting are so attractive and the application potential of a successful technique is so great, that the Bronco experiment should be conducted. A joint Government-industry experiment is favored because of the advantages of sharing both cost and technology. Bronco originally was considered a high-rish experiment because of inadequate data on nuclear-explosive technology in different rock media and on retorting random-sized and graded oil-shale particles. Now, however, nuclear-fracturing data are available for more than 200 contained nuclear explosions. Also, results of the batch-retorting experiment are encouraging, and even more reliable data should be available from the larger scale retort now being erected. Radioactive contaminants may be a problem but not an unsurmountable one. Hopefully, final plans for early phases of the experiment Bronco should be developed within the near future.

ESTEVAN LIGNITE: MINING AND MARKETING

By R. W. Zeindler, P. E.[1]

General

The Estevan lignite area is located in the southwestern portion of Saskatchewan, just north of the United States border and the State of North Dakota. Lignite has been mined since the turn of the 20th century with all production prior to 1930 being produced from underground operations. In many coal areas the early operations were small and simply followed the outcrop coal of the river valley into the hillside. The Truax-Traer Coal Company introduced strip mining to the area and by 1956 underground operations had ceased with all of the tonnage being produced using strip mining techniques. At one time, there were over 100 mines producing 2 million tons annually. Today over 2 million tons per year are produced by three companies: Manitoba & Saskatchewan Coal Company (Limited), Battle River Coal, and Utility Coals Ltd.

The map (fig. 6) indicates the approximate coal limits of the field, the area of operation of the three companies, and the general topographic and industrial features of the area.

Geology

The coal in the Estevan area, which is of lignitic rank, is a portion of the Ravenscrag formation of the Tertiary age. The Ravenscrag formation is equivalent to the Fort Union formation of North Dakota and consists of interbedded lignite seams in variable thicknesses of sand, clay, sandstone, and shale.

Generally speaking, the coal horizons are horizontal but have a slight dip to the south. In the west there are severe irregularities which have not been fully explained or detailed.

Four seams have been mined in the area, but correlation of the seams throughout the field has not been definitely established, particularly for the upper seams. The Department of Industry in Saskatchewan is working on a project to correlate the seams by a computer analysis of all drilling to date. Isopach maps were made of the individual horizons and seams with variable success. Because indications suggest that three seams are present in the field rather than four, the computer study is being continued with detailed analyses.

The Btu content of the lignite varies from east to west; the highest values are in the eastern part of the field. The range is from 6,000 Btu to 7,500 Btu. The moisture content is approximately 35 percent, with ash contents from 5 to 7 percent.

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[1]Manager, Mining Division, Luscar Ltd., Edmonton, Alberta, Canada.

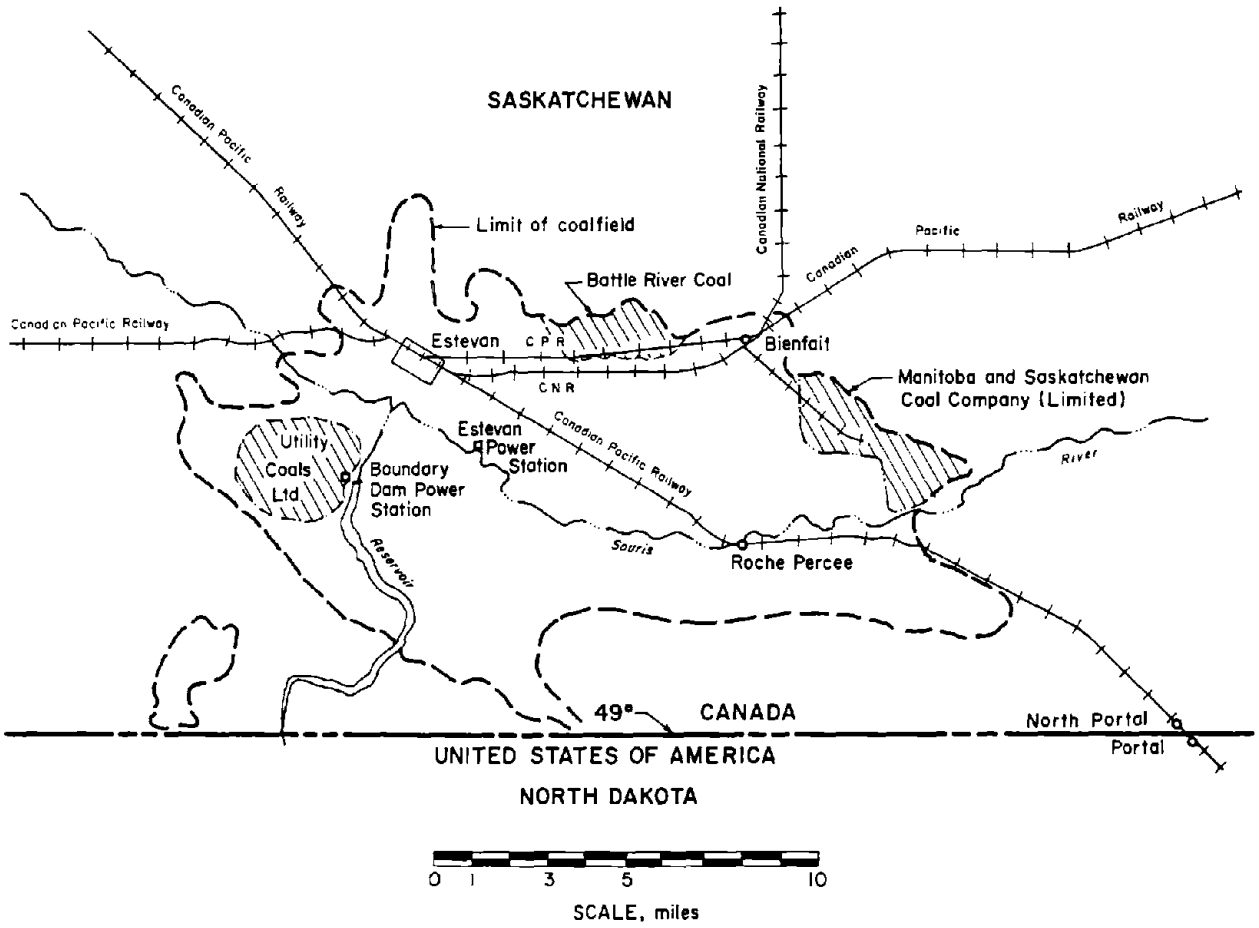

FIGURE 6. - Estevan Lignite Coalfield.

As in other areas where electric power is generated from lignite, the problem of controlling the sodium content of the ash is of paramount importance. Tests recently concluded in the Estevan area indicate that 3-in cores can be recovered with little or no loss of core. Isopach maps can be produced showing the sodium content, which could assist materially both mining and power companies.

Based on the premises assumed in the calculations, the estimated reserves of the area vary widely. Dr. D. B. MacKay of the Federal Department of Mines and Resources established a reserve total in excess of 900 million tons in 1946.[2] In 1962, Mr. W. J. Pearson of the Saskatchewan Department of Mineral Resources estimated strippable reserves in excess of 400 million tons.[3]

[2]Doerr, C. F., and C. M. Thompson. Saskatchewan Lignite--Then, Now, and Tomorrow. Index 67, Proc. Saskatchewan Industrial Exposition and Mineral Symposium of 1967. Aug. 27-Sept. 1, 1967, Regina, Saskatchewan, Canada, pp. 74-88.

[3]Pearson, W. J. Recoverable Coal Reserves in the Estevan Coalfield. Annual Report, Dept. of Mineral Resources, Province of Saskatchewan, August 1962, pp. 1-5.

Mining

Manitoba & Saskatchewan Coal Company (Limited)

Two seams are mined by the Manitoba & Saskatchewan Coal Company. Assuming that four seams exist in the field, the company is mining the lower two seams because the upper two seams have been eroded in this area.

The lower of the two seams is the most extensively mined and averages 8 to 9 ft in thickness. The seam is quite regular in horizontal configuration and quality. A Marion 7400 dragline with a 200-ft boom and 10- or 11-cu-yd bucket does the stripping in a normal side-casting procedure. Pit width averages 80 to 100 ft with depth of overburden ranging from 60 to 80 ft. No overburden drilling and shooting are required except in some winter months when the frozen ground is shot to maintain the efficiency of the dragline.

The upper seam is stripped by a Marion 7200 with a 120-ft boom and 7-cu-yd bucket. Overburden depth averages 20 ft with the coal seam being 4 to 5 ft in thickness.

Only very small tonnages remain as a reserve of the upper seam, which is not as extensive in area as the lower seam. The lower seam has not been mined when below the upper seam because economics and sales have not warranted operating at the depths of the lower seam in these areas.

Coal is drilled, shot, and loaded primarily using an 8-cu-yd electric shovel. In addition a small 4-yd diesel shovel loads coal behind the 7200. Fifty-ton haulers are used to haul the coal to the preparation plant. Standard methods of crushing, screening, and loading are used. Oil treatment is applied where necessary. Most tonnage is shipped by rail with some minor tonnages being sold locally in trucks. The slack is hauled in trucks under contract to the Estevan Plant of Saskatchewan Power Corporation.

The company's 1,000-hp diesel locomotive switches in the mine yards and transfers loaded and empty cars to the railroad yards in Bienfait 5 miles away.

Battle River Coal (A Division of Alberta Coal Ltd.)

The seam mined is the lowest of the four seams. All other seams have been either eroded or mined previously. As at the Manitoba & Saskatchewan Coal Company, the seam averages 8 to 9 ft in thickness and is quite regular. Two draglines were used, a Marion 7800 and a Bucyrus Erie 500W. The 7800 was recently moved cross-country to the Utility Coal Company operation. This involved walking the unit approximately 10 miles and required extensive planning because a main highway and the Souris River were crossed. Before moving, the 7800 uncovered a considerable tonnage to provide a reserve of stripped lignite.

The stripping is now done solely with the 500W, which is equipped with 12- to 15-cu-yd buckets and removes approximately 50 to 60 ft of overburden. The coal seam is usually not drilled or shot but is loaded directly by two

5-yd electric shovels. Forty- and 50-ton haulers are used to haul the coal to the crushing and screening plant. Most tonnage is shipped by rail, although some minor truck tonnage is sold locally and slack coal is shipped to the Estevan Plant of Saskatchewan Power Corporation.

As at the Manitoba & Saskatchewan Coal Company, switching of the railcars is done by locomotives owned and operated by the mining company.

Utility Coals Ltd.

This company has been and is supplying the coal required by the two generating plants of Saskatchewan Power Corporation, the Boundary Dam Station, and the Estevan Generating Station. Approximately 1.5 million tons per year are burned by these plants.

Drilling indicates the presence of two seams in the area although only one seam has been mined to date. The correlation of the two seams with the seams mined by Battle River Coal and Manitoba & Saskatchewan Coal Company has not been definitely established. The seam being mined at present has rapid elevation changes and detailed planning is required for stripping.

Several pits are maintained to assist in balancing the sodium content of the ash. A 750B shovel, 15W dragline, and 7800 dragline do the required stripping. Overburden depths and pit widths vary. A 170B, 9-yd shovel, and a 100B, 5-yd unit are used for coal loading. When the coal is deeply frozen, a dozer rips the coal to assist the loading shovels. Forty-five-ton and recently acquired 65-ton bottom dump trucks haul coal to the Boundary Dam Station. Coal delivery to the Estevan Plant of Saskatchewan Power Corporation is contracted.

Table 2 summarizes (according to working function) the type and size of equipment used at the various mines.

TABLE 2. - Major equipment utilized in lignite mining[1]

Operation	Company		
	M & S	Battle River	Utility Coal
Stripping.....	7400 dragline..... 7200 dragline.....	500W dragline...	7800 dragline. 750B shovel. 15W dragline. 5W dragline.
Loading.....	120B shovel--8 cu yd 54B shovel--4 cu yd.	120B shovel--5 cu yd (2).	170B shovel--9 cu yd. 100B shovel--5 cu yd.
Hauling.....	50-ton truck (3)....	50-ton truck (5) 40-ton truck (3)	65-ton truck (3). 45-ton truck (6). 17-ton truck (contract haul) (9).

[1]Numbers in parentheses indicate number of units.

Char and Briquetting Plant

(A Division of Manitoba & Saskatchewan Coal Company)

The concept of a briquetting plant in this area started with the Lignite Utilization Board of Canada, which was established jointly by the Federal Government of Canada and the Provinces of Manitoba and Saskatchewan in 1918. A Lurgi-type carbonizer was built shortly thereafter 1/2 mile from the present preparation plant of Manitoba & Saskatchewan Coal Company. In 1927 the plant was operated by Western Dominion Coal Company; it was sold in 1936 to Dominion Briquettes and Chemicals Limited, and then sold to a division of Husky Oil Canada Limited. In late 1968, the plant was purchased by the Manitoba & Saskatchewan Coal Company.

Approximately 100,000 tons per year of lignite are used to produce between 40,000 to 45,000 tons of char with an analysis of 70 to 80 percent fixed carbon, 10 to 16 percent ash, and 6 to 12 percent volatile matter. Of the char produced, about 15,000 tons are used to make a domestic fuel briquet for heating purposes with a heat content of approximately 12,000 Btu. The remainder is shipped as char to various industrial users. At present most of the char is used in the production of barbecue briquets.

A line diagram (fig. 7) gives the general schematic arrangement of the plant.

Marketing

Originally the principal lignite market was for heating both domestically and industrially with little lignite being used in the generation of power. However, it is in the area of power generation and industrial uses, other than heating, that the future of lignite will exist.

Saskatchewan Power Corporation operates two plants in the area, the Estevan Generating Station and Boundary Dam Power Station, with coal supplied by Utility Coals Ltd. Small amounts of coal are supplied by the other two producers to the Estevan Generating Station.

The Estevan Station has a total 70-mw installed capacity, consisting of four units, 5, 10, 20, and 30 mw. Energy requirements from this plant are projected to require between 250,000 to 475,000 tons of lignite annually, although somewhat higher tonnages can be utilized depending on overall Provincial power requirements.

The Boundary Dam Station is in the process of expanding. At present, two 66-mw generators are operating and another two 150-mw units will be completed in the near future. Additional units can be added if required and if economics warrant. The Station, with the total capacity of 432 mw, is projected to use 2.2 million tons of lignite annually.

Two other producers, Manitoba & Saskatchewan Coal Company and Battle River Coal Company, supply lignite to two generating plants of Manitoba Hydro at Brandon and Selkirk. The station at Brandon at present has a 120-mw capacity with an additional 100-mw under construction. The plant at Selkirk has 156-mw installed capacity.

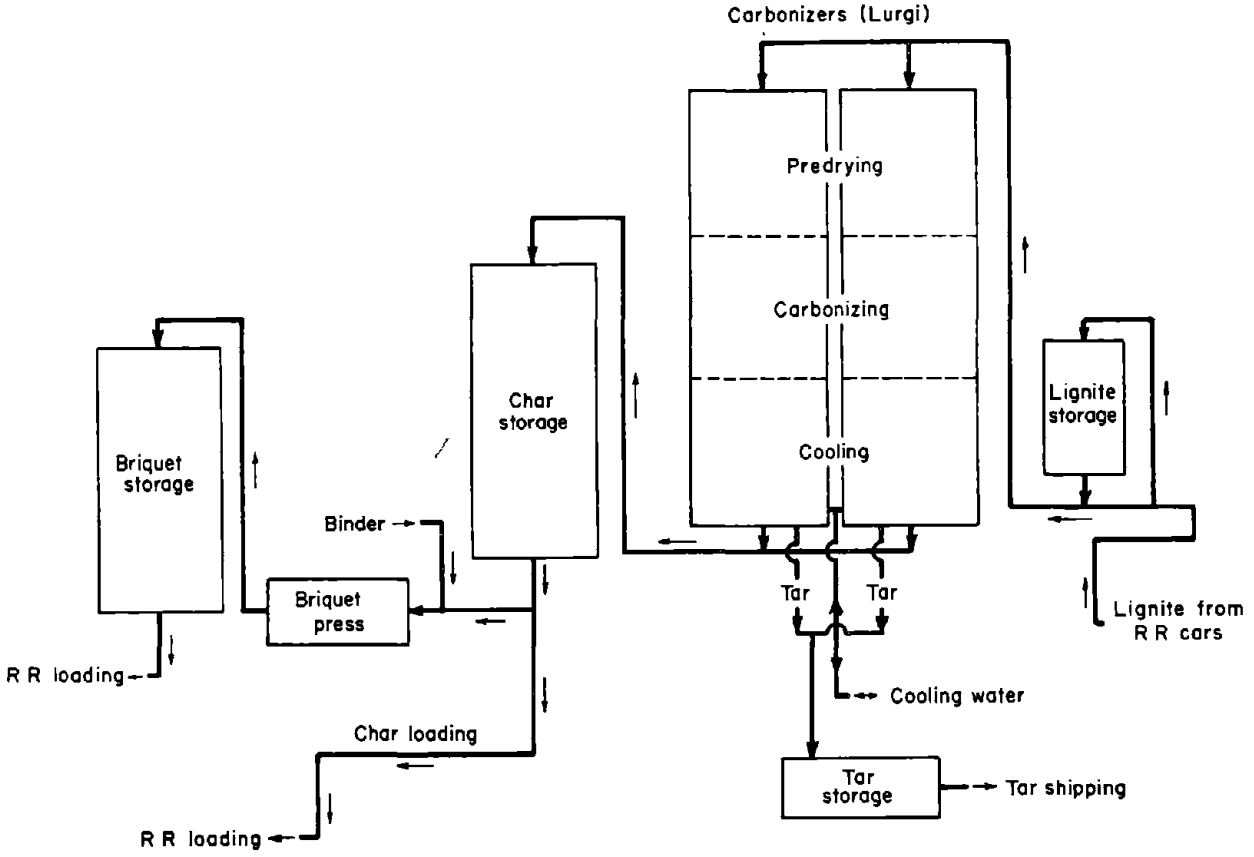

FIGURE 7. - Flow Diagram for Char Plant, Bienfait, Saskatchewan, Canada.

The growth requirements of Saskatchewan and Manitoba have made it desirable and economical to tie the two provinces together with an interconnection. This will provide better utilization of the existing and projected plants, whether hydro or thermal. The projected expansions and expected greater utilization of the thermal plants will provide for increased tonnages of lignite.

The domestic market for sized lignite is one that is steadily decreasing as consumers switch to other fuels or other methods for heating. The existing market for some tonnage in this broad area necessitates providing a well-prepared, sized product.

Industrial users, outside of power companies, purchase lignite for various applications. A good example of this application is the paper companies. Although, in general, this market has decreased, a substantial tonnage remains and will probably continue for some time.

As in the United States, research is continuing for the application of lignite in ore reduction, fertilizers, and hydrogenation. It is evident that increasing amounts of lignite will be used in power generation. The future markets for char or carbon derivatives will require additional investigation, and these are presently being carried on. Because the reserves of the Estevan field are sizable, the lignite from the area will continue to serve the Canadian and, possibly, the United States markets.

EFFECTS OF SURFACE MINING ON ENVIRONMENT

By Thomas A. Gwynn[1]

Introduction

There are new ideas in reclamation but mostly there is just increased awareness and better performance by the industry. Most of us in the lignite industry like to think of ourselves as fairly good citizens and dislike the label of a "despoiler of America's pristine beauty." Yet we are torn between that which is desirable and that which is economically feasible.

Let us put our problem into perspective in approaching the subject of reclamation. The United States will approximately double its present consumption of minerals and mineral fuels in the next 15 to 25 years. During the past 30 years the United States has used more minerals and fuels than did the entire world in all previous history. Seven or eight times as much energy will be required during the next 32 years as the cumulative total used in all previous history.

Three Caltech professors wrote a best selling book "The Next 100 Years,"[2] but after 10 years the authors revised their forecasts and now report that the earth's population is growing more rapidly than expected and that the world is likely to run into a fuel crisis within 10 years. Certainly the demands on our mineral wealth have been so great and have been increasing at such a rapid pace that lower and lower grade ores are being sought every day. These demands require the handling of increased amounts of both ore and waste. This is resulting in the increased demand for great amounts of energy from oil, natural gas, coal, and hydroelectric power, not to mention atomic energy and solar energy. Shortages in some of these areas are already appearing with the discovery of natural gas and oil now falling behind the consumption. Consumption of oil in the United States will increase to 18 million barrels per day by 1980 according to Dr. Charles Jones,[3] President of Humble Oil. Present estimates by the industry are that 6 million barrels of this oil must come from synthetic sources including coal and oil shale.

These rather alarming statistics are presented only for the purpose of illustrating the scope of the problem we will be facing in the years ahead. We will be disturbing more areas of the earth's surface to recover the fuel we need. Thus, surface mining in our area of the Great Plains and northern Rockies must of necessity increase manyfold. We must therefore expect increasing pressure from citizens' groups, sportsmen's organizations, environmental study groups, newspapers, and, of course, our friends in State and Federal

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[1] Company geologist, Montana-Dakota Utilities Co.; Manager, Reclamation & Conservation, Knife River Coal Mining Co., Bismarck, N. Dak.

[2] Brown, Harrison Scott, James Bonner, and John Weir. The Next Hundred Years. Viking Press, New York, 1957, 193 pp.

[3] Perkins, Richard F. Coal Resources of Rocky Mountains and Their Future Utilization. Pres. at the Am. Assoc. Petrol. Geol. meeting, Albuquerque, N. Mex., February 1969, 14 pp.

Government. Nor is it wrong that these groups should be concerned about our mining operations.

It is not abstract, unrealistic, or idealistic to suggest that more and more man is stumbling over his own garbage in his daily activities. It may be more difficult to sell residents of Montana, North Dakota, or Canada this, but nevertheless it is a fact. Those of us who are fortunate enough to live in this part of the country become graphically aware of these wastes and environmental changes when we visit the heavily populated areas south, east, and west of here and feel the smog burning our eyes, see the sun dimmed by layers of smoke, smell the results of industry, or see the results of garbage and industrial wastes in our rivers and lakes.

When it comes to erosion and pollution of our rivers, more than 640 acres a year of topsoil from North Dakota alone goes down the Missouri River, and it has been stated that the greatest producer of sediment in the State of North Dakota is the highway department. Obviously some change is inevitable and none of us are foolish enough to suggest that the Great Plains should be preserved for great bands of roving buffalo. Nevertheless, within our ability to do so, we should control the change of our environment resulting from industry so that this world continues to be a decent place in which to live.

In days past, many in the coal mining industry have ignored the public and have ignored their responsibility to reclaim mined areas. Credit must, of course, be given to many progressive companies and many progressive States where substantial reclamation has been done and where the majority of the lands mined are again productive in one way or another. It was interesting to hear many of the old diehards in our industry speak at a meeting of the American Mining Congress in Denver last fall expressing a change in thinking regarding the necessity for laws requiring reclamation. The same individuals commented one after another that had the companies been farsighted enough to lend positive support in drafting reasonable legislation and had all these companies been positive in policing their "own backyards," much of the problem would not exist and some of the agitation for unreasonable legislation might have been avoided. These same gentlemen strongly encouraged all companies to support and take an active part in drafting reasonable laws in those States not yet so controlled.

At the same time, it is incumbent on us as an industry to actively and accurately tell our story to the public so that every citizen in the States where we operate realizes that we are doing more than just making money--we are also providing them with cheap electric power, with fuel for the many industries that give them the civilization they demand; we are contributing substantially in taxes to provide schools, hospitals, and other civic benefits; and we provide the base for a thousand and one other products and services used in everyday life.

Reclamation in North Dakota

Efforts at reclamation in North Dakota, Montana, and Wyoming have been sporadic during the past 10 years. Some companies have made a substantial

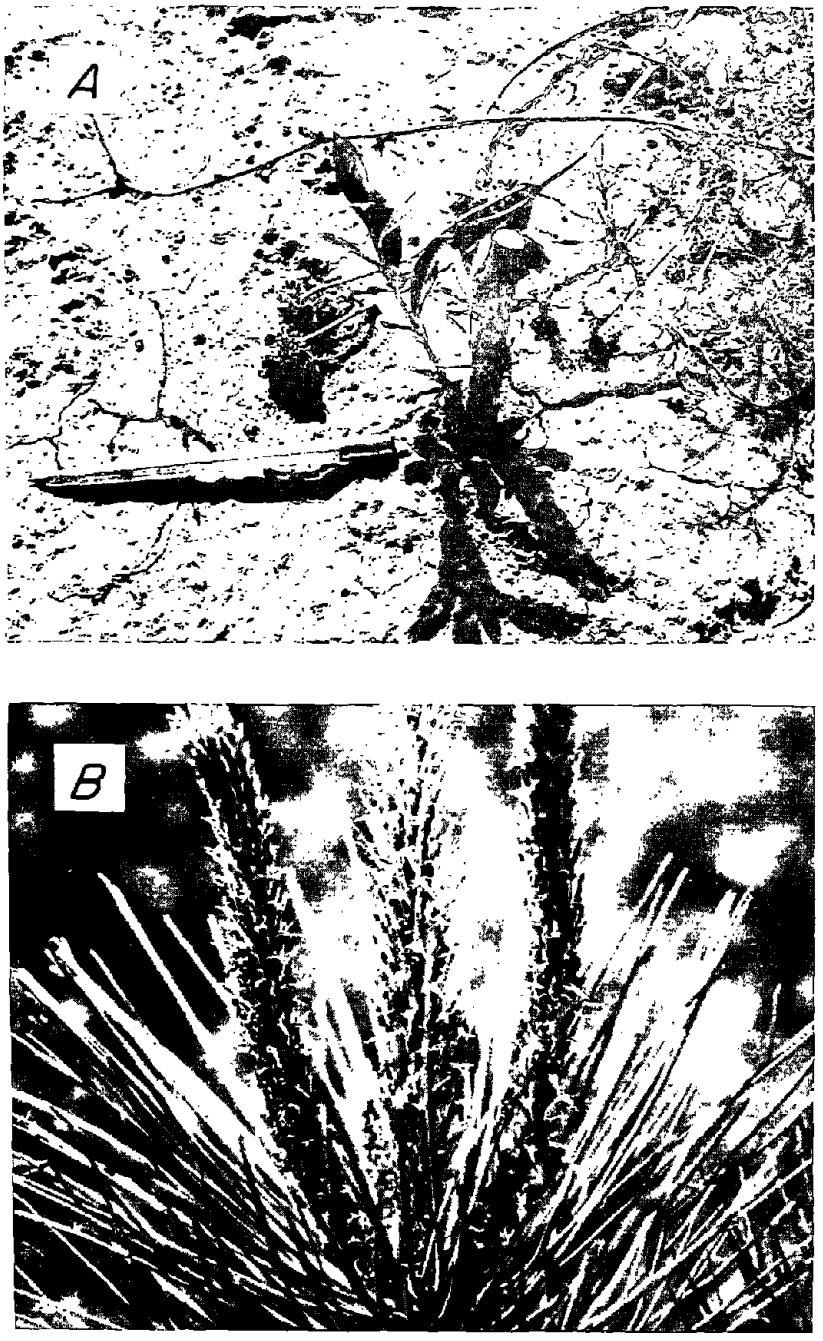

FIGURE 8. - *A*, Initial Planting of Seedlings; *B*, a Sample of Annual Growth of Ponderosa Pine.

effort in this respect and have undertaken research, some leveling, and some reclamation of other kinds. Other companies have done little or nothing leaving the spoils untouched. Although some people may argue that the creation of a few hills in North Dakota is beneficial in a State that is otherwise flat, we have found the aesthetic senses of some "flatlanders" offended by the sight of land that is not horizontal. In some instances, leveling is followed by seeding and planting seedlings or cuttings as illustrated in the top view of figure 8. Results are sometimes gratifying, as evidenced by the healthy annual growth leaders on the small Ponderosa Pine (fig. 8B).

As is to be expected, the various special interest groups have their own special preferences for the type of reclamation that should be undertaken to create an end result that meets with their concept of the best eventual use of these lands. The Game and Fish Department would prefer that the spoils be left without leveling in order to create rough terrain, providing better cover for game. The Soil Conservation Service and most farm-oriented groups, on the other hand, would like the lands level so that farm machinery can operate properly. We had better realize now that no matter what type of reclamation is undertaken, we will not as an industry please everyone. A sample of productive mined lands for agricultural purpose (top view) and for game habitat (bottom view) is given in figure 9.

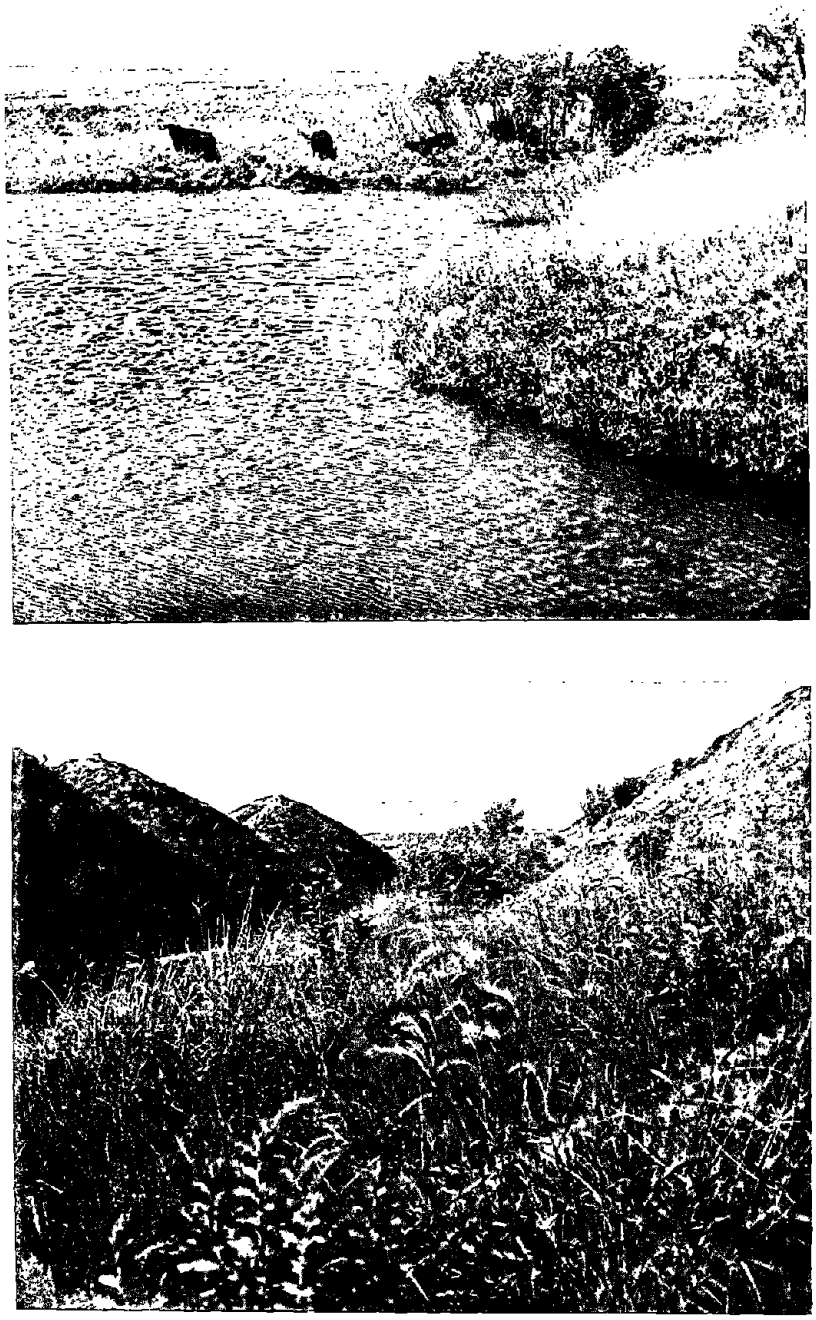

FIGURE 9. - Reclaimed Mine Lands Used for Agricultural Purposes (Top) and for Game Habitat (Bottom).

We feel that in North Dakota we have found some good answers. It has been demonstrated clearly that given time, the mined areas can be made to produce. When dealing with a low-cost fuel like lignite, it has proven unrealistic to think in terms of complete leveling of the "spoils" in most areas and, where the soil is heavy clay, this has been found to be detrimental. Partial leveling is, however, warranted in some cases, and in low population areas with low land values, these mined lands are being turned into grazing lands, game management areas, and recreation centers.

With our light rainfall and short growing season reclamation takes years to accomplish. The tremendous length of time that it takes to develop an inch of topsoil indicates the patience that is needed for any type of reclamation.

So it has become evident that meaningful laws at the State level are necessary. Since laws are obviously going to come, it is only sensible that the mining industry take a heavy part in drafting them so that insofar as possible they not be restrictive or punitive or otherwise unfavorable to such an extent that mining operations are curtailed or placed in a poor competitive position with other fuels.

North Dakota Reclamation Law

The 1967 session of the North Dakota State Legislature directed the Legislative Research Committee (LRC) to make a study of strip mining in North Dakota for the purpose of recommending a proposed law at the next session. After many meetings and field examinations by the LRC, during which time the industry assisted in this period of study, a proposed bill was settled upon and submitted to the 1969 Legislature for action. This bill, probably the third toughest reclamation bill in the United States, is generally patterned after the Illinois Act. Interestingly enough, this bill was prepared and proposed by the industry and was adopted with only slight modification by the LRC. This bill represented an effort on the part of the industry to cooperate in developing a State law that would be as tough as possible, but within the limits in which the industry could function.

Briefly, the North Dakota bill, which is now law, requires mining operators to present a plan of reclamation to the State. After surface mining operations are completed, the operator must carry out reclamation of mined lands to provide any one of a number of uses including forestry, grazing lands, croplands, wildlife habitats, recreational areas, or home or industrial sites. To accomplish this, any operator must obtain a permit before he engages in surface mining if the overburden exceeds 10 ft. This permit can be obtained from the Public Service Commission (State Mine Inspector) by posting a bond and paying a fee. This fee is as follows:

10 acres or less:	$25.00 plus $7.50 additional per acre between 2 and 10 acres.
10 to 50 acres:	$100.00 plus $3.50 additional per acre for each acre between 11 and 50 acres.
50 acres or more:	$275.00 plus $2.50 additional per acre for each acre over 50 acres.

The purpose of the fees are to provide funds to administer this law.

Regarding reclamation under this law, each operator must meet the following requirements:

1. All spoils within 660 ft of any public road, public building, or cemetery must be graded to a rolling topography traversable by farm machinery with slopes no greater than 25 percent grade unless the original grade in the area exceeds that.

2. Operator must, where possible, assist in impounding water for lakes or ponds by constructing the necessary dams.

3. When lands are to be planted with trees, adequate access roads must be constructed.

4. Lands to be used for pasture must have the peaks or ridges of the spoils "struck off" to a minimum width of 35 ft at the top.

5. Lands to be used for hay must have the peaks and ridges graded to a slope not exceeding 25 percent, and the lands must be traversable by farm machinery.

6. Adjacent property owners are protected by a regulation that controls how close mining can take place next to property lines.

To control reclamation, the operator must file annual reports and must also prepare reclamation plans for approval of the Commission. The Commission will base its approval upon the advice and technical assistance of the State Soil Conservation Commission, State Game and Fish Department, the State Forester, and other agencies. It is then the operator's responsibility to carry out the reclamation and, when this has been completed to the satisfaction of the Commission, the bonds are released.

Montana Reclamation Law

In Montana a reclamation law was passed in 1967 providing for a voluntary agreement between the State and individual operators. This agreement provides for developing the mined lands to their highest potential. The plan of reclamation must be approved by the Montana Bureau of Mines and Geology, with annual inspections to determine the compliance thereof by the operator. As an incentive to the operator, he may receive a refund for the cost of reclamation up to a maximum of one-half the annual license tax presently being paid to the State of Montana. Knife River Coal Mining Company operates a strip mine at Savage, and during 1967 and 1968 the normal reclamation conducted in those years did not reach one-half of the annual license tax.

Although the Montana law, which is based on the Colorado law, is working in the case of Knife River Coal Mining Company, it nevertheless must be recognized that this is a "permissive" law and has its drawbacks. The most obvious weakness is that if Federal legislation does come, and sooner or later it will, it is highly questionable that Montana's law will meet the required minimum standards. Hence, the biggest threat to Montana mining will be the danger of Federal intervention. During the 1969 session of the legislature another reclamation law was passed applicable only to those coal mining companies who have not entered into a voluntary agreement with the State. The new law is a watered down version of the Illinois law.

Wyoming Reclamation Law

Reclamation has been attempted with varying degrees of success in Wyoming. Operating under extremely severe weather handicaps, some mining companies have met with limited success in establishing vegetation where, frankly, God never intended it to be. A bill passed by the Wyoming Legislature this year provides for mined land reclamation and requires specifically that operators of open-cut mines grade the spoils to reduce peaks and ridges to a rolling topography. Other requirements include construction of dams where lakes could be formed, adequate covering of any materials that could generate acid, encouragement of revegetation of lands, and filing of leases, maps, and reports by the operators to show lands reclaimed. Actually, the requirement to grade all mined lands to reduce all peaks and ridges to a rolling topography could

constitute, in a sense, a more rigid requirement than that in the North Dakota bill. And, with due respect, there seems to be few good arguments for doing any leveling of terrain unless a specific use is in mind which requires such work to be done. If climatic and soil conditions destine an area to be a "goat pasture" forevermore, there seems to be little validity in the argument that the "goat pasture" need be leveled and certainly the ability to beautify the "goat pasture" does not lie within our present ability in some cases.

Future of Reclamation

Reclamation must be a part of our every day mining operation and must be an anticipated expense. Reclamation must be the result of marrying the best technical assistance we can get to the hard economic facts of the coal mining business, and must be carried on with sensitivity to the needs of the area and to the feelings of the residents. Since increased Federal interest in spoils reclamation is a certainty, we must ask companies to participate aggressively in establishing just and realistic reclamation laws. We must overcome the ostrich attitude our industry has had in the past because the conservation movement and increased public awareness of our environment are here to stay. In general, wholesome attitudes toward reclamation seem to be the attitude of most companies operating in Montana, Wyoming, and North Dakota, as well as in numerous other States.

I would like to quote from an article by past Secretary Udall, a man who has generated considerable controversy in past years but nevertheless a man whose aims concerning the beauty and quality of our country are noble.[4]

> The conservation goal of America's third century as a nation must be the development and protection of a quality environment which serves both the demands of nature for ecological balance and the demands of man for social and psychological balance.
>
> The landscapes and cityscapes that comprise the face of our continent present a partial statement about the state of our civilization, in much the same manner as the cut of a man's clothes tells something of the man himself. As the republic nears its 200th birthday, the cut of the century side bespeaks ambivalence.
>
> The need for a new national attitude toward our environment has grown until today it is an absolute necessity for human survival. Technology has stretched and magnified our natural resource potential in many areas... But it cannot provide us with one square inch of additional planetary surface, nor do more than gloss over the mounting environment insults to humanity.
>
> It becomes increasingly apparent that runaway population, noise and psychological pressure of too-close living will eventually run us out of space and nervous energy even if food and minerals and fuels were never to flag.
>
> This is the problem and the challenge our industry and our civilization face.

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[4] The United States Department of the Interior. It is Your World. The Grass Roots Conservation Story. Conservation Year Book No. 5, Washington, D.C., 1969, p. 17.

THE IMPORTANCE OF ASH IN THE COMBUSTION OF COAL

By William T. Reid[1]

Introduction

Whether coal is burned in fixed or fluidized beds, in pulverized form, or in gasifiers, its ash constitutes a major problem. All coals contain inorganic matter. Some, notably the coals from Alabama and Kentucky, contain only a few percent ash, but the ash content of most coals in the United States averages about 10 percent. In other parts of the world, ash may make up a much greater fraction of coal; 30 to 40 percent is not uncommon.

It is evident that this noncombustible material must influence the way in which coal is burned and its heat is utilized. In fact, although coal rank and physical properties play an important part in selecting fuels, it is the properties of the ash in the coal that mainly affect the way in which the coal is burned.

Coal ash has only a minor direct action on combustibility. Some coal-ash constituents, the alkalies for example, are catalysts for combustion reactions, but such effects are insignificant on a large scale. The really significant factors related to coal ash are its fusibility, which establishes limits for temperature during and after combustion, and its contribution of chemical reactants that lead to external corrosion of heat-receiving surfaces exposed to the products of combustion.

Occurrence of Ash in Coal

Before discussing fusibility, it is interesting to review how ash occurs in coal. There are two main sources of ash--inherent and extraneous. Inherent ash is the inorganic chemical compounds present in the original plants that became coal. Extraneous ash is the mineral matter deposited physically and mixed with the plant substance while the organic matter was accumulating, or captured later by the coalbed from mineral-laden water.

Inherent ash seldom exceeds 2 percent of the weight of the coal. It is composed of iron, calcium, magnesium, phosphorus, potassium, and sulfur combined organically with the plant tissues. Other constituents include silicon, aluminum, manganese, and sodium, which may not have been essential to plant growth but were captured nonetheless by the growing organism.

Extraneous ash makes up the remainder of the inorganic matter in coal. Silt, partings of shale, sediment, and a great variety of minerals that find their way into coalbeds make up this major contribution to noncombustible material. Petrographic means have been used most widely to identify the four main groups of these minerals. Table 3 lists them briefly. Probably 95 percent of the mineral matter in most coals is made up of kaolinite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$),

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pyrite (FeS_2), and calcite ($CaCO_3$). Variations of kaolinite are common, including such minerals as illite, muscovite, hydromuscovite, and montmorillinite, but such changes have little effect on ash characteristics. Similarly, marcasite may be present in place of pyrites, and dolomite may replace calcite, but again, without major effect because of such mineralogical differences.

TABLE 3. - Minerals in coal

Mineral group	Chemical composition
Shale.....	$(K,Na,H_3O_3,Ca)_2(Al,Mg,Fe,Ti)_4(Al,Si)_8O_{20}(OH,F)_4$
Clay.....	$Al_2O_3 \cdot 2SiO_2 \cdot xH_2O$
Sulfur.....	FeS; $FeSO_4$; Na_2SO_4
Carbonate....	$CaCO_3$; $CaCO_3 \cdot MgCO_3$

A great many other minerals are present in coal, but usually in small quantities. An exception is quartz, which can exist in seams or partings in coalbeds. In Australian brown coals, for example, sand can occur in streaks of considerable size. This extraneous silica can react with the high-CaO and alkali-rich inherent ash in the brown coal to cause serious slagging problems.

Mineral matter, when heated as by combustion, undergoes physical changes and chemical transformations. Eventually, they end up as oxides that interreact to form glassy slags at a high enough temperature. The influence of the original mineralogical forms on the rate of these reactions is not well understood. For example, although fuels technologists realize that the original mineralogical makeup of coal ash must affect the nature of fly ash, the complicating factors of time, temperature, and turbulence in a pulverized-coal-burning combustion system are so complex that no worthwhile relationship has ever been developed.

Figure 10 illustrates the types of reactions that occur when the mineral matter is heated in coal.[2] Of all the reactions, those occurring above 1,800° F are most important in slagging and clinkering reactions and in external corrosion.

Fusibility of Coal Ash

Cone-Fusion Test

Clinkering in fuel beds posed problems as soon as firemen tried to increase the output of their boilers by burning more coal on a given grate.

[2]Reid, William T. External Corrosion and Deposits. Elsevier Publishing Co., New York (in press).

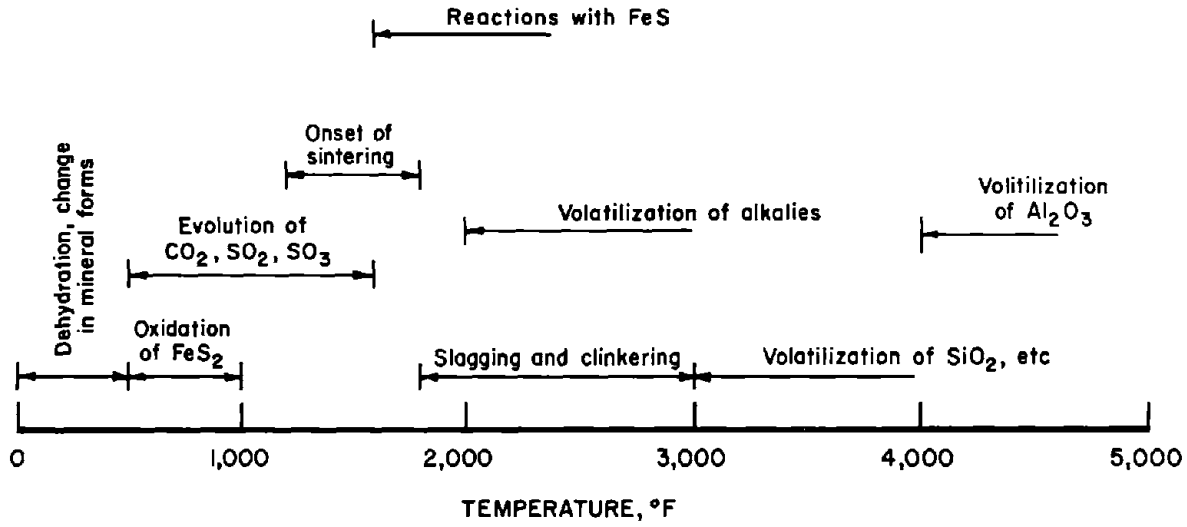

FIGURE 10. - Effect of Heating on Minerals in Coal.

By the early 1900's, clinkering had become a serious problem. Accordingly, in 1918, Fieldner and his associates in the Bureau of Mines developed the cone-fusion test[3] that has been the standard procedure in this country for measuring the fusibility of coal ash since that year.[4] The only significant change in that prodedure made over the years has been the inclusion recently of the temperature where the ash cones reach four states of melting rather than three.

The cone-fusion test has been used widely. Often it is the only criterion for ash fusion listed in coal-buying specifications. Nevertheless, it is an unfortunate fact that its utility is general rather than specific. For example, a difference of 100° F in any of the states of fusion is not particularly meaningful. Hence, only a broad interpretation can be placed on the spread between initial deformation temperature, softening temperature, hemispherical temperature, and fluid temperature. All too often, comparison of such data between different ashes is confusing rather than helpful.

Broadly, cone-fusion measurements are most useful in placing coal ashes into four broad categories based on softening temperature:

	Range, ° F
Low fusion.....	1,800-2,100
Moderate fusion	2,100-2,400
High fusion....	2,400-2,700
Refractory.....	2,700-3,000

[3]Fieldner, A. C., A. E. Hall, and A. L. Feild. The Fusibility of Coal Ash and the Determination of the Softening Temperature. BuMines Bull. 129, 1918, 146 pp.

[4]American Society for Testing and Materials. Tentative Method of Test for Fusibility of Coal Ash. D-1857 in 1967 Book of ASTM Standards, Part 19, Gaseous Fuels; Coal and Coke. Philadelphia, Pa., 1967, pp. 356-361.

Fuels technologists may not agree on the limits for each of these classes, but their use of cone-fusion data generally falls into some such classification.

Viscosity of Coal-Ash Slags

Beginning early in the 1930's, it was found that cone-fusion measurements were not adequate to explain slagging in pulverized-coal-fired boiler furnaces nor the flow characteristics of coal-ash slags in wet-bottom furnaces. Accordingly, studies were started by the Bureau of Mines in 1938 to measure the true rheological properties of molten coal-ash slags.[5]

Figure 11 shows the viscometer used for these measurements. Based on the Margules principle, the viscometer consists of two concentric cylinders: The outer stationary cylinder is a 1.5-in-diameter platinum crucible; the inner rotating cylinder is a 0.5-in-diameter platinum-rhodium bob driven externally by a geared-down motor at controllable speeds. A calibrated music-wire suspension between the motor and the bob, with an electrical contact arrangement to measure twist in the suspension, measures viscosity as a function of the torque necessary to rotate the bob at any given speed. Such an instrument can measure true Newtonian viscosity; but further, it can measure the apparent viscosity of pseudoplastic slags in which an internal structure forms as the slag is cooled from the Newtonian region.

Where only Newtonian flow is to be measured, the drive motor is disconnected, weights are added to the bob to increase its inertia, and the bob is made to oscillate in simple harmonic motion. The log decrement of this oscillation is then a measure of Newtonian viscosity. Such a viscometer is strongly affected by the formation of internal structure in the slag, and hence it is a sensitive indicator of any deviations from true viscous flow.

Figure 12 is a typical viscosity-temperature curve for a coal-ash slag behaving as a Newtonian fluid even at temperatures down to 2,025° F, as measured in the log-decrement viscometer. The observed viscosity at any temperature is the same whether the slag is being cooled or heated, and the slag behaves literally like a glass.

Figure 13 is for another slag in which a solid phase begins to separate at 2,540° F, converting the slag from a Newtonian fluid to a pseudoplastic solid, which no longer behaves as a true fluid. When reheated to 2,560° F, the solid redissolves in the melt, and the slag once more becomes Newtonian. It is interesting to note that the only essential difference in the composition of these slags is the much higher level of Fe_2O_3 in the non-Newtonian slag.

Figure 14 illustrates the case of a slag in which the development of an internal structure is measured with the driven rotating-bob viscometer. At

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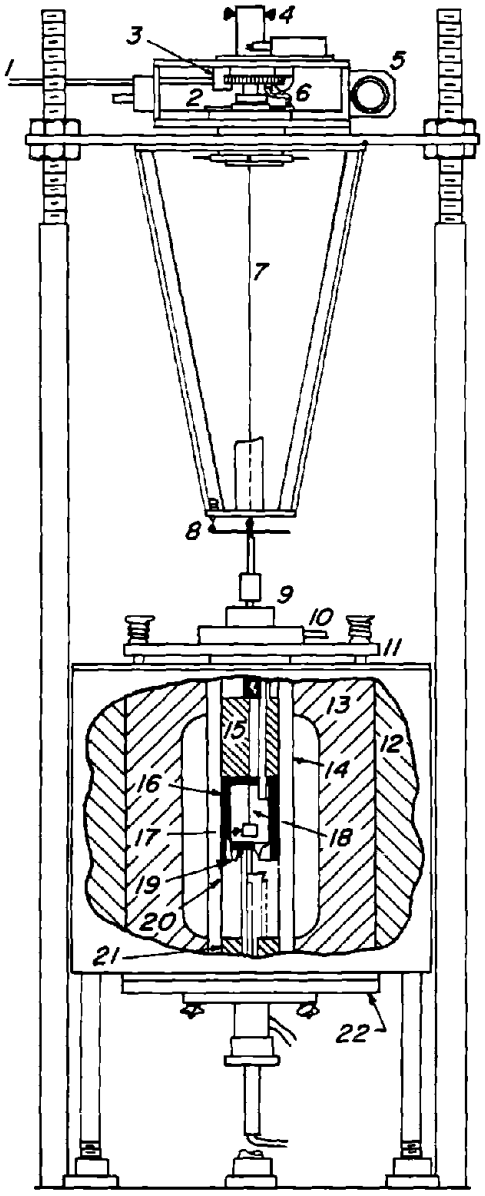
[5]Nicholls, P., and W. T. Reid. Viscosity of Coal-Ash Slags. Trans. ASME, v. 62, 1940, pp. 141-153.
Reid, W. T., and P. Cohen. The Flow Characteristics of Coal-Ash Slags in the Solidification Range. Trans. ASME, v. 66, 1944, pp. 83-97.



1 Shaft to driving motor
2 Dial
3 Worm gear drive
4 Suspension clamps
5 Signal lamp
6 Upper contacts
7 Calibrated suspension
8 Lower contacts
9 Removable cover, water cooled
10 Gas inlet
11 Upper terminal block, water cooled
12 Loose Sil-O-cel
13 Porous kaolin
14 Globar tube
15 Upper kaolin plug, removable
16 Crucible
17 Rotating bob
18 Slag
19 Slag thermocouple
20 Controller thermocouple
21 Lower kaolin plug
22 Lower terminal block, water cooled

FIGURE 11. - Coal-Ash Slag Viscometer.

2,420° F, there is a direct proportionality between torque applied and rotational speed, so that the flow is Newtonian. At 2,399° F, this proportionality is no longer maintained, and by extrapolating, a measurable torque can be applied with no resulting rotation of the bob. The apparent viscosity here, based on the slope of the line, is 314 poises; the internal yield stress, f, is 60.4 dynes per sq cm. As the slag is cooled still further, both the torque intercept and the slope increases so that, at 2,303° F, the apparent viscosity is 21,300 poises and the yield stress is 7,270 dynes per sq cm. If this slag is left undisturbed at these lower temperatures, the internal yield stress increases because the slag is thixotropic; work done on the system, as by rotating the bob, returns the system to its equilibrium state. Hence, time is

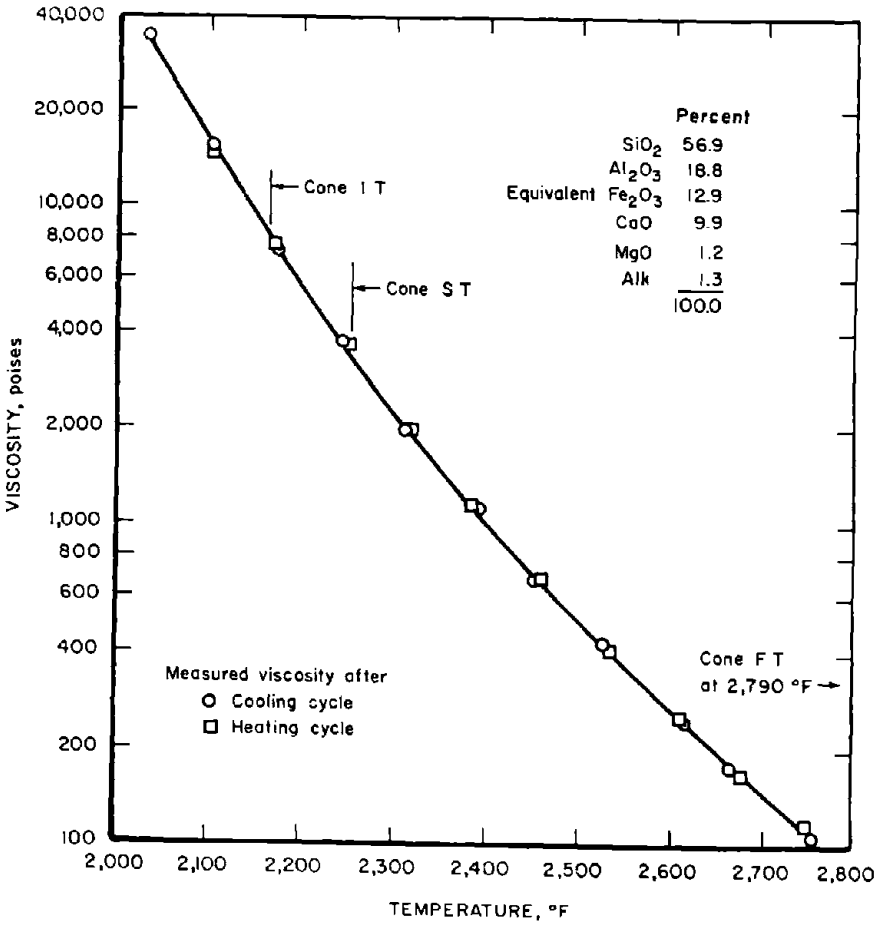


FIGURE 12. - Viscosity of a Typical Glassy Slag.

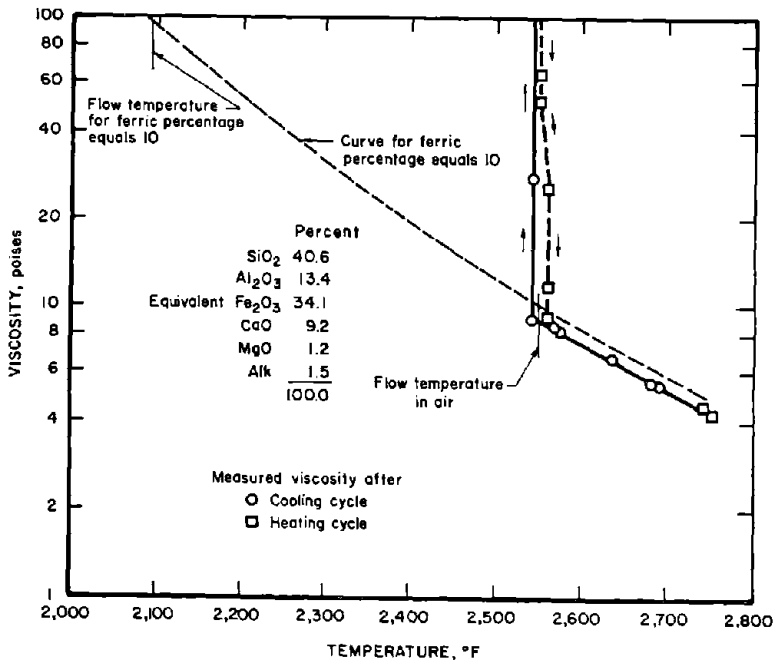


FIGURE 13. - Typical Pseudoplastic Slag.

required after changing the rotational speed for a definite ratio to be reached between applied stress and rate of shear.

It is evident, then, that some coal-ash slags undergo major changes in flow properties when they are cooled and that these changes depend upon time and temperature, as well as upon chemical composition. Because this change is so significant, the point where it occurs is termed the "temperature of critical viscosity" (T_{cv}). At higher temperatures a slag behaves like a glass, at lower temperatures, like a pseudoplastic solid.

Relation Between Viscosity and Composition

At first glance, the effect of changes in composition on viscosity of a system with seven variables--SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, alkalies, and temperature--would seem to be formidable. Indeed, it is in locating T_{cv} that the only good relationship has been developed. In the Newtonian range, viscosity, temperature, and composition are easily related.

Figure 15 shows how the viscosity of slags in air at 2,600° F depends on the "silica percentage" of the slag, or the percentage of SiO_2 in the sum of SiO_2, Fe_2O_3, CaO, and MgO found by chemical analysis. Despite wide variations in the SiO_2/Al_2O_3 ratio, in Fe_2O_3, and

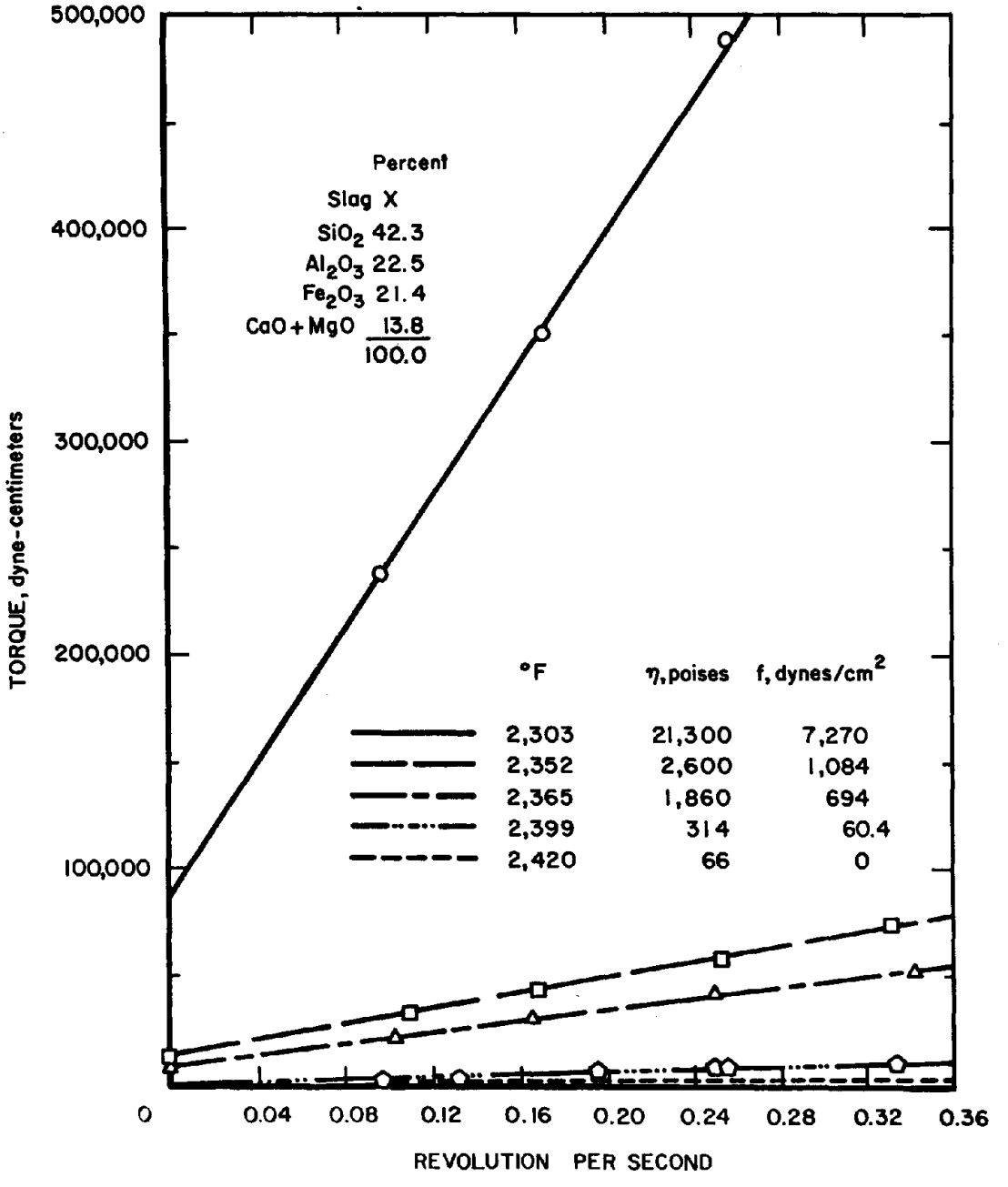


FIGURE 14. - Development of Internal Yield Stress.

in CaO and MgO, this simple empirical semilog plot agrees surprisingly well with the experimental data. A simplified approximate equation for the curve of figure 15 is:

$$\text{Log } (n - 1) = 0.066 \text{ (silica percentage)} - 2.4,$$

where n is the viscosity at 2,600° F.

A more accurate correlation has been developed by Hoy and his coworkers at BCURA,[6] who showed that

$$\log \eta = 4.468 \left(\frac{S}{100}\right)^2 + 1.265 \left(\frac{10^4}{T}\right) - 7.44,$$

where η is viscosity in poises, S is silica percentage, and T is in degrees Kelvin, based on a large number of measurements of viscosity in their laboratories.

These same workers, using data from 63 coal-ash slags with a wide range of composition, were able to relate T_{cv} to composition, as by

$$\text{Temperature of critical viscosity, } T_{cv} = 2{,}990 - 1{,}470 \left(\frac{SiO_2}{Al_2O_3}\right) + 360 \left(\frac{SiO_2}{Al_2O_3}\right)^2 - 14.7\ (Fe_2O_3 + CaO + MgO) + 0.15\ (Fe_2O_3 + CaO + MgO)^2,$$

where T_{cv} is in degrees Celsius, and the chemical constituents are expressed on the basis that $SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + MgO = 100$.

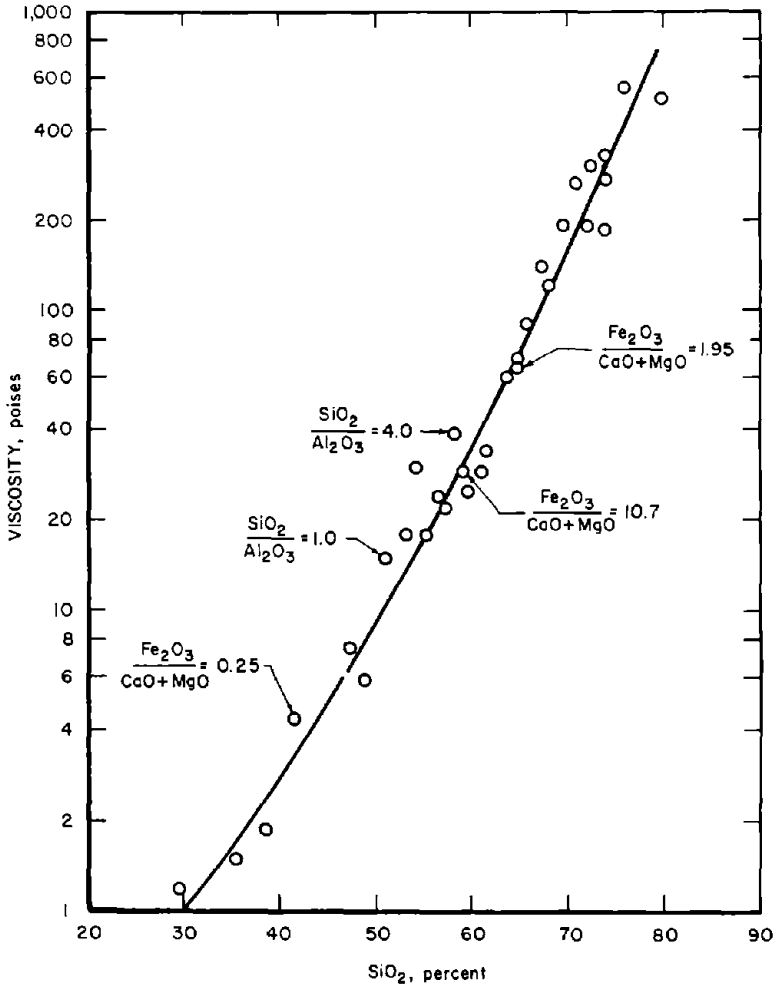


FIGURE 15. - Silica Percentage Versus Viscosity.

The special case of lignite ash has been considered by Duzy,[7] who defines "lignite-type ash" as ash having more CaO + MgO than Fe_2O_3. Using the silica ratio, the base-to-acid ratio $(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)/(SiO_2 + Al_2O_3 + TiO_2)$, and the dolomite ratio $(CaO + MgO)/(CaO + MgO + Fe_2O_3 + Na_2O + K_2O)$, he

[6] Hoy, H. R., A. G. Roberts, and D. M. Wilkins. Behavior of Mineral Matter in Slagging Gasification Processes. Inst. Gas Eng., Comm. 672, London, November 1964, 24 pp.

[7] Duzy, A. F. Fusibility-Viscosity of Lignite-Type Ash. ASME Paper 65-WA/FU-7, pres. at ASME Annual Meeting, Nov. 7-11, 1965, 8 pp.

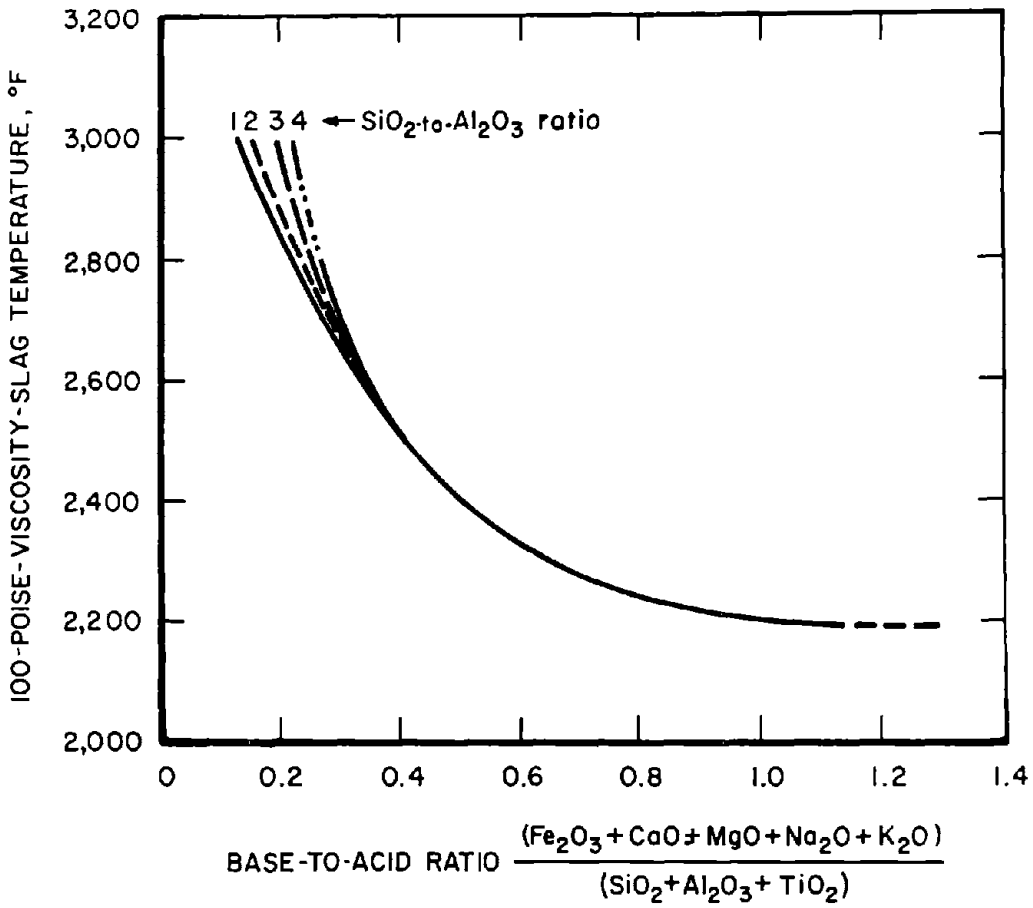


FIGURE 16. - Temperature for 100-Poise Viscosity at Different Base-to-Acid Ratio for a Ferric Percentage of 20.

shows that the silica ratio is not useful as a single predictive parameter, and that the other ratios are related generally to the ash-softening temperature but not specifically.

Sage and McIlroy[8] correlated the base-to-acid ratio effectively with viscosity. Figure 16 shows the effect of change in this ratio on the temperature where the measured viscosity is 100 poises with 20 percent of the iron oxides in the ferric state. It is important to note here that this curve is for apparent viscosity, since in many cases the slag contains some solids and does not act as a Newtonian fluid. Hence, the rate of shear will affect the flow characteristics of such slags, and these data must be used with caution.

Analyses have been made of the influence of viscosity and the temperature at which solids separate (T_{cv}) on the accumulation of slag on heat-receiving

[8] Sage, W. L., and J. B. McIlroy. Relationship of Coal-Ash Viscosity to Chemical Composition. Trans. ASME, J. Eng. Power, v. 82, Series A, No. 2, 1960, pp. 145-155.

surfaces, such as the wall tubes of pulverized-coal-fired boiler furnaces.[9] This is a highly complex problem, with about 19 parameters being involved. These theoretical analyses have never been applied in the field, mainly because of problems in identifying conditions closely enough within a large boiler furnace. Figure 17 shows the nature of the problem in a typical boiler furnace.[10]

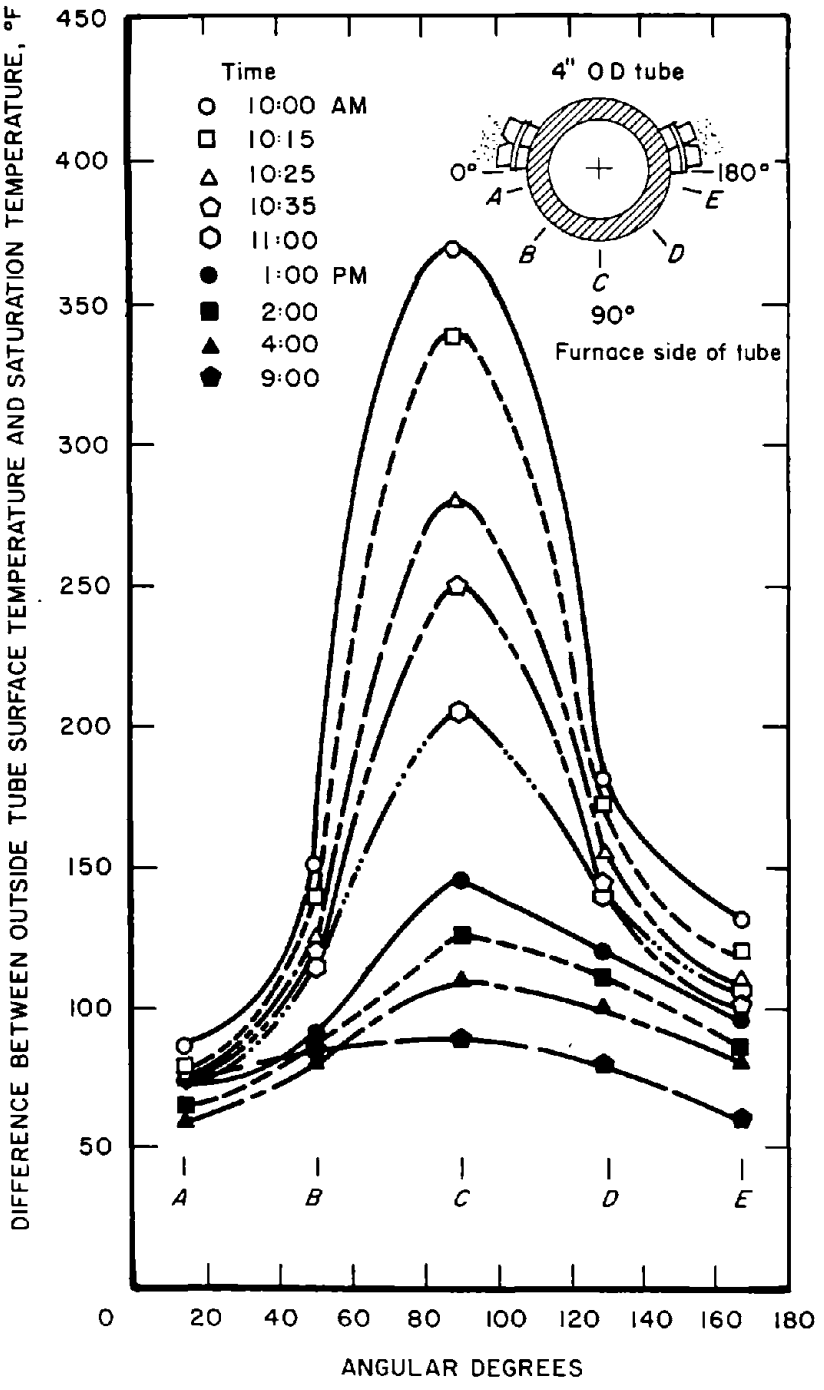


FIGURE 17. - Effect of Slagging on Heat Flux in a Large Boiler Furnace.

Ash Fouling of Superheaters and Reheaters

In recent years, with the growing trend to dry-bottom furnaces, accumulation of deposits on superheaters and reheaters has become more troublesome than wall slagging. Ash characteristics that influence this sintering are much more involved than those affecting flow, since surface conditions of the tiny particles of ash are involved as well as their chemical composition. Empirical means have had to be developed for measuring sintering characteristics of ash, since the basic actions taking place are essentially undefined.

[9] Reid, W. T., and P. Cohen. Factors Affecting the Thickness of Coal-Ash Slag on Furnace-Wall Tubes. Trans. ASME, v. 66, No. 8, 1944, pp. 685-690.

[10] Ely, F. G., and L. B. Schueler. Distribution of Heat Absorption and Factors Affecting Performance of Twin-Branch 2500-psi Boiler. Furn. Perf. Factors Supp. to Trans. ASME, v. 66, 1944, pp. 23-32.

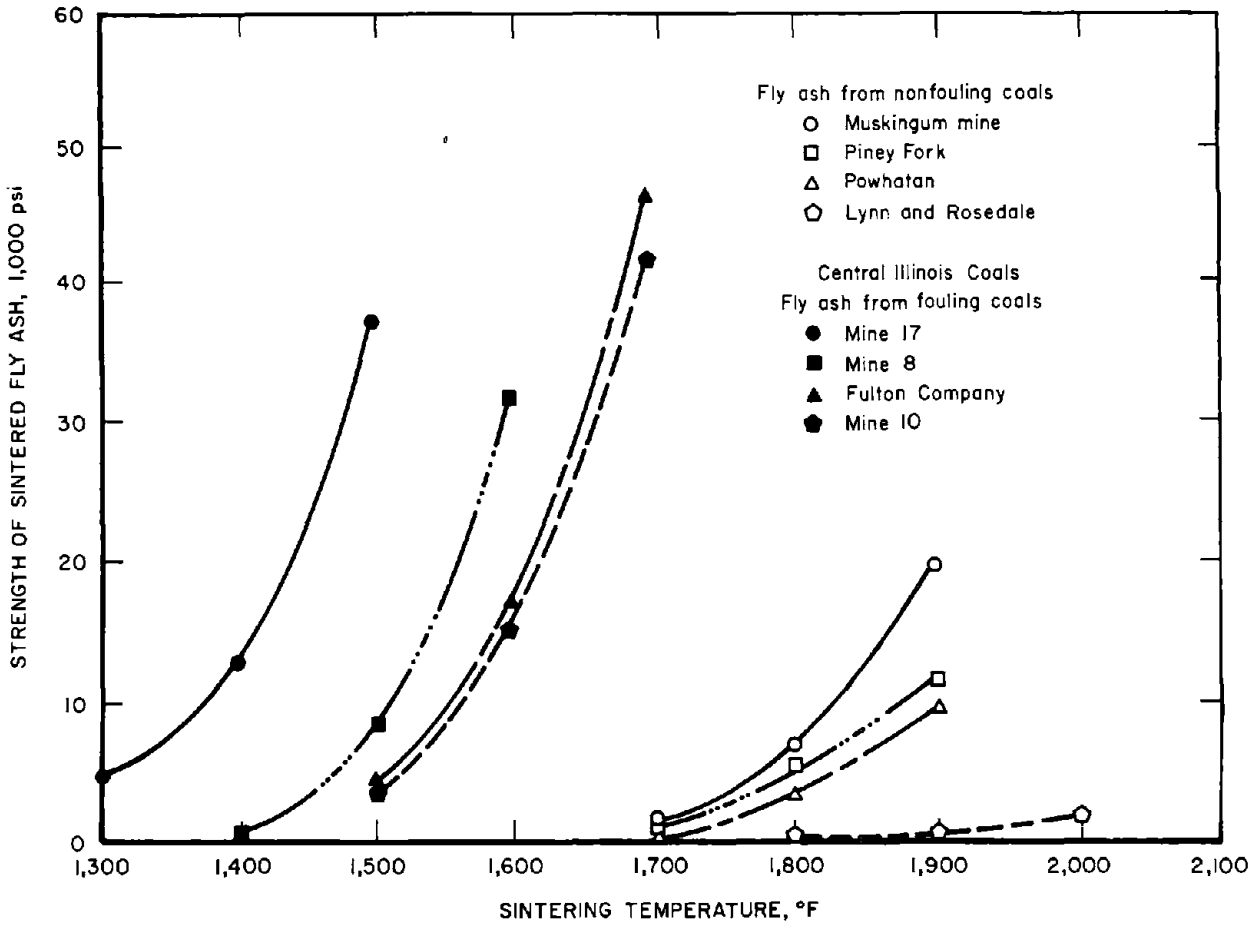


FIGURE 18. - Strength of Sintered Fly Ash From Fouling and Nonfouling Coals.

One of the most successful of these is that of Barnhart and Williams.[11] A sample of the coal to be investigated for fouling tendency is ashed in a laboratory combustor closely duplicating conditions in a full-scale boiler furnace. This ash is formed into pellets 0.75 in high and 0.67 in. in diameter at a pressure of 150 psi. In turn, these pellets are heated in air at temperatures ranging between 1,300° and 2,000° F for 15 hr, are cooled slowly, and crushed in a mechanical testing machine. The strength of the sintered pellets is taken as a measure of the fouling tendency of that coal ash. Figure 18 illustrates the differences observed with a variety of coals, both fouling and nonfouling.

Correlation of composition with this fouling test has just been provided by Attig and Duzy,[12] based on many years of experience with the sintering test. Figure 19 shows the sintering strength of ash as a function of the base-to-acid

[11]Barnhart, D. H., and P. C. Williams. The Sintering Test, an Index to Ash-Fouling Tendency. Trans. ASME, v. 78, 1956, pp. 1229-1236.

[12]Attig, R. C., and A. F. Duzy. Coal Ash Deposition Studies and Application to Boiler Design. Proc. Am. Power Conf., Illinois Inst. Technol., Chicago, Ill., v. 31, 1969, pp. 290-300.

ratio and the sodium oxide content of the ash, using soluble Na_2O for ash from low-temperature ashing procedures, and total Na_2O when the ash is by the conventional ASTM proximate analysis. The fouling tendency at the top of the figure is for ash prepared by normal ASTM procedures.

Garner,[13] working with Australian brown coals, has measured their fouling tendency in a laboratory combustor burning 500 pounds of test coal in a 10-hr period. Air-cooled tubes in the gas passage collect ash deposits, which are then weighed as a measure of the fouling tendency of that coal. By a complicated regression analysis, he has developed the relation

$$\text{Weight of deposit} = 0.030\ (SiO_2) + 0.092\ (Fe_2O_3) + 0.061\ (CaO) + 0.264\ (MgO) + 0.432\ (Na_2O) - 10.6.$$

Sodium here, as in Attig and Duzy's correlation, is the dominant factor in the accumulation of deposits. This relationship, although fitting Garner's data, should be used with care for coals differing widely in ash composition from Australian brown coals.

External Corrosion

Although "coal ash" has been blamed as the cause of serious metal wastage in pulverized-coal-fired superheaters and reheaters, the silicates that comprise the major part of the material being deposited on the tube surface take no direct part in the corrosion reaction. Essentially, the only elements present in the original coal that lead to external corrosion are sodium, potassium, and sulfur.

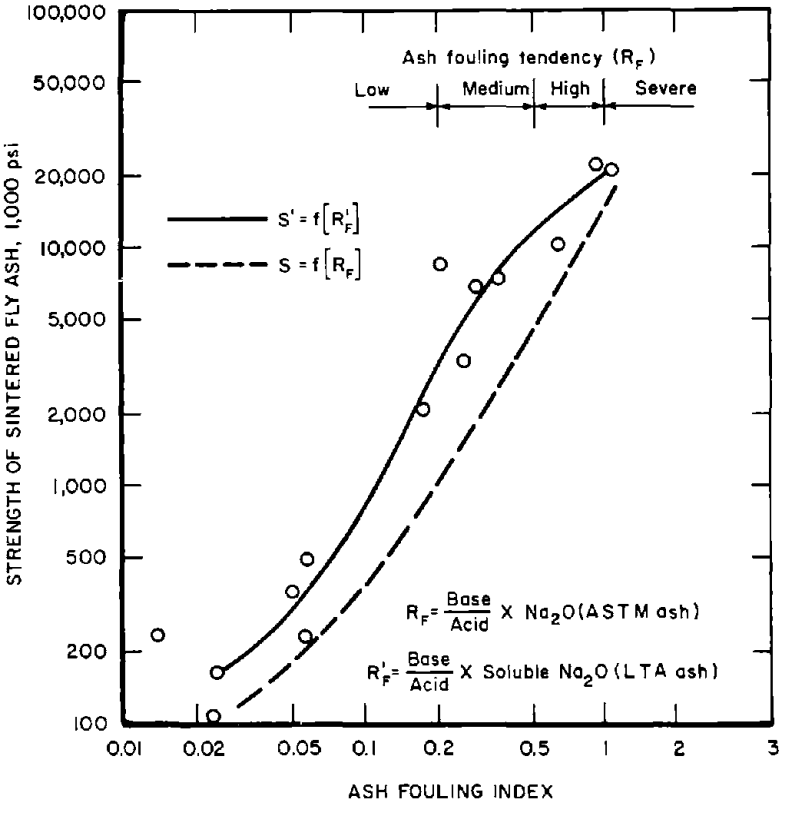


FIGURE 19. - Fouling Tendency of Coal Ashes.

As a result of work dating back to 1942, a fairly good understanding has been developed of the actions that take place. Differences of opinion still occur on details, but essentially the sequence of events is as follows:

[13] Garner, L. J. The Formation of Boiler Deposits From the Combustion of Victorian Brown Coals. J. Inst. Fuel, v. 40, No. 314, 1967, pp. 107-116.

1. Sodium and potassium are volatilized in part from ash constituents in the 3,000° F flame.

2. Pyrites are dissociated thermally and, with the organic sulfur in the coal, provide 2,000 to 3,000 ppm SO_2 in the flue gas.

3. About 1 percent of the sulfur in the coal appears in the flue gas as SO_3 by reaction of SO_2 with oxygen atoms present in the flame.

4. The volatilized sodium and potassium thus are converted at least in part to the sulfates, and, with the unconverted oxides, deposited on the relatively cool metal surfaces where the sulfation reactions continue, ending up with a thin layer of Na_2SO_4 and K_2SO_4 on the Fe_2O_3 outer layer of the oxide scale.

5. Ash particles are captured by this sulfate layer and eventually a moderately thick layer of ash builds up on the tube surface.

6. Sulfur dioxide present in the flue gas reaches the interface between Fe_2O_3 and the alkali sulfates, and in the presence of excess O_2, oxidizes to SO_3 on the catalytic Fe_2O_3 surface. Apparently this reaction reaches near-equilibrium levels of SO_3, and almost certainly it is responsible for a concentration as high as 1,000 ppm of SO_3.

7. At such high concentrations of SO_3, reactions occur with the Fe_2O_3 and the alkali sulfates to form $Na_3Fe(SO_4)_3$ or $K_3Fe(SO_4)_3$, which are molten at about 1,100° F in a high-SO_3 atmosphere.

8. These molten trisulfates can provide an electrolyte for further corrosion by galvanic action, but essentially they remove the adherent outer layer of Fe_2O_3 always present on tube scale, so that the tube oxidizes further to replace its normal scale at that temperature.

The major argument against this mechanism is that the trisulfates may be formed, not by reaction between SO_3 and alkali sulfates with the Fe_2O_3 on the tube surface, but with the Fe_2O_3 present in the ash deposited on the tube. The resulting trisulfates are then thought to migrate to the tube surface along the temperature gradient existing in the deposit. At the tube surface, the trisulfates would react with iron, causing wastage.

The reactions are as follows, with potassium behaving similarly:

$$3Na_2SO_4 + Fe_2O_3 + 3SO_3 \rightleftharpoons 2Na_3Fe(SO_4)_3 \quad (1)$$

$$10Fe + 2Na_3Fe(SO_4)_3 \rightleftharpoons 3Fe_3O_4 + 3FeS + 3Na_2SO_4 \quad (2)$$

Reaction 1 proceeds whether the source of the Fe_2O_3 is the tube scale or the ash deposit. Reaction 2, which can only occur if the trisulfates have been formed first in the ash deposit, will take place only if metallic iron is in contact with the trisulfate. It is difficult to see how this can be, since no iron is ever exposed at these temperatures, only an oxide scale; no

reaction has been identified between iron oxides and the trisulfates. Nevertheless, the fact that reaction 2 does occur at least occasionally is shown by the presence of small amounts of FeS at times in corrosion areas. This is possibly explainable by cracks or imperfections in the oxide scale exposing elemental Fe.

Whichever mechanism predominates, it is evident that coal ash, other than supplying the needed alkalies and sulfur, takes part in corrosion mainly by supplying the proper environment for the formation of SO_3 at a high enough level to form the trisulfates.

Conclusions

Inorganic matter in coal leads to many problems in the utilization of our most abundant fossil fuel. Chief among these problems are the difficulties caused by ash accumulating on heat-receiving surfaces where the low thermal conductivity of the deposits interferes with heat transfer. Plugging of gas passages by massive deposits of ash in superheaters and reheaters is another major cause for concern. Studies of ash properties, mainly of the rheology of slags at high temperatures and the sintering of deposits at moderate temperatures, are providing the knowledge by which the actions of ash can be predicted.

Explanations are now available on the mechanisms by which constituents in coal ash lead to external corrosion of superheaters and reheaters. Essentially, the alkalies and the sulfur from the inorganic matter in coal are mainly responsible.

180-MW J. E. CORETTE PLANT BURNS MONTANA SUBBITUMINOUS COAL

By R. J. Labrie[1] and H. E. Burbach[2]

Introduction

Montana Power Company serves nearly 170,000 electric power customers in a service area of about 90,000 sq mi. This is equivalent in area to all of the New England States plus half of the State of New York. The 1968 area peak load was 787,000 kw. This load was met by 520,000 kw of hydroelectric capacity, the 66,000-kw Frank Bird gas and oil-fired steam electric station, and new 180,000-mw J. E. Corette coal-fired plant, and various power contracts with neighboring utilities.

The J. E. Corette Plant is located on the Yellowstone River at the outskirts of Billings, Mont. Billings is a city of about 79,000 people in the south central part of the State. This location was selected for the new plant so that its operation could be combined with that of the existing Frank Bird station which was completed in 1951. Consequently, one crew now operates both plants. It also provides an additional source of power at the southeastern end of Montana Power's system where the load is growing at a rapid rate and where the load exceeded the generating capability. A further reason for selecting this location was its proximity to the company's coal mining properties.

The site of the plant is a 76-acre plot located along the Yellowstone River. The foundation was placed on shale which was overlayed with about 22 ft of mixed river gravel. Concrete was poured 3 ft into the shale to support the major structures within the plant.

Bechtel Corporation supplied the engineering and was prime contractor for the project. The cycle was selected and major equipment purchased in early 1964. Construction began in spring 1966, but was suspended during the 1966-67 winter months. Boiler erection began in spring 1967 and continued during the winter months since facilities for adequate weather protection existed by this time. Turbine roll was early in July 1968, and the plant was in commercial operation in September. This schedule was planned so that costs would be kept to a minimum and the unit would be on line by October 1, 1968.

The J. E. Corette unit has a maximum continuous net rating of 163,000 kw, but will produce 180,000 kw for 4 hr when operating at its peak rating. The plant is expected to operate at about 60 percent plant factor over its lifetime and was sized to develop as much peak as possible with a standard frame turbine. It represented about 24 percent of the system peak capability when it went on the line. This was about the largest single unit that the system could absorb economically due to system reserve considerations. Construction

[1]Asst. chief engineer--generation, Montana Power Co., Butte, Mont.
[2]Supervisor, proposition engineering department, Combustion Engineering, Inc., Windsor, Conn.

of the plant was delayed for several years by purchasing power from neighboring utilities so that it would operate at nearly full load when it came on line.

General Design Considerations

The plant cycle was selected for 17 cents per million Btu fuel and about a 60-percent load factor. On this basis, an 1,800-psig, 1,000°/1,000° F unit, with three low-pressure and two high-pressure heaters, was selected. Due to improvement in condenser design and the number of feedwater heaters, it was decided to use a deaerating-type condenser and to eliminate the deaerating feedwater heater. The existing Frank Bird Plant control room was extended to provide room for the new turbine-generator panel and accessory facilities so that a single operator could operate both turbine-generator boards.

Since the climate in the Billings area is quite dry, the plant was designed for semioutdoor operation. The existing Frank Bird unit, a pioneer in outdoor construction for a unit this far north, had proven that this was practical and economical.

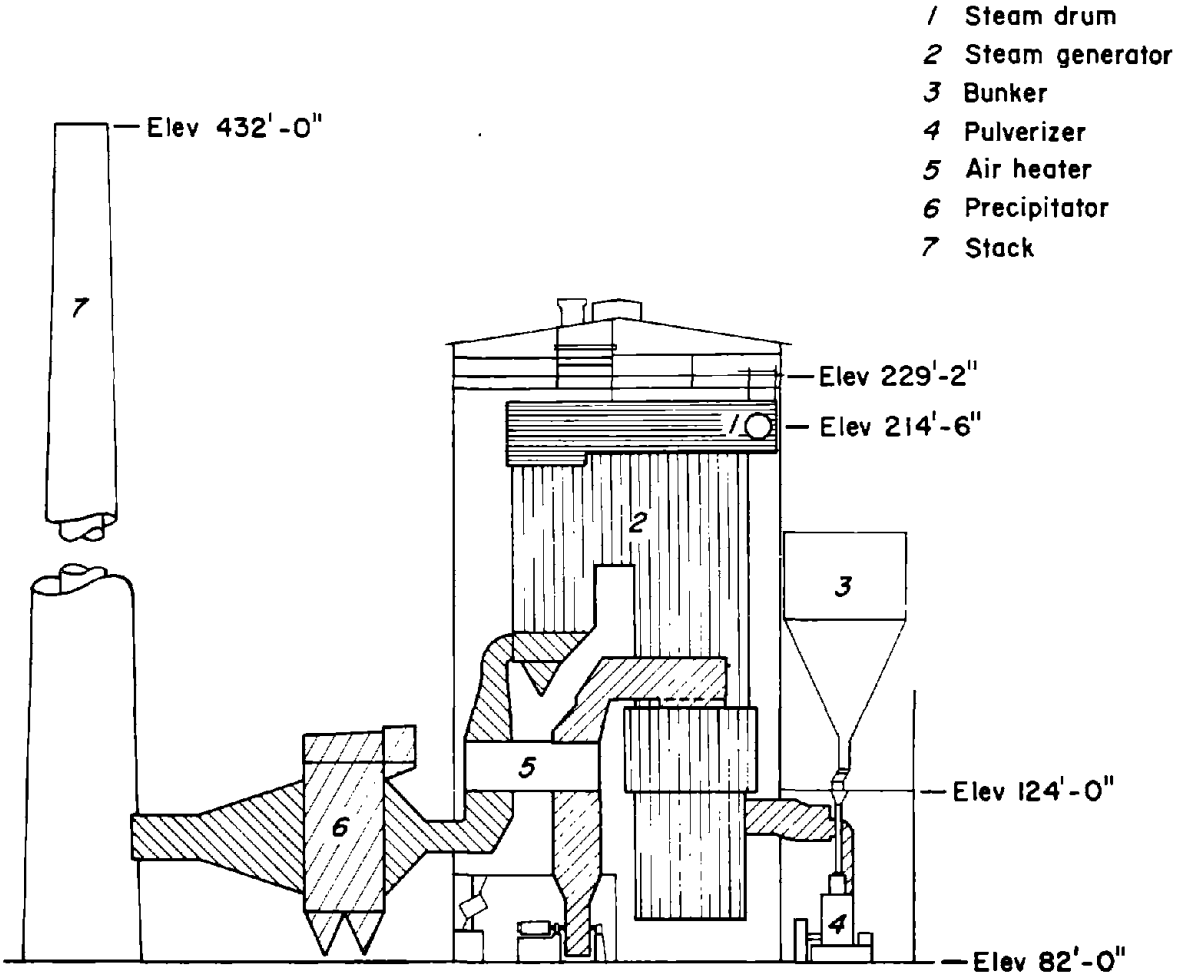


FIGURE 20. - Side Elevation of J. E. Corette Plant.

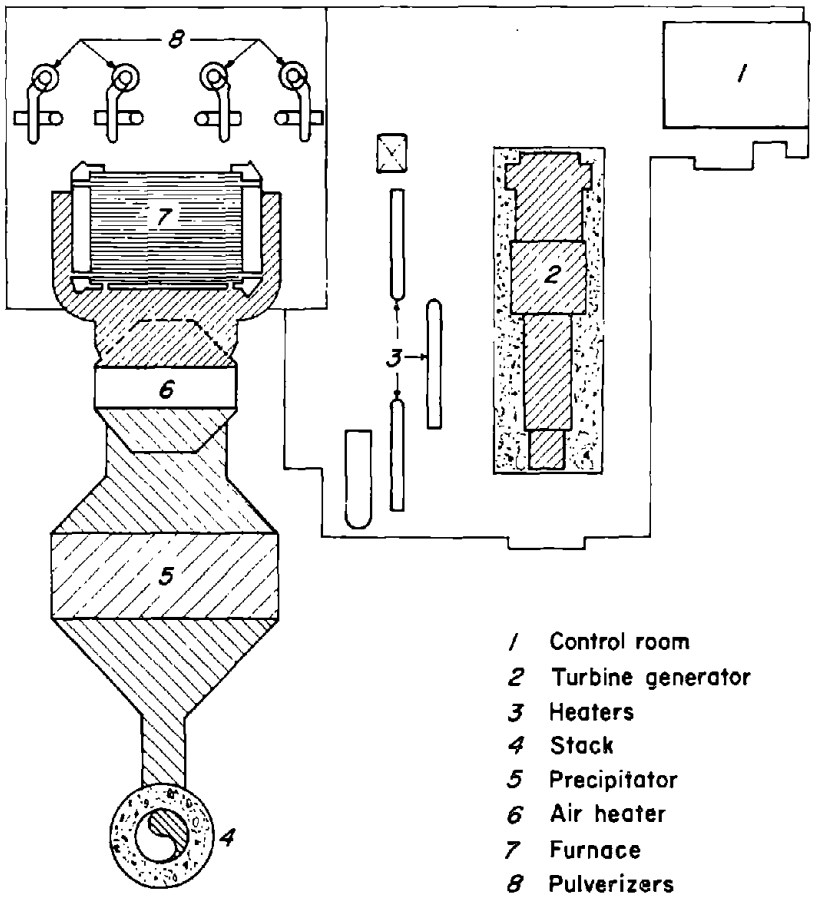


FIGURE 21. - Plan View of J. E. Corette Plant.

A pressurized unit was selected on the basis of economics and the outdoor construction.

Figures 20 and 21 show the general arrangement of the equipment. The turbine generator is to the left side of the steam generator, rather than being in front of the steam generator which is the more common arrangement. The plant has a 3,600-rpm, tandem-compound turbine; a 192-mva generator manufactured by Westinghouse Electric Corporation; and an open-furnace, pressurized, natural-circulation, steam-generating unit manufactured by Combustion Engineering, Inc.

The turbine generator has a guaranteed name plate rating of 163,000 kw at 1,800 psig and 1,000° F primary and reheat steam temperatures, with a 3-1/3-in Hg absolute exhaust pressure. The turbine generator is capable of a maximum load when it operates at 5-percent overpressure and a 2-1/2-in Hg backpressure with a feedwater heater out of service. Under this peaking condition, the gross capability is 190,881 kw.

The C-E steam generating unit is designed for a maximum continuous rating (MCR) of 1,166,000 lb per hr at superheater outlet conditions of 1,890 psig and 1,005° F with feedwater supplied at 463° F. The reheater is designed to reheat 994,000 lb per hr to 1,005° F from inlet conditions of 669° F and 491 psig. The steam generator produces 1,224,000 lb of steam per hr with the feedwater heater out of service at the overpressure condition. The thermal efficiency of the steam generators when operating at the MCR is 86.46 percent. Design pressures of the boiler and reheater are 2,250 and 650 psig, respectively.

The steam generator has C-E tilting tangential coal and air nozzles located in the four corners of the furnace. The subbituminous coal is pulverized in four 703 RPS C-E bowl mills located in front of the steam generator; the coal feed is regulated by C-E volumetric feeders.

Combustion air is heated in a Ljunstrom air preheater. Two forced-draft fans, manufactured by American Standard, with air-foil-type wheels operating at 1,200 rpm, provide the combustion air requirements.

The electrostatic precipitator, manufactured by Research-Cottrell, is installed outdoors between the Ljunstrom air preheater and the stack. A 350-ft-tall concrete stack with an independently supported steel lining follows the electrostatic precipitator.

Steam Generator

The Corette Plant is presently the largest unit in service burning Montana subbituminous coal. It has a natural-circulation, fusion-welded, furnace wall system with 2-1/2-in-OD tubing on 3-in centers. The steam drum is 66 in. in diameter. An open furnace, 40 ft wide and 28 ft deep, with a height of 113 ft, was selected to provide sufficient combustion volume and radiant cooling surface to burn the subbituminous coal. The steam generator is shown in figure 22. Wide-spaced superheater platens at the furnace outlet provide final cooling of the combustion gases, reducing their temperature below the ash fusion temperature before entering the closer spaced pendant reheater. When operating at MCR, the furnace combustion rate is 15,400 Btu per hr per cu ft.

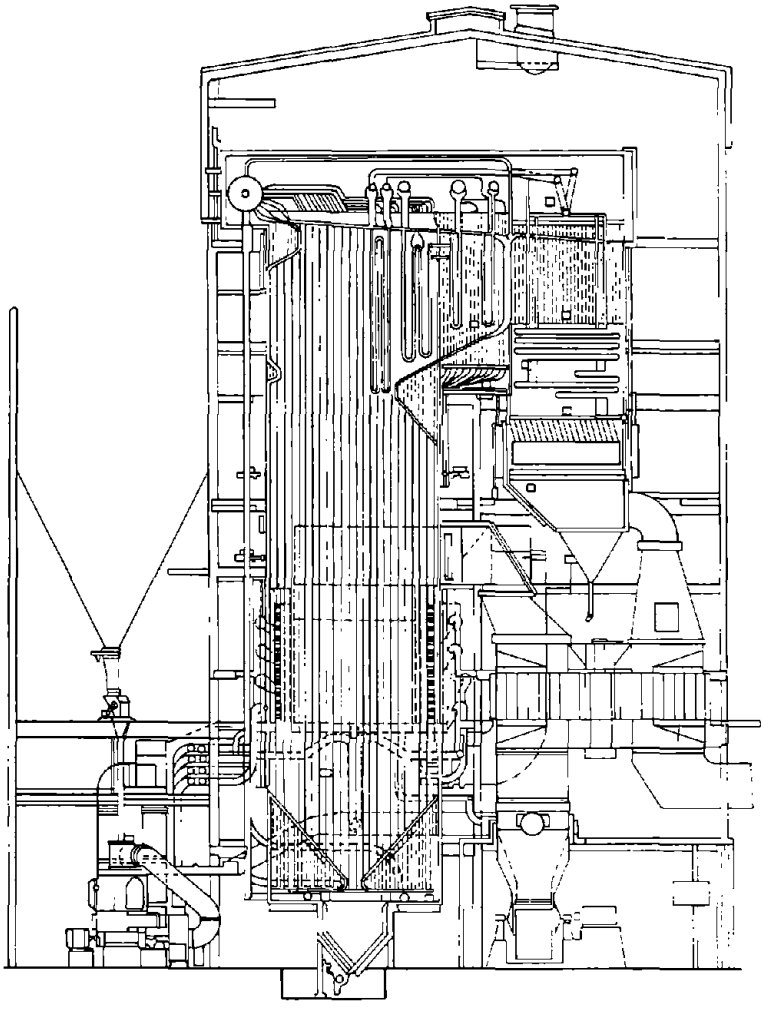


FIGURE 22. - Side Elevation of Steam Generator.

Based on experience firing similar coals, it was established that a furnace that would provide sufficient cooling of the combustion products and result in a flue gas temperature below the ash fusion temperature when entering the closer spaced heating surface would give satisfactory operation from the standpoint of eliminating ash plugging of pendant surface. The fuel which formed the basis for the selection and design of the steam generator is described in table 4. The average coal found in the Colstrip field is similar to that designated in table 4

where its analysis, and that of the design fuel, is compared with those from an Eastern and an Illinois utility. Maximum flue gas velocities through the superheater, reheater, and economizer were limited to approximately 64 ft per sec. No erosion is anticipated since the fuel being burned has relatively low silica and low total ash.

TABLE 4. - Comparison of coals

	Design fuel	Montana Colstrip	Eastern utility	Illinois utility
Proximate analysis, percent:				
Moisture	23.5	25.5	5.0	15.4
Volatile matter	29.2	27.7	33.6	35.0
Fixed carbon	39.2	38.3	53.1	38.6
Ash	8.1	8.5	10.3	11.0
Heating value, Btu/lb	8,980	8,750	13,240	11,200
Sulfur in coal, percent	-	0.8	1.8	3.2
Grindability index	53	-	-	-
Ash fusibility, reducing atmos., ° F:				
Initial deformation temperature	2,250	2,050	2,170	1,995
Softening temperature	2,360	2,250	2,250	2,120
Fluid temperature	2,510	2,350	2,440	2,290
Ash analysis, percent:				
SiO_2	41	36.4	40.0	46.4
Al_2O_3	13	18.5	24.0	16.2
Fe_2O_3	15	5.1	16.8	20.0
TiO_2	-	0.7	1.3	1.0
P_2O_5	-	0.2	0.1	0.1
CaO	18	15.6	5.8	7.1
MgO	4	6.6	2.0	0.8
Na_2O	-	0.2	0.8	0.7
K_2O	-	0.4	2.4	1.5
SO_3	-	14.9	5.3	6.0
Lb ash/million Btu	-	9.7	7.9	10.5
Lb H_2O/million Btu	-	29.1	3.8	14.7
Base/acid ratio in ash	-	0.50	0.43	0.47

The initial section of the superheater is the horizontal section in the rear pass. Desuperheaters are located between the horizontal superheater outlet header and the platen superheater inlet header. Final superheating of the steam to 1,005° F is accomplished in the finishing pendant superheater which follows the reheater. The reheater is located beyond the platen superheater. The economizer is a longitudinal, extended-surface, staggered-type and follows the low-temperature superheater.

The economizer outlet tubes form the sidewalls of the rear pass of the steam generator. The front and rear walls of the rear pass are cooled with steam. All four walls have peg fins and skin casing to complete the pressure-tight gas envelope.

The superheater and reheater penetrations from the penthouse into the gas passes are sealed with a welded, high-crown seal. This type of seal prevents the escape of combustion products from the furnace and also acts as the support point for the pendant superheater and reheater elements.

The guaranteed range of constant steam temperature is 700,000 to 1,224,000 lb per hr primary flow, and 601,400 to 1,144,000 lb per hr reheat flow. Over these load ranges, the reheat steam temperature is controlled with the tilting tangential nozzles backed up with desuperheating; the primary steam temperature is controlled by interstage desuperheating. The tilting tangential nozzles are capable of being positioned from minus 30° to plus 30°, thereby providing a means of changing furnace effectiveness and furnace outlet gas temperature. As the load on the unit and furnace conditions change, the tilt position is automatically adjusted by the reheat outlet temperature control to maintain a constant reheat temperature. Interstage desuperheaters are provided in the primary steam circuits to limit the steam temperature to 1,005° F.

The pendant superheater sections and the pendant reheater are placed in a parallel flow configuration with the flue gas. The finishing superheater and reheater sections with their 1,000° F steam are placed in the relatively cooler gas temperature zones, thereby minimizing superheater and reheater tube wall metal temperatures.

Fuel Burning System

When operating at the design rating, 180,000 lb of coal per hr with a heating value of 8,980 Btu per lb is required. The coal is pulverized by four C-E pulverizers, each with a capacity of 50,400 lb per hr when grinding coal of a 53 Hardgrove and 23.5 percent moisture to a fineness of 70 percent through 200 mesh. The pulverizer and exhauster is shown in figure 23.

Pulverized coal is admitted to the furnace through the tilting tangential nozzles located in the four corners of the furnace. The windboxes are 22 in wide and have an overall height of 20 ft and are aimed at an imaginary circle in the center of the furnace. The action of adjacent fuel streams on each other provides a highly turbulent condition in which the fuel particles and combustion air are completely intermixed and very efficient combustion takes place. This results in minimum carbon loss and maximum furnace heat absorption. The long retention time of the fuel and air mixture in the furnace with tangential firing is one of the contributing factors to the low carbon loss and reduced furnace temperature. A schematic arrangement of a corner is shown in figure 24.

To insure successful operation with low-rank coals, there are several factors that must be taken into consideration when designing the fuel firing system. This requires a very thorough knowledge of the characteristics of the coal.

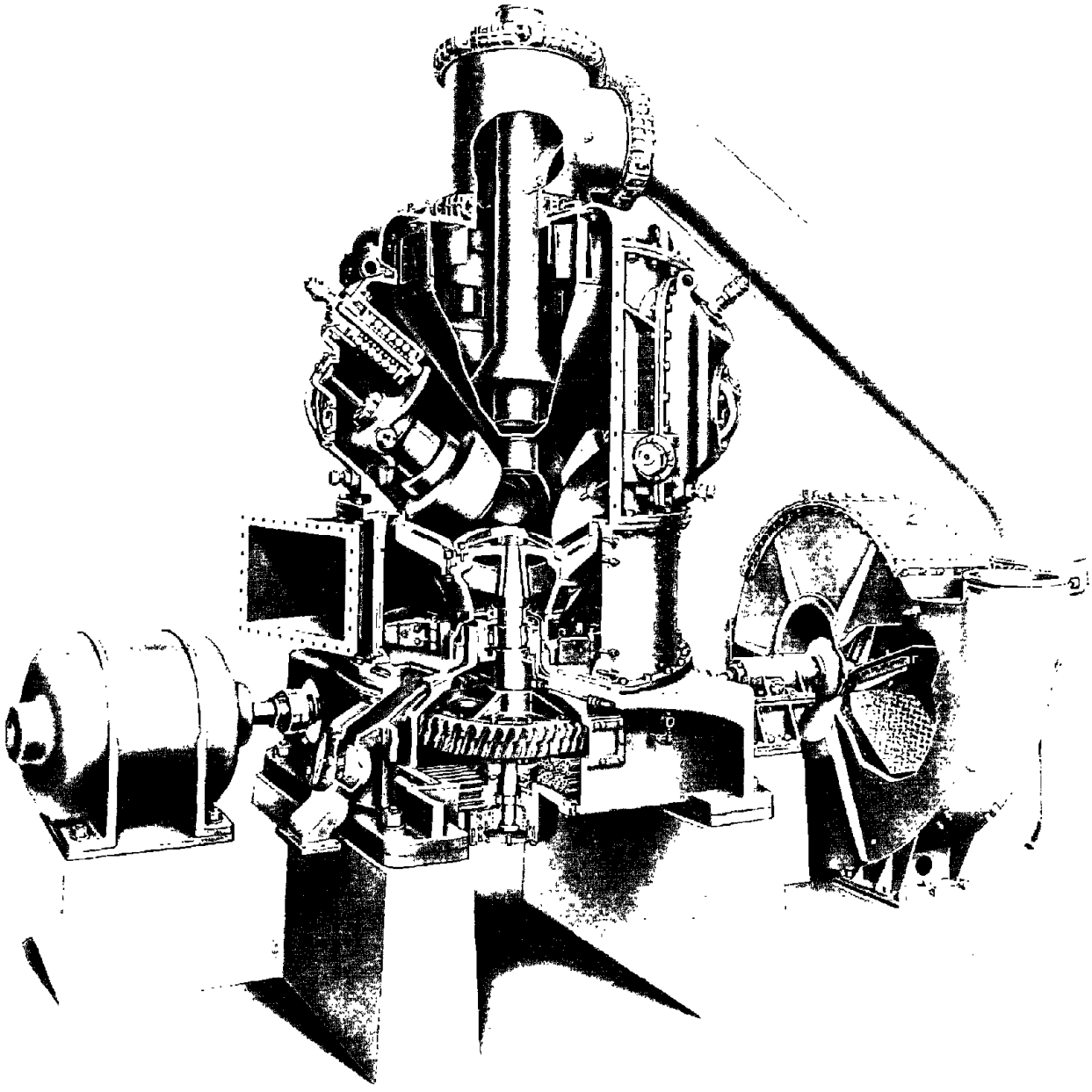


FIGURE 23. - Pulverizer and Exhauster.

Because of the grinding and classifying characteristics of the C-E bowl mill, it is ideally suited for use on the higher moisture lignites and subbituminous coals. In the mill, raw coal is delivered to the center of the rotating bowl. Centrifugal force moves the material over the grinding ring where it passes under the spring-loaded rollers. Partially ground coal passes over the edge of the bowl where it is picked up by the hot air stream, flash dried, and carried upward toward the classifier. The larger coal particles drop out of the air stream and back into the bowl. The smaller particles and fine material enter the classifier through a number of openings with externally

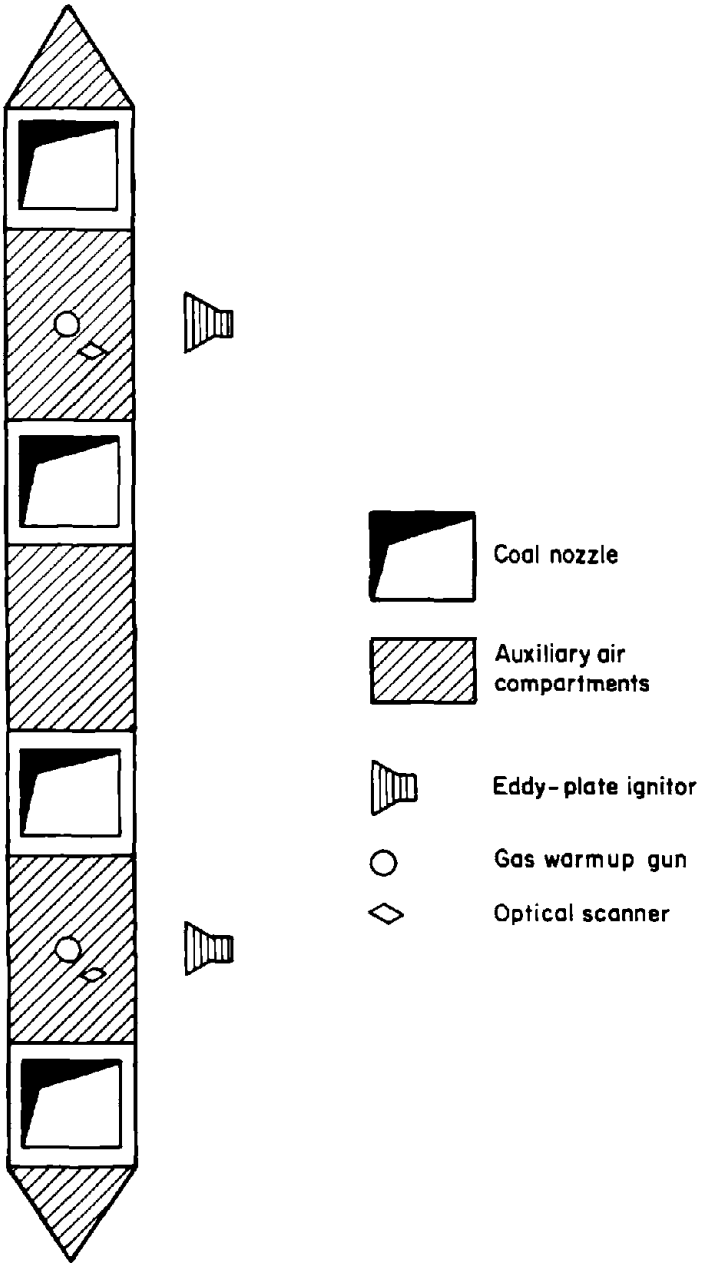


FIGURE 24. - Arrangement of Ignitors, Warmup Guns, and Coal Nozzles.

adjustable vanes. A spinning action is imparted to the coal-air mixture. Oversize material is rejected in the classifier and returned to the bowl for further grinding. The fine particles are carried out of the pulverizer by the air stream to the burners. About 75 to 85 percent of the classifier input is returned to the grinding chamber where it mixes with the incoming raw coal. This circulation produces predrying of the raw coal and enables the bowl mill to handle high-moisture coals without impairing pulverizer capacity or classification.

Hot air from the air heater, properly tempered as necessary for the particular moisture content of the coal to be burned, enters the lower portion of the pulverizer tangentially. The pulverizer design permits the use of air at the mill inlet at temperatures up to 825° F. Foreign material entering the pulverizer passes over the edge of the bowl and falls through the air stream to the base of the pulverizer. Scrapers sweep this material around to the discharge spout and drop it into a refuse hopper. At the Corette Plant, a hot air temperature of 600° F is used to properly handle the 24.5-percent moisture coal.

Natural gas is used to ignite this unit. Eddy-plate, side-pilot ignitors are mounted adjacent to the gas warmup guns, which are positioned between fuel nozzles. When starting up the unit, or for stabilization of the pulverized coal, the eddy-plate ignitor, which is spark-ignited, is used to ignite the gas warmup gun.

This unit is equipped with a C-E burner control system and optical scanners. The complete philosophy of the ignition of tangentially fired pulverized coal and its burner control system is discussed in a paper by Cooper.[3]

Air and Gas Systems

The steam generator has a single Ljunstrom air preheater. It has enameled cold-end elements for corrosion protection and is designed to provide 650° F air to the furnace with 100° F inlet air at the maximum continuous rating of the steam generator. This in turn cools the exhaust gases from 760° F down to 300° F. Associated with the Ljunstrom air preheater is a steam air heater that is designed to heat the incoming air from minus 25° to 100° F before entering the air preheater.

The air heater control is set up for a minimum of 100° F inlet and an average cold-end condition of 175° F. The combination of low sulfur content in the coal and the enameled elements may make it possible to reduce this average temperature somewhat in order to get cooler inlet gas to the electrostatic precipitator; this would improve precipitator efficiency.

Two American Standard, air-foil-type fans operating at 1,200 rpm and equipped with inlet vanes and outlet dampers for regulation supply combustion air through the two steam air heaters to the Ljunstrom air heater. Combustion air for the eddy-plate, side-pilot ignitors comes from a pilot-air-booster fan that has its suction at the forced-draft fan discharge. Sealing air for the soot blowers, observation ports, other furnace opening, pulverizers, and coal feeders comes from the forced-draft fan discharge before the steam air heaters of the Ljunstrom air preheater. The forced-draft fans are installed in a concrete block room that is fitted with air intakes for measuring combustion air flow.

The Research-Cottrell electrostatic precipitator has a guaranteed efficiency of 96 percent at 300° F and 600,000 cfm, with a 2.0-grain-per-cu-ft loading (fig. 25). This rating is also dependent upon the ultimate analysis of the coal. Principal variables that affect efficiency, once a given precipitator is installed, are gas volume and temperature, ash quantity and resistivity, and coal moisture and sulfur content. The first two items are functions of the load carried by the plant and, to some extent, the way the steam air heater is controlled. The rest of the items, of course, are dependent upon the source of the fuel. A change in any of these items will cause a variation in precipitator efficiency. In the near future, testing is planned to determine the extent of these variations under different operating conditions.

The Montana air pollution regulations are among the most stringent in the nation. The particulate emission standards require a 96-percent collection efficiency for this plant with this coal. No consideration is given to stack height. The low sulfur content of the Montana coal increases its ash resistivity and makes the ash more difficult to precipitate. This may cause a problem

[3]Cooper, T. H. Burner Control Ignition Systems for Pulverized Coal. Southeastern Elec. Exchange, April 1966, 12 pp.

FIGURE 25. - Electrostatic Precipitator.

in meeting the particulate emission standards for larger plants due to the failure of the standards to recognize stack height as a means of air pollution control. The ash resistivity is 1.9×10^{13} ohm cm at 300° F and 6 percent moisture. The sulfur is as low as 0.4 percent on an "as received" basis in many samples.

Sulfur emission standards are due to be adopted in the State very soon. These standards surely should recognize the effect of stack height. With this low sulfur coal and a reasonably tall stack, very acceptable ground level concentrations can be obtained.

The plant's 350-ft-tall, insulated, steel-lined, concrete stack has a top inside diameter of 11-1/2 ft, which produces an exit velocity in excess of 50 mph at full load. This, together with the 300° F thermal head, enables the plume to penetrate an inversion layer 1,500 ft thick with a negative 10° lapse rate.

Ash Removal System

Bottom ash drops from the furnace into a W-type wet hopper. From here, the clinkers are ground and sluiced to ponds about 1,000 ft downstream from the plant. A United Conveyor standby precipitator, vacuum-type, fly ash collecting system also feeds ash into the bottom ash sluicing system. Additional fly ash is collected from the economizer hoppers by a vacuum system and fed into this same sluicing facility.

The United Conveyor main precipitator fly ash collecting system takes the ash from the precipitator hoppers and transports it with positive air pressure to a 300-ton ash silo adjacent to the plant. Ash from the silo can be loaded dry or via a dustless unloader to either railroad cars or other bulk transport vehicles. The dry loading facility is provided so that the ash can be marketed, whereas, the dustless unloaders provide a means of adding enough moisture so that the ash can be compacted in a landfill disposal area.

Steam soot blowers, manufactured by the Culps-Vulcan Division of Blaw-Knox Company, are installed on the boiler. The furnace is cleaned with two rows of 12 wall blowers each above the burners, and six locations of double-sided, long, retractable soot blowers in the pendant superheater, reheater, and horizontal superheater zones.

Weather Protection and Power Requirements

The unit is semienclosed; the turbine generator enclosure, operating floor, and upper portions of the boiler are of outdoor construction. The boiler is a semioutdoor type; the turbine is an indoor type, but located outdoors and provided with a rollaway housing.

The area below the operating floor, the coal mill bay, the burner area, and the FD fans are all enclosed. All exposed outdoor lines subject to freezing are electrically traced. Because the top of the steam generator is outdoors, a monitor roof, fabricated of sheet metal and placed above the top level of supporting structural steel, is used for overhead weather protection. This design eliminates the roof penetrations of the supporting steel or hanger rods common to the weather roof that is placed between the supporting steel level and top of the penthouse. Vertical siding material extends around the perimeter of the structural steel from the monitor roof to a point just below the upper level of the penthouse.

The exterior of the furnace walls is insulated with mineral fiber bats. The duct work and other areas are insulated with calcium silicate block. All exterior surfaces of the furnace walls have a ribbed aluminum casing. The duct work and other areas have a flat aluminum lagging. The top surface of the penthouse is insulated with 9 in of pourable insulation, which is cast monolithically to eliminate the problem of cutting and closely fitting insulating block around the numerous hanger rods and supports in this area.

The number and horsepower rating of the drives of the major items of auxiliary equipment are as follows:

	No.	Hp
Boiler feed pumps.....	2	2,250
Condenser circulating pumps	2	250
Pulverizers.....	4	450
FD fans.....	2	1,500
Condensate pump.....	2	500

Boiler and Condenser Water

Makeup water is provided from the city water system through a zeolite softener to a 24,000-lb-per-hr evaporator. The condensate system is provided with a deaerating-type condenser, but with no deaerating feedwater heater. Chemicals are added at the condensate pump to provide for the scavenging of oxygen and carbon dioxide. Trisodium phosphate is added at the drum to prevent formation of hard magnesium and calcium compounds. About 0.5 percent blowdown from the drum is necessary to maintain the silica level low enough to prevent excessive carryover.

Conductivity, pH, and dissolved oxygen are monitored at various points. Also, the drum is checked for silica at least daily; and periodically for iron and copper.

Preoperational acid cleaning of the steam generator using inhibited hydrochloric acid was performed on the water walls, drum, and drainable parts of the superheater.

Circulating water for the condenser is taken from the Yellowstone River through an intake canal and structure located downstream from the two plants. The discharge structure and canal are adjacent to and downstream from the intake facilities. There is a tie between the two systems so that warm discharge water can be recirculated into the intake system in the winter. Two circulating water pumps provide a total of 56,960 gpm to the condenser. Also, cooling water can be provided for the Frank Bird Plant from these facilities.

The intake canal is arranged so that its flow is in a reverse direction to that of the river and at a velocity of from 1 to 2 ft per second. With this arrangement, the difficult problem of taking cooling water from a river that carries slush and block ice, silt, moss, leaves, and gravel should be solved.

Montana water pollution regulations permit a 4° F temperature rise in the river at the discharge point. The temperature rise at minimum flow will be about 1.7° F when operating at full load. In the winter, there will, of course, be very little temperature rise because the plant will be recirculating its own discharge water.

Fuel and Handling Facilities

Coal for the Corette Plant is obtained from a strip mining operation at Colstrip, Mont., 120 railroad miles east of Billings. These properties are

owned by Western Energy Company, a wholly owned subsidiary of the Montana Power Company. Coal reserves are leased from the Northern Pacific Railway Company, the United States Government, and the State of Montana.

The mine was developed in 1924 to supply coal for Northern Pacific's steam locomotives. It is geared to produce about 8,000 tons of coal per shift using a Bucyrus-Erie 550B loading shovel with a 16-cu-yd bucket. The average haul is about 3,000 ft in the present pit operation. Two 100-ton, bottom-dump haulers move the coal from the loading shovel to the tipple. A Bucyrus-Erie 1050B with a 27-cu-yd bucket will be used for overburden removal at about a 2.5 to 1 stripping ratio.

The coal is mined from a 25-ft-thick seam that is virtually free of partings; thus, cleaning facilities are not necessary. A crushing facility at the mine tipple reduces the coal from mine run size down to the 1-1/4- by 0-in size required at the plant. All of the crushing is done at the mine in order to prevent a dust and noise problem at the plantsite. Crushing is accomplished using a McNally-Pittsburgh 30- by 60-in double roll primary crusher, a set of screens to bypass the fines, and an AC-7D American Rolling Ring secondary crusher. The coal is then loaded into 100-ton railroad cars via a 100-ton surge hopper and hydraulic load-out gate.

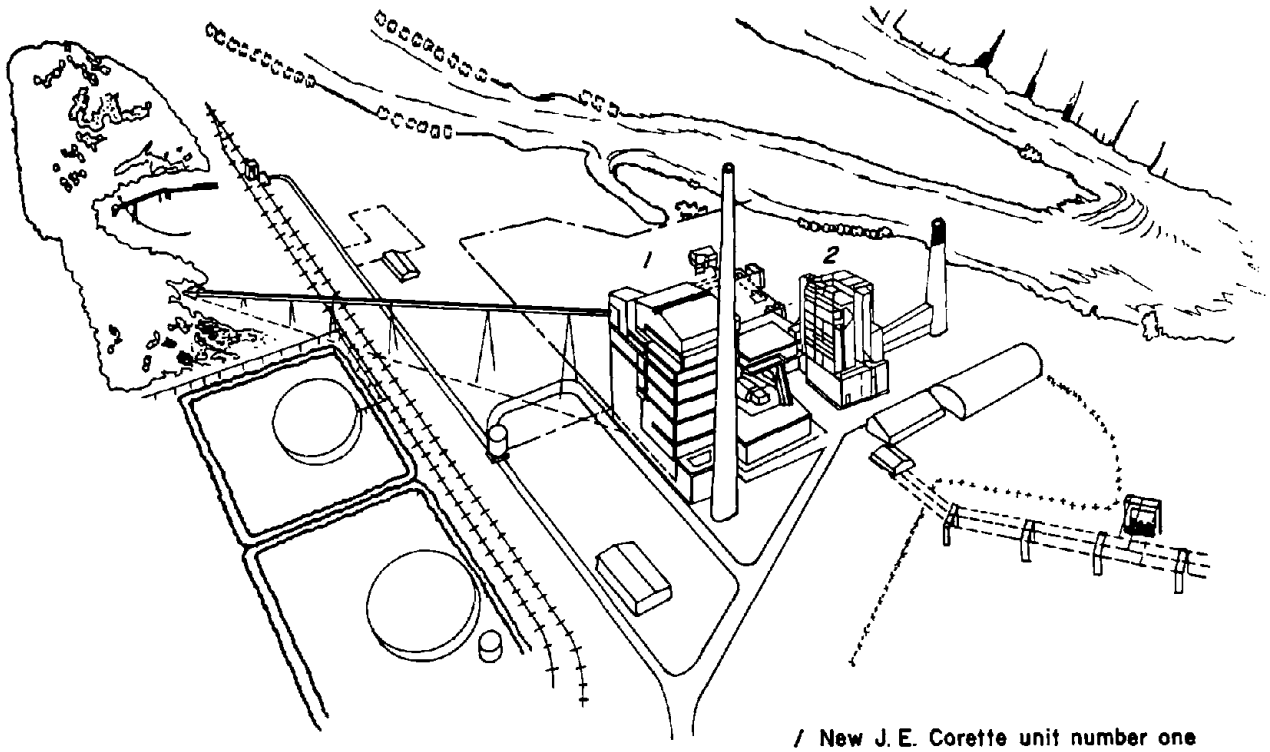
The railroad cars are positioned under the tipple with a 1,000-hp Alco GE diesel locomotive which is remotely controlled by the tipple operator. Coal is hauled from the mine to the plant by Northern Pacific. Fifty-three 100-ton, three-bottom (six-gate) cars are used in the service. A 5,000-ton trainload of coal is normally mined in one shift, hauled to the plant the same night, and unloaded the following day. At peak load, the plant requires three trainloads of coal per week.

When the loaded cars arrive at the plant, they are positioned over an unloading hopper by another 1,000-hp GE diesel locomotive which is also remotely controlled. A heavy-duty car shaker is provided at this point to assist the unloading operation. The coal is unloaded into a 100-ton hopper and conveyed to a radial stacker. One man operates the locomotive and the car shaker; he also starts and stops the stacker system. The stacker then automatically deposits the coal in a 6,200-ton active storage pile. From here, coal is fed to the reclaim tunnel or moved to the dead storage area with a Cat 824 rubber-tire dozer. (See fig. 26.)

The 6,200-ton active storage pile is large enough to run the plant at full load over a 3-day weekend. Thus, it will not normally be necessary to call out the coal crew on weekends or holidays.

There is adequate room to place more than 100,000 tons of coal in dead storage. This amount, of course, is fluctuated to even out the mining cycle and to compensate for conditions affecting reliability of delivery.

The 1,600-ton plant bunker system was sized to provide 18 hr for repair of a breakdown in the reclaim system with the plant operating under full load conditions.



/ New J. E. Corette unit number one
2 Existing Frank Bird unit number one

FIGURE 26. - Plant Arrangement Showing Coal-Handling Facilities.

The plant uses 100 tons of coal per hr at peak load, which is taken from beneath the active storage pile into the reclaim system by four 100-ton-per-hr vibrating feeders and fed onto the 200-ton-per-hr main conveyor. The conveyor transports the coal to a transfer tower above the plant bunkers. At the transfer tower, the coal passes a magnetic separator, then through a 3-in scalping screen with an oversize reject chute to two 100-ton-per-hr flight conveyors. These deliver the coal to the plant bunkers. The reclaim system is automatic in that it starts every 20 minutes and shuts down when the bunkers are full. The entire coal-handling system was supplied by Stephens-Adamson.

The mining, hauling, and unloading facilities were laid out for quick delivery to minimize freezing problems in the railroad cars during winter operations. This has worked well, but it is apparent that with this high-moisture coal, four-bottom (eight-door) railroad cars would unload much more rapidly and less car shaking would be necessary.

Both the stacker and reclaim conveyors have creep drives which are run continuously in cold weather to prevent belt warpage. The stacker conveyor rise angle is 15°6', and the reclaim is 11°20'. These angles were considered conservative when the plant was designed. They have since been proved to be necessary because under extreme conditions coal has slipped on the stacker belt. This occurred at a time when there was a layer of frost on the belt and the coal had remained in railroad cars for several days. The problem was eliminated by installing heaters at the takeup pulleys to keep the belt dry.

Care must be exercised when moving coal from dead storage into the active storage pile. It has been necessary to push back about the top 5 ft of the dead storage pile to prevent frozen lumps from getting into the reclaim system.

Initially there was some buildup of frozen fines in the reclaim system on the vibrating feeders, the conveyor idlers, the scalping screen, and the transfer tower chutes. This is being rectified by applying heat in appropriate places and by readjusting the belt scraper arrangement.

Room has been provided in the scalping screen oversize reject chute for the installation of a small crusher. Future operation may prove that this is necessary; however, at the moment oversize material is being handled manually.

Effect of Fuel on Design of Steam Generator

Each item of the coal analysis represents a specific characteristic that must be evaluated in designing a steam generating unit. Particular attention must be given to moisture, ash content and composition, grindability, and ash fusibility.

One of the basic characteristics of a low-rank coal is the high quantity of moisture and ash present in the coal. Since this has a direct bearing on the higher heating value, it is convenient to express the relationship as pounds of moisture and ash per million Btu of fuel fired, as was done in table 4 for an average Colstrip coal analysis and typical Eastern and Midwestern bituminous coals.

High-moisture content affects low-temperature corrosion, heat transfer rates, and will decrease boiler efficiency by increasing both latent and sensible heat losses. Moisture is also particularly significant in pulverizing operations.

The percentage of mineral matter in coal is significant because of the effect its ash may have on the slagging and fouling of boiler surfaces, unburned carbon losses, and stack emission of particulate matter; the burden it places on ash handling and disposal facilities; the erosion of boiler surfaces; and the rate of wear of pulverizer parts.

The measurement of ash fusibility has long been recognized as an index for evaluating performance with regard to slagging and deposit buildup. If the ash is at a temperature below its softening temperature, it probably will settle out as a dust and, as such, is comparatively simple to remove. If, however, the ash is near its softening temperature, the resulting deposit is apt to be porous in structure. Depending on the strength of the bond, the deposit may fall off from its own weight or may readily be removed by soot blowing. However, if the deposit is permitted to build up in a zone of high gas temperature, its surface fuses more thoroughly and may exceed the melting temperature with resulting runoff as slag.

As the percentage of basic metals in ash increases, the melting temperatures increase, and the possibility of slagging on furnace walls decreases

proportionally. However, as the ash increases in calcium and sodium content, the rate of deposition increases on tube surfaces. The sodium oxide content, in particular, has a catalytic effect on the rate of deposition; and investigations have shown that ash with a sodium content above 5 percent fouls at an accelerated rate.[4] The subbituminous coal from the Colstrip mine has a low sodium oxide content in the ash. In addition, the pounds of ash per million Btu is less than a typical Midwestern bituminous coal. Low-rank coals normally have from 14 to 23 lb of ash per million Btu, as compared with 10 lb of ash per million Btu at Colstrip. Because of these factors, low rates of ash deposition in the furnace and on heat absorbing surface, and relative ease of cleaning were anticipated in the design of this unit. Operating experience to date has confirmed this.

The only slag that has been forming is below the burner level. This is self-limiting and breaks loose easily with load changes. The unit is designed for the addition of a row of wall deslaggers at this level if further operation at high load indicates a need. Twelve wall deslaggers above the burner level are operated for 4 min every 4 hr. Deslaggers near the top of the furnace are operated intermittently about once a week to clear up the furnace TV picture. Half of the retract soot blowers, those near the superheater, are operated every 24 hr for 45 min. The other half are operated about once every 3 days. The air heater steam cleaners are operated for about 90 min once per shift. The ash that collects behind the slag screen and in the back part of the boiler is very light and is easily removed.

Analysis of fuel samples taken over several months indicates an extremely uniform fuel supply. Day to day operation of the steam generator is greatly simplified by this. Operating procedures can be established without considering wide variations in heating value, ash content, ash analysis, and ash softening temperature.

Plant Operation

The operating and maintenance crews for the J. E. Corette Plant and the Frank Bird Plant total 32 men. This includes a plant superintendent, an assistant superintendent, a results engineer, and 4 four-man operating shifts consisting of a shift foreman, an operator, an auxiliary operator, and an electric dispatch man who operates the area substations but is available when needed. There are also four mechanical maintenance men, three electrical maintenance men, a four-man coal crew, and a yard man. An extra operator is present during plant startups. At the Frank Bird station, a fireman is also required when operating at high loads because half of the fuel burners are not automated.

The coal has good handling characteristics; that is, it does not oxidize and heat up rapidly and is generally quite clean with only a small amount of pyrites. It can stand in the active storage pile for about 2 weeks before it

[4]Knust, R. B., T. B. Hamilton, and R. P. Hensel. Large Steam Generator Design as Influenced by Low Rank Coals. Proc. Am. Power Conf., v. 30, 1968, pp. 295-320.

starts to steam; no heating has been noticed in the compacted dead storage pile. There has been no heating in the bunkers, but, of course, when an extended plant shutdown is contemplated, the bunkers will be run dry. Also, there is no heating difficulty in either the feeders or the pulverizers as long as the air is shut off when the devices are taken out of service.

One pulverizer has been inspected for wear and looks very good. The coal apparently has low abrasive characteristics.

The pressurized boiler seems very tight. The only dust leakage that has been noticed is coming from the joints in the burner fuel lines. Steps are being taken to seal these more tightly.

There have, of course, been a number of problems discovered during the startup period, such as control lines that need more winterizing and some deficiencies in manufactured equipment; however, these problems are being solved and with generally good cooperation from the manufacturers. We believe that we have a relatively simple and economical plant with a good fuel and that we should get many years of reliable service with very low maintenance expenses.

ASH FOULING AND AIR POLLUTION STUDIES USING A PILOT-PLANT TEST FURNACE

By G. H. Gronhovd,[1] A. E. Harak,[2] and P. H. Tufte[3]

Introduction

During the past 10 years, there has been a large increase in the total installed generating capacity of powerplants burning lignites from the Northern Great Plains area. In many respects, these lignites have proven to be a very satisfactory fuel for the generation of low-cost power. However, losses in boiler availability resulting from ash fouling on heat transfer surfaces has been, and continues to be, a serious operating problem.

In 1963, the Bureau of Mines initiated several research programs designed to study various aspects of the ash fouling problem. The results of some of this work were presented at the 1967 Lignite Symposium[4] and showed that there were large variations in ash analyses both between and within mines and that there was a strong correlation between sodium content[5] and degree of fouling based on full-scale field tests. Since that time ash fouling studies have been continued using a specially constructed pilot-plant furnace at the Bureau's Grand Forks Coal Research Laboratory. The objective was to burn coals, primarily Western low-rank with large differences in ash characteristics, and to relate the rate of fouling in the test furnace with the ash chemical analysis and other variables, such as excess air, gas temperature, and tube metal temperatures. This report covers the results of a 1-1/2-year test program using this furnace.

Furnace Design

The arrangement of the pilot-plant furnace is shown in figure 27. The combustion chamber has a 30-in diameter, is 8 ft high, and is refractory lined.

Lignite is prepulverized in a hammer mill pulverizer and charged to a volumetric feeder. Combustion air is first preheated in a tubular air heater

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[3]Chemical engineer, Grand Forks Coal Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.

[4]Gronhovd, G. H., A. E. Harak, and L. E. Paulson. Ash Fouling Studies of North Dakota Lignite. Paper in Technology and Use of Lignite, Proceedings: Bureau of Mines-University of North Dakota Symposium, Grand Forks, N. Dak., Apr. 27-28, 1967, comp. by Wayne R. Kube and James L. Elder. BuMines Inf. Circ. 8376, 1968, pp. 76-95.

[5]Where "sodium content" is used in this report, it is taken to mean percent Na_2O in ash.

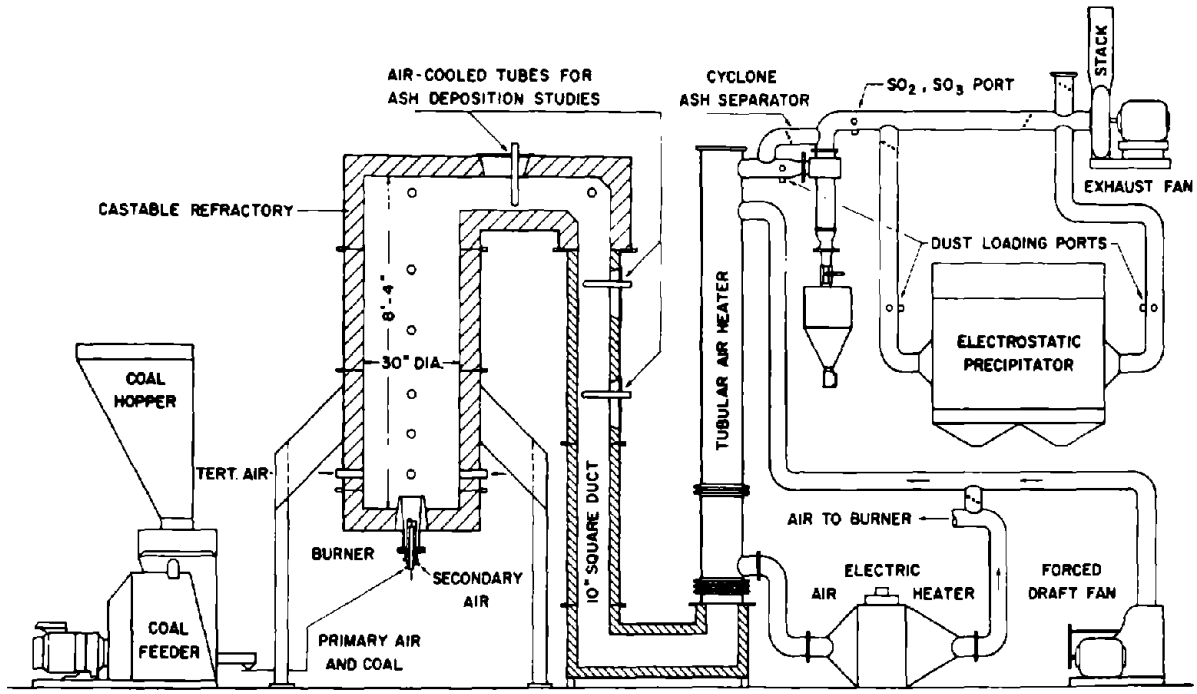


FIGURE 27. - Schematic Arrangement of Pilot-Plant Furnace and Auxiliary Equipment.

and then given a final preheat using an electric air heater. When burning 30-percent-moisture lignites, air is usually preheated as high as 700° to 900° F. The pulverized coal is dropped into the throat of a venturi section of the primary air line to the burner. Heated secondary air is introduced into the burner, and heated tertiary air is added through two tangential ports located in the furnace wall about 1 ft above the burner cone. The percentages of the total air used as primary, secondary, and tertiary are usually about 10, 30, and 60, respectively. Flue gas at 2,000° F passes out of the furnace into a 10-in-square duct that is also refractory lined. Located in this duct are three probe banks designed to simulate superheater or reheater surfaces in a commercial boiler. The first probe bank is vertical; the second and third are horizontal.

Figure 28 shows the construction of the probe banks, each of which is fastened on a hinged door to facilitate inspection and cleaning. The probes are 1.66-in-OD, type 304 stainless steel pipes and are cooled by compressed air. Each probe has two thermocouples embedded in the upstream edge. One of the thermocouples on the center probe is attached to a temperature-recorder-controller that regulates the cooling air to the probes. Usually the metal temperatures for probe banks 1, 2, and 3 are controlled at 1,000°, 1,000°, and 800° F, respectively. Gas velocity between the tubes at probe bank 1 is about 25 ft per second. Gas temperatures and velocities at probe banks 2 and 3 are dependent upon the fouling at the preceding bank. Usually the gas temperatures entering banks 2 and 3 are about 1,750° and 1,600° F, respectively.

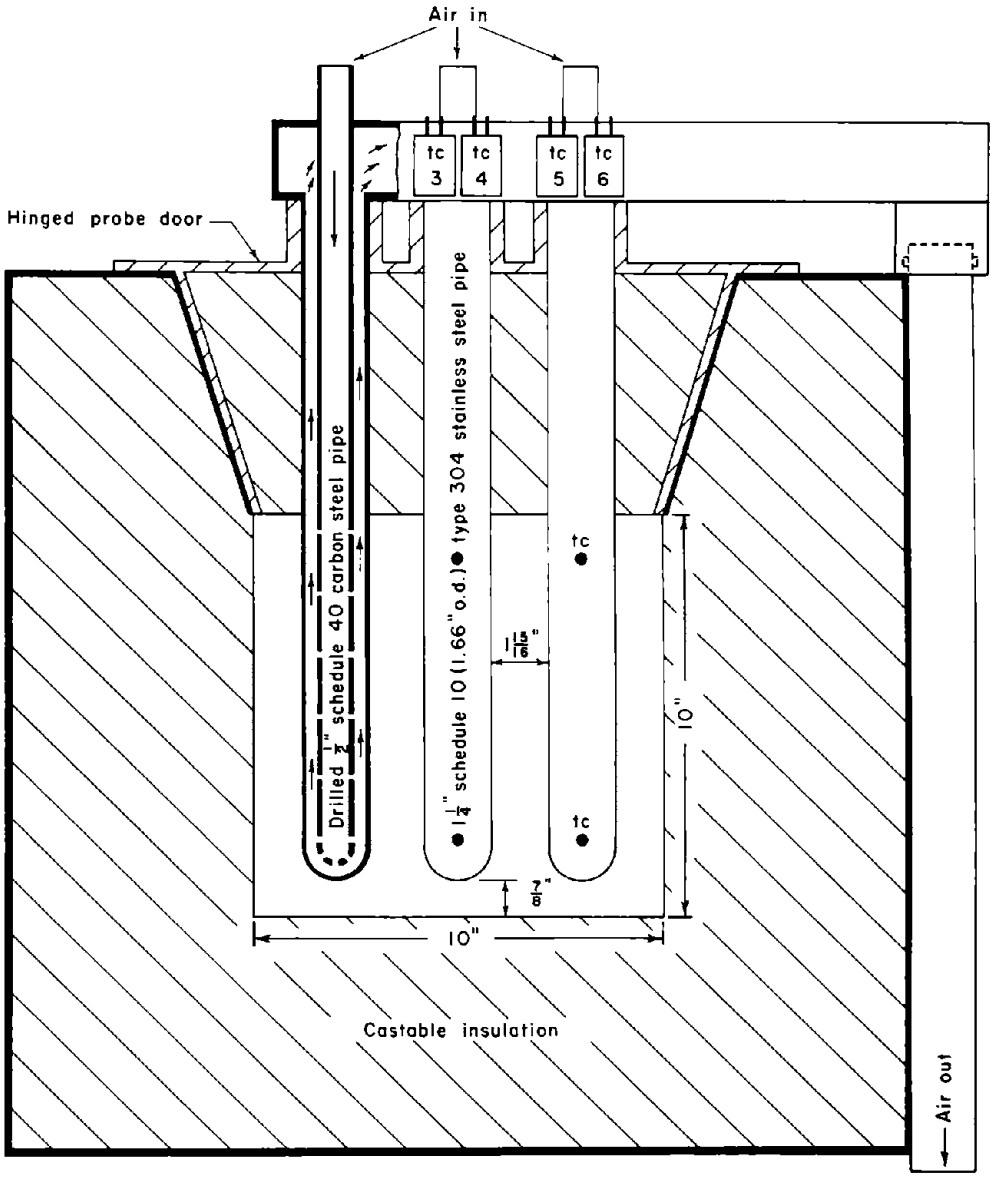


FIGURE 28. - Details of Deposit Probe Construction.

After leaving the probe duct, the flue gases pass through the tubular air heater and cyclone ash separator before being discharged to the stack. An electrostatic precipitator has recently been installed, and the flue gas can be routed through it. Figure 29 is a general view of the furnace and panel board.

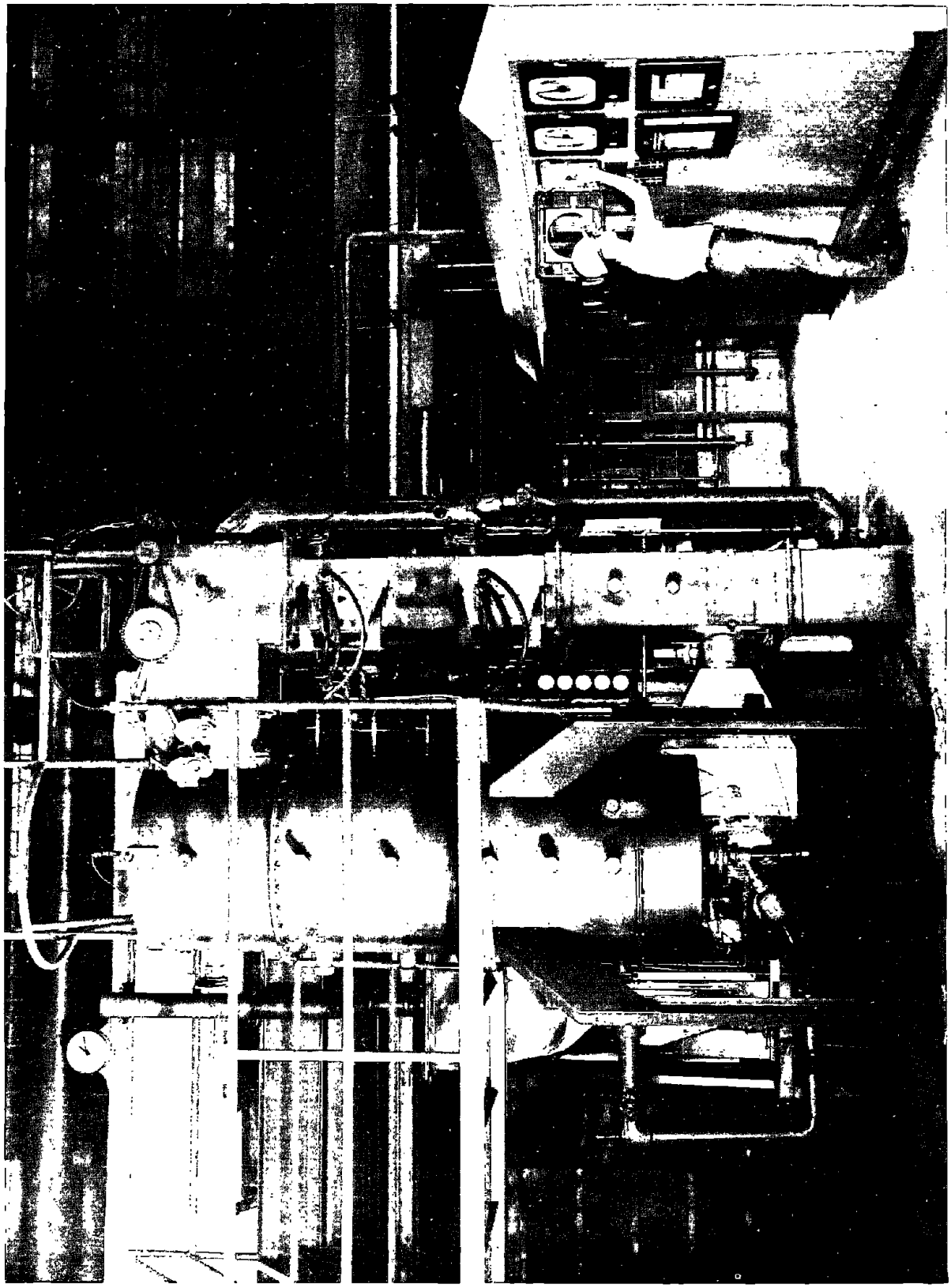


FIGURE 29. - General View of Pilot-Plant Furnace.

Test Procedure

The relative fouling tendencies of the test coals are determined by burning the samples at specified conditions for a standard time. When starting with a cold furnace, the following schedule is used to permit completion of a test in one 8-hr shift:

	Hours
Preheat on gas.....	1-1/2
Preheat (gas and coal)	1
100 percent coal.....	5-1/4
Total.....	7-3/4

Steady state conditions are usually achieved for the last 3 hr of the test (fig. 30). The coal feed rate is adjusted to keep the flue-gas temperature entering the first probe bank at about 2,000° F with about 30 percent excess air. When using 30-percent-moisture lignite, the feed rate is about 75 lb per hr, and the total heat input is 550,000 Btu per hr. The volumetric heat release is about 13,500 Btu per hr per cu ft, which is similar to that in a modern commercial boiler. At half-hour intervals, coal samples are collected

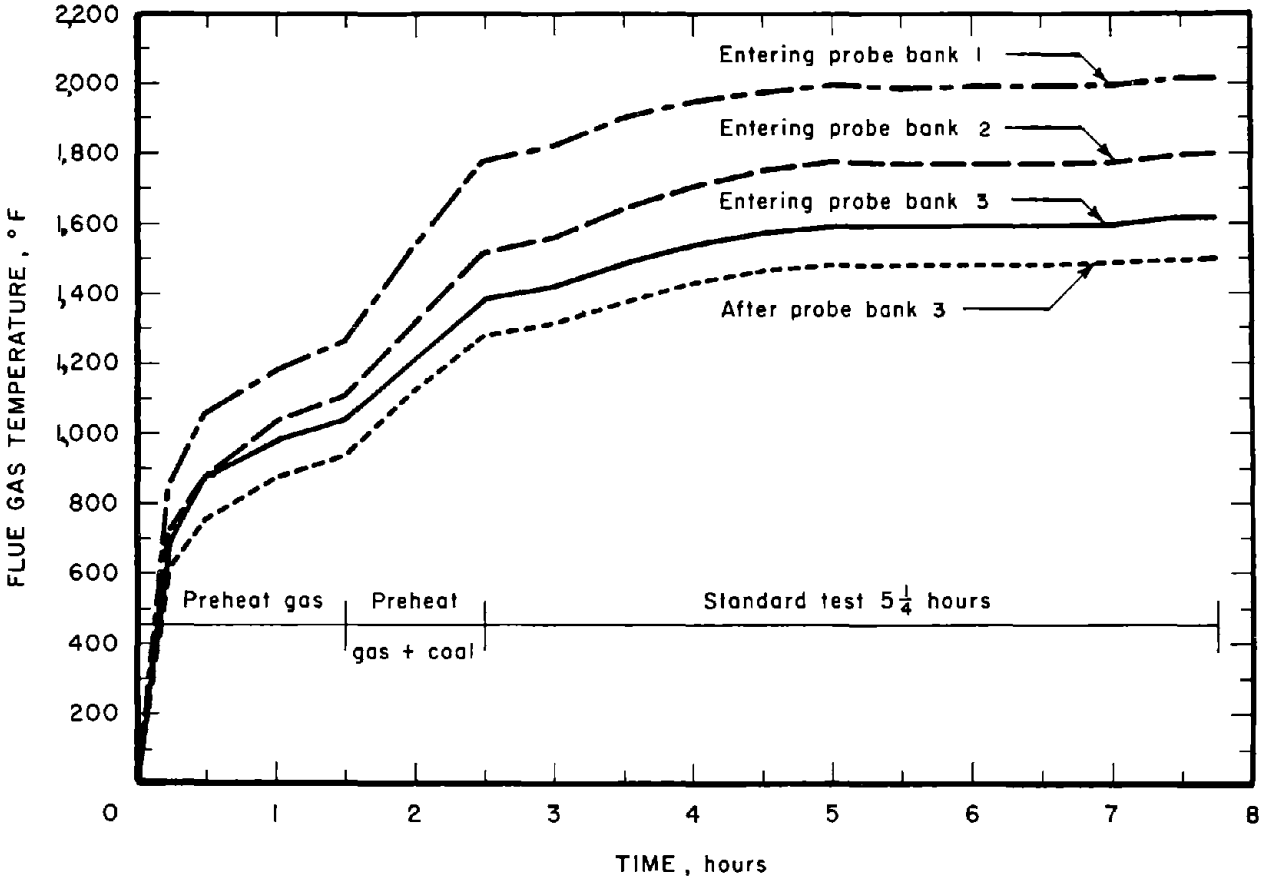


FIGURE 30. - Flue-Gas Temperature Pattern for a Typical Furnace Test.

and flue-gas analysis run. Oxygen and carbon dioxide in the flue gas are continuously monitored by recording analyzers. During a test, three or four samples of flue gas are taken at the outlet of the dust collector and analyzed for sulfur dioxide and sulfur trioxide contents. An infrared analyzer has recently been installed to continuously monitor the sulfur dioxide in the flue gas.

At the completion of the test period, the probe doors are opened and color and black-and-white photographs are taken of each deposit. The deposit is then removed from the probes in two fractions, an inner and an outer layer, and each is weighed and analyzed separately. Normally, the inner white layer is less than 10 grams, compared with 100 to 500 grams for the outer sinter deposit.

The current procedure, adopted after about 1 year of testing, is to remove the bottom section of the furnace and clean the walls after each test. The ash collected on the furnace walls, probe duct walls, air heater tubes, and in the dust collector are all weighed as part of the ash balance. When burning a typical high-fouling lignite, the ash balance might be as follows:

Location	Input ash, percent
Total deposit on three probe banks....	5
Deposit on furnace wall.....	20
Deposit in probe duct and air heater..	20
Fly ash collected by cyclone separator	20
Unaccounted for.....	35

The test furnace was first operated in July 1967. Operation of the unit has been very satisfactory as evidenced by the fact that nearly 180 standard 5-1/4-hr tests have been completed in 19 months. The only major problem in the program has been the lack of good reproducibility in weight of deposits for some coals. Usually, a minimum of two tests are made with each coal, and it is not unusual to find variations in deposit weights for replicate tests of from 20 to 40 percent for some of the high-fouling coals. These differences cannot be attributed to variations in the coal. Each coal sample is carefully riffled before a test series is started, and analysis of the coals for individual runs using the same coal show excellent reproducibility. Much attention is paid to reproducing furnace conditions, such as gas temperature, excess air, and ratio of primary, secondary, and tertiary air. The factor that is most suspect of not being reproducible for the various runs is the condition of the furnace wall at the beginning of each test. To insure good turbulence and carbon burnout in the combustion zone, tangential tertiary air jets are used to impart a strong swirl to the flame. This causes some of the flame to sweep the furnace wall and results in a subsequent buildup of ash on the wall. The amount of ash deposited on the probe banks should be directly related to the dust loading of the gas passing over the tubes for any given coal. The more ash collecting on the furnace walls, the less there will be available to deposit on the probes. During the early part of the program, the furnace walls were cleaned only every five to 10 runs; however, for the last

50 runs, the furnace bottom has been taken off and the walls cleaned after each run.

Quite early in the program, a carload of lignite was obtained from the North Beulah mine in Mercer County, North Dakota. This sample is referred to as "Beulah Standard" lignite and has been used extensively to study reproducibility. It has also been used to study other variables such as gas temperature and chemical additives.

There is evidence to indicate that cleaning the furnace walls after each test does improve reproducibility, but it is still not good enough to show the effects of small changes in ash analysis. Occasionally, the ash on the furnace walls will become molten during a test. When this occurs, more ash is trapped on the walls and the probe deposit weights are reduced. Efforts to reduce the wall effect by reducing flame swirl have not been very successful to date because this results in reduced turbulence and less coal burnout. Despite this reproducibility problem, much meaningful data has been obtained. Full-scale field tests using several of the same coals that were tested in the pilot-plant furnace indicate that relative fouling tendencies observed in the field were similar to those obtained using the test furnace.

Test Results--Fouling Studies

Relative Fouling Tendencies of Various Coals

Pertinent data for tests on 31 different coal samples are shown in table 5. The coals were obtained from nine different States and include 25 lignites, three subbituminous coals, and four bituminous coals. Samples with extremes in ash analysis were requested from the various mines; the analyses shown for any given mine should not be taken as necessarily representative.

The coals shown were all burned for the standard 5-1/4-hr test period; the data shown are the average for at least duplicated runs. Based on the weight of deposit collected on probe bank 1, each coal is ranked in terms of relative fouling potential by the following scale:

Deposit weight on probe bank 1	Relative fouling potential
Below 150 grams.....	Low
150-300 grams.....	Medium
Above 300 grams.....	High

Fifteen samples fell in the "low-fouling" category and eight each in the "medium-fouling" and "high-fouling" categories.

TABLE 5A. - Summary data from lignite ash fouling tests

Sample[1]	No. of tests	Dry coal rate, lb/hr	Moisture content as-fired, percent	Coal analysis, dry basis					Ash fusibility, ° F[2]			Coal ash analysis, percent										Relative fouling potential[3]
				Volatile matter, percent	Fixed carbon, percent	Ash, percent	Sulfur, percent	Heating value, Btu/lb	IT	ST	FT	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	Na_2O	K_2O	SO_3	
BAUKOL-NOONAN MINE, BURKE COUNTY, NORTH DAKOTA																						
BN-1	2	54.7	21	41.41	48.37	10.22	0.51	10,840	2,045	2,085	2,130	27.2	14.7	5.7	0.4	0.3	17.3	4.3	17.6	0.4	12.2	Medium
BN-3	3	52.9	27	41.40	48.83	9.77	.54	11,120	2,110	2,160	2,205	32.0	16.4	6.2	.4	.3	19.3	5.3	7.9	.3	11.9	Do.
BN-U	2	47.6	28	41.95	49.09	8.97	.53	10,990	2,120	2,165	2,210	29.3	14.7	7.0	.4	.3	20.3	5.1	8.5	.5	14.1	High
BAUKOL-NOONAN MINE, OLIVER COUNTY, NORTH DAKOTA																						
C-1	2	53.6	30	45.68	46.52	7.81	0.85	10,950	2,415	2,455	2,495	18.3	11.3	11.1	0.3	0.3	27.9	8.9	1.9	0.3	19.8	Low
BEULAH MINE, MERCER COUNTY, NORTH DAKOTA																						
B-1	4	57.5	25	43.24	44.71	12.05	1.82	10,360	2,235	2,285	2,340	17.9	12.8	15.8	0.4	0.1	20.9	5.3	1.1	0.2	25.5	Low
B-2	4	57.2	28	39.63	48.57	11.80	1.31	10,490	2,085	2,130	2,180	19.9	9.8	9.3	.4	.3	19.0	6.8	9.4	.4	24.8	High
B-HL	4	52.7	30	41.81	47.75	10.44	1.35	10,760	2,250	2,310	2,360	17.8	11.5	9.6	.4	.4	22.4	7.0	5.1	.4	25.5	Medium
B-STD	8	52.0	30	41.55	47.71	10.73	1.03	10,550	2,220	2,270	2,315	20.2	11.3	9.8	.4	.5	21.8	8.0	6.3	.3	21.4	High
PEERLESS MINE, BOWMAN COUNTY, NORTH DAKOTA																						
G-1	3	53.7	32	42.70	44.92	12.38	1.47	10,570	2,240	2,280	2,325	24.6	13.4	7.0	0.4	0.3	21.7	8.4	3.2	0.3	20.7	Medium
GLENHAROLD MINE, MERCER COUNTY, NORTH DAKOTA																						
GH-1	2	52.9	31	44.23	47.34	8.34	0.94	11,000	2,220	2,260	2,295	16.1	8.8	12.2	0.4	0.1	22.3	5.5	9.6	0.5	24.5	Medium
GH-2	2	51.9	33	44.31	46.84	8.85	.68	10,820	2,210	2,240	2,270	21.6	9.7	8.0	.3	.1	25.3	6.1	9.9	.6	18.7	High
GH-3	2	52.7	30	43.69	44.99	11.33	.86	10,530	2,115	2,145	2,175	35.1	12.1	7.2	.5	.1	17.0	4.5	6.9	1.0	15.6	Do.
GH-4	1	51.5	32	43.51	47.66	8.83	.90	11,090	2,140	2,190	2,280	17.2	8.0	11.0	.3	.2	24.0	6.0	11.5	.5	21.3	Do.
GH-5	2	51.6	27	44.28	46.67	8.64	.74	10,830	2,055	2,110	2,160	27.1	11.6	5.1	.4	.2	21.6	6.2	9.3	.8	17.8	Do.
INDIAN HEAD MINE, MERCER COUNTY, NORTH DAKOTA																						
Z-2	2	50.3	27	41.10	47.19	11.71	1.37	10,790	2,095	2,140	2,185	19.8	11.6	9.0	0.3	0.8	22.6	6.2	7.6	0.3	21.9	High
VELVA MINE, WARD COUNTY, NORTH DAKOTA																						
V-1	4	55.8	32	41.72	51.27	7.01	0.30	10,780	2,540	2,580	2,615	13.4	7.9	6.7	0.2	0.2	39.2	10.4	7.8	0.4	13.8	Low
V-2	3	58.3	29	38.37	50.22	11.41	.29	10,100	2,340	2,385	2,425	33.1	14.3	4.0	.5	.1	32.2	6.2	2.8	.2	6.5	Medium
V-3	2	56.9	31	40.96	50.18	8.85	.33	10,580	2,455	2,490	2,525	22.3	10.1	6.6	.4	.4	39.2	9.5	1.4	.3	9.8	Low
V-4	2	52.3	34	42.18	49.51	8.32	.36	10,870	2,425	2,470	2,515	24.4	11.1	6.3	.4	.2	32.9	8.0	4.0	.5	12.2	Low
SAVAGE MINE, RICHLAND COUNTY, MONTANA																						
S-1	3	53.9	34	40.98	47.26	11.77	1.04	10,230	2,250	2,300	2,350	21.3	13.0	10.0	0.3	0.8	22.7	9.3	0.4	0.3	21.9	Low
S-2	3	54.9	30	42.18	44.03	13.78	.80	10,230	2,050	2,100	2,150	35.7	20.3	5.3	.6	.6	16.4	7.0	.4	.9	12.8	Low
PIKE COUNTY, ALABAMA																						
ALA-1	1	48.6	43	42.11	42.40	15.48	4.01	10,130	2,250	2,300	2,350	27.6	20.7	4.3	0.4	0.1	12.2	10.1	0.3	0.1	24.2	Low
ROCKDALE, TEXAS																						
TEX-1	2	59.2	28	44.23	37.85	17.92	1.86	10,540	2,070	2,120	2,170	39.3	17.8	7.3	1.4	0.2	16.3	1.7	0.2	0.1	15.6	Medium
MALOKOFF, TEXAS																						
TEX-2	2	49.9	32	44.88	47.10	8.02	0.75	11,340	2,095	2,145	2,195	25.5	14.3	11.9	1.0	0.1	20.7	6.2	0.8	0.2	19.2	Low

TABLE 5B. - Summary data from subbituminous coal ash fouling tests

CENTRALIA, WASHINGTON																					
CEN-1	3	54.6	17	41.69	45.69	12.61	0.57	11,240	2,250	2,300	2,350	46.2	25.7	6.1	3.7	1.3	9.6	1.5	0.5	0.2	5.2	([4])
COLSTRIP, ROSEBUD COUNTY, MONTANA																					
CS-1	2	44.4	21	39.86	50.40	9.74	0.84	11,620	2,190	2,220	2,250	35.4	19.0	5.6	0.8	0.3	17.8	4.4	0.3	0.1	16.3	Low
GLENROCK, WYOMING																					
GR-1	2	49.2	22	45.43	44.59	9.98	0.82	11,110	2,120	2,155	2,190	30.5	15.7	6.6	0.6	0.4	25.5	3.7	0.3	0.5	16.4	Low

TABLE 5C. - Summary data from bituminous coal ash fouling tests

MINE NO. 10, CHRISTIAN COUNTY, ILLINOIS																					
ILL-1	2	46.3	12	39.73	43.74	16.53	4.99	11,540	1,905	1,945	1,985	43.7	17.0	21.3	0.5	0.3	7.0	1.0	1.5	1.4	6.1	Medium
RIVER KING MINE, ST. CLAIR COUNTY, ILLINOIS																					
ILL-2	2	51.2	8	37.05	42.55	20.41	5.32	11,130	1,965	2,030	2,100	47.6	17.6	19.2	0.9	0.4	6.1	2.2	0.5	1.6	3.8	Low
SUNNYSIDE MINE, CARBON COUNTY, UTAH																					
SS-1	2	41.4	4	39.90	54.06	6.05	0.74	13,860	2,445	2,500	2,555	59.2	24.6	4.5	1.1	1.7	4.6	0.4	1.1	0.3	2.5	Low
ARKWRIGHT MINE, MONONGALIA COUNTY, WEST VIRGINIA																					
ARK-1	1	37.0	1	38.24	54.83	6.93	2.13	14,020	2,140	2,190	2,270	44.8	29.4	15.4	0.5	0.3	4.2	1.0	0.8	0.5	3.7	Low

[1] Spot samples, not necessarily representative of mine.

[2] Standard Method of Test for Fusibility of Coal and Coke Ash, ASTM Designation D 1857-68. Initial deformation temperature--IT, Softening temperature--ST, Fluid temperature--FT. ASTM Standards, Gaseous Fuels; Coal and Coke, Part 19, March 1969, American Society for Testing and Materials. Philadelphia, Pa., pp. 331-336.

[3] Based on weight of deposit collected on probe bank I during standard test:

Weight, grams	Rating
0-150	Low
150-300	Medium
Above 300	High

[4] During test ash built on refractory duct walls and eventually bridged across tubes. Ash did not appear to bond much to the metal tubes.

One of the original program objectives was to develop a correlation between the individual ash constituents and the rate of fouling in a test furnace as Garner[6] has done in a similar test program in Australia. However, the reproducibility of results has been such that the effect of small changes in ash composition cannot be determined with a high degree of confidence. By far the most obvious correlation in the 31 tests reported is between the sodium content of the ash and the rate of fouling. Typical probe deposits from high- and low-sodium lignites are shown in figures 31 and 32. With one exception, all of the coals having less than 1 percent sodium oxide in the ash were low fouling. The exception was the Rockdale, Tex., lignite which had an unusually high (39 percent) silica content for a lignite and fell into the medium-fouling category. With one exception, none of the coals having more than 3 percent sodium were rated as low fouling. The exception was the North Dakota Velva lignite which has unusually high-calcium content. Coals having large differences in moisture, ash, sulfur, ash fusion temperature, and ash analysis were included in the test program; however, none of these factors appear to be nearly as important with regards to ash fouling as the sodium content.

Figure 33 shows the relationship between sodium content and rate of fouling for lignites from the Beulah mine. This ash has a calcium content of about 20 percent, which is about average for North Dakota lignites. The fouling rate tends to level off as the sodium content reaches 8 to 10 percent. This "saturation effect" has been noted for other lignites also; for example, tests have shown that the rate of fouling may be no higher for a lignite having 25 percent sodium than for one having 8 percent.

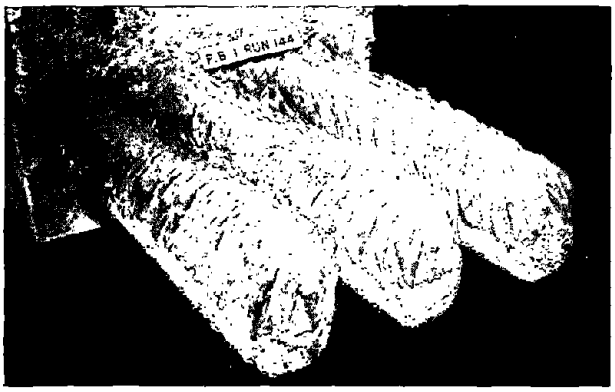
Effect of Calcium Content

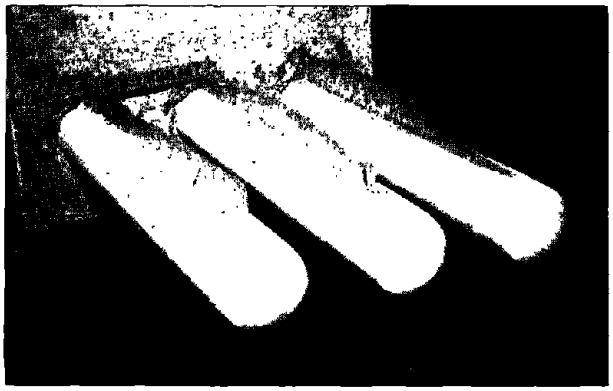
Included in figure 33 is the deposition rate for a high-calcium lignite as a function of sodium content. The Velva lignite ash contains as much as 40 percent or more calcium, which is twice that found in most other North Dakota lignites. At the higher sodium levels, the fouling rate with this high-calcium lignite was only about half as great as that obtained with a normal calcium content lignite. The Velva coal has a lower ash content, but even when the results are calculated to an equal ash input basis, the rate of fouling is lower for the high-calcium coal. These results would indicate that in North Dakota lignites, high-calcium content tends to reduce the effect of sodium on the deposition mechanism. The ash fusion temperature is, of course, consistently higher for the high-calcium coal; however, evaluation of the test results do not, in general, show good correlation between ash fusion temperature and rate of fouling.

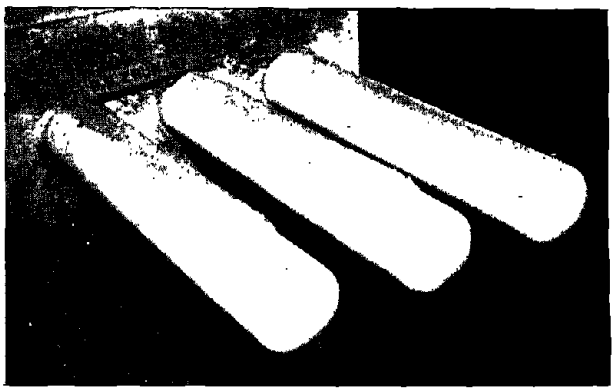
Changing Sodium Content by Treatment of Lignite

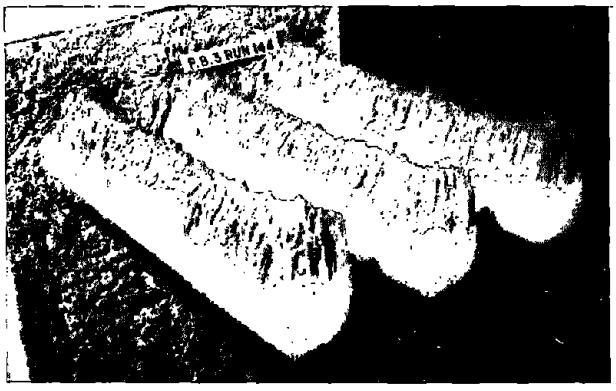
Some of the high-sodium lignites were subjected to ion-exchange treatment by washing with calcium-containing tapwater; the treated samples were burned in the test furnace. As shown in table 6, it was found that the fouling rate for the ion-exchanged lignite now having 1 percent sodium was about the same as for a natural lignite having the same sodium content. The original sodium

[6]Garner, L. J. The Formation of Boiler Deposits From the Combustion of Victorian Brown Coal. J. Inst. Fuel, v. 40, No. 314, March 1967, pp. 107-116.









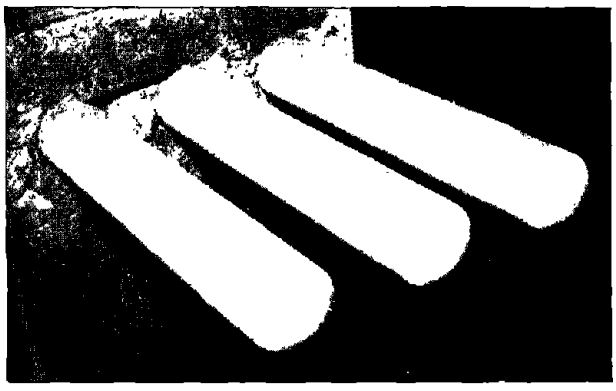


FIGURE 31. - Typical Probe Deposits From a High-Fouling (9.7 Percent Na_2O in Ash) Lignite. Deposit weight probe bank 1 = 362 grams.

FIGURE 32. - Typical Probe Deposits From a Low-Fouling (0.6 Percent Na_2O in Ash) Lignite. Deposit weight probe bank 1 = 35 grams.

level was then restored to the ion-exchanged sample by adding sodium bicarbonate; the fouling rate corresponded to that of the original high-sodium sample. Sodium-containing chemicals were added to other lower sodium lignites,

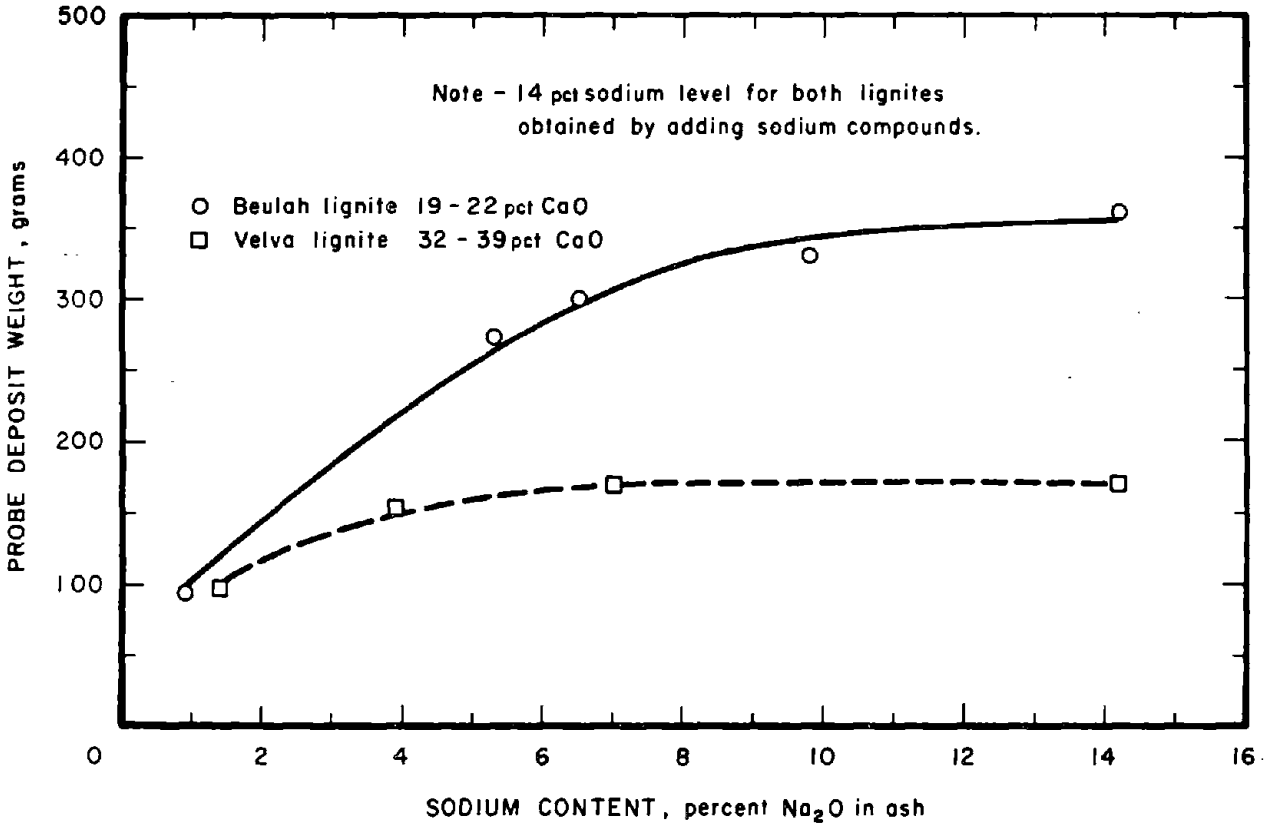


FIGURE 33. - Comparison of Fouling Rates Between High- and Normal-Calcium Lignites as a Function of Sodium Content.

subbituminous, and bituminous coals; in every instance, the result was a dramatic increase in the rate of fouling.

TABLE 6. - The effect of sodium removal and addition on fouling rate for various coals

Coal burned	Na_2O in ash, percent	Deposit weight on probe bank 1, grams
Beulah natural low-sodium lignite.....	1.1	118
Beulah natural high-sodium lignite.....	6.3	399
Beulah natural high-sodium lignite treated by ion exchange.....	1.0	127
Above sample plus $NaHCO_3$ to restore sodium	6.7	438
Savage natural low-sodium lignite.....	.4	36
Above sample plus $NaNO_3$.....	8.0	345
Glenrock natural low-sodium subbituminous.	.3	15
Above sample plus $NaNO_3$.....	8.7	469
Illinois natural low-sodium bituminous....	.5	<50
Above sample plus $NaHCO_3$.....	4.9	1,800

Additives to Lignite

To reduce fouling problems from burning high-sodium lignites, the following alternatives could be considered:

1. Burn low-sodium lignite.--Unfortunately, it appears that the chances of finding large reserves of low-sodium lignite in the Northern Great Plains area are not good.

2. Remove the sodium from the lignite before combustion.--The only known method of doing this is by ion exchange because the sodium is bound to the organic structure of the coal and cannot be separated by mechanical means or removed readily by water washing. Research is continuing to determine possible practicability of an ion-exchange process.

3. Improve boiler designs to tolerate higher fouling coals.--This will undoubtedly result in more expensive boilers.

4. Add material to the fuel which will alter the ash fouling mechanism.--Part of this program has been a study of the effect of various chemical additives on the quantity and quality of the ash deposits when burning "Beulah Standard" lignite for the standard test time. Since test lengths were only 5-1/4 hours, it was felt that high addition rates should be used to detect the effects. It is, of course, open to question whether this approach gives a realistic picture of the effects that might be obtained at much lower addition rates over long periods in a commercial boiler. The results of the additive tests are given in table 7. Of the seven additives tested, kaolin appeared to be the most effective in reducing strength and deposit weight. However, none of the additives was as effective in reducing deposit weight as was a reduction of sodium content from 6 to 1 percent.

Effect of Other Variables

Other factors which might affect the ash fouling rate were also studied using the "Beulah Standard" lignite. These were percentage of excess air, tube metal temperature, lignite moisture content, test length, and gas temperature at the probe bank.

Tests were run at excess air levels of from 5 to 50 percent. Within the limits of reproducibility, no effect on fouling could be established. Likewise, no significant effect was found when the lignite moisture content was reduced to 20 or 15 percent, as compared with the normal 30 percent as-fired.

In other tests, the probe metal temperatures were varied from 800° to 1,200° F. The total deposit rate shows a moderate increase over this temperature range (fig. 34). As demonstrated previously,[7] the inner white layer reduces in quantity as the tube temperature increases.

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[7]Work cited in footnote 4.

TABLE 7. - Selected data from tests using various additives to "Beulah Standard" lignite

	Additive							
	None	Calcium chloride ($CaCl_2$)	Sodium chloride (NaCl)	Sand (SiO_2)	Kaolin ($Al_2O_3 \cdot 2H_2O \cdot 2SiO_2$)	Lime (CaO)	Calcium carbonate ($CaCO_3$)	Dolomite ($CaCO_3 MgCO_3$)
Additive rate, lb/100 lb coal.....	0	2	2	2	2	2	2	2
Analysis of coal ash including additive, percent:								
SiO_2.....	20.2	19.1	19.5	36.6	26.5	16.6	17.1	20.0
Al_2O_3.....	11.3	11.2	11.2	8.7	17.4	9.3	10.0	10.3
Fe_2O_3.....	9.8	8.7	9.6	9.2	8.1	8.9	8.4	9.0
CaO.....	21.8	30.2	20.3	16.4	17.5	32.8	30.2	26.5
MgO.....	8.0	5.9	7.1	5.8	6.2	6.4	7.3	11.7
Na_2O.....	6.3	4.6	10.2	5.0	4.8	5.8	5.9	5.6
SO_3.....	21.4	18.9	20.2	17.3	18.3	19.5	20.1	15.4
Ash softening temperature.....° F..	2,270	2,500	2,250	2,140	2,180	2,500	2,450	2,480
Deposit weight, grams:								
Probe bank 1.....	405	333	432	265	195	495	400	332
Probe bank 2.....	224	257	418	119	138	352	301	216
Probe bank 3.....	91	152	273	76	66	125	128	47
SO_2 in flue gas....ppm..	460	400	800	400	600	50	300	400
Bulk deposit strength...	Normal	Weaker[1]	Normal[2]	Stronger	Weaker	Weaker	Normal	Normal

[1]Hard inner layer on tube and severe corrosion to number 304 stainless steel tube.
[2]Heavy crystalline inner layer on tube, identified as mostly sodium chloride.

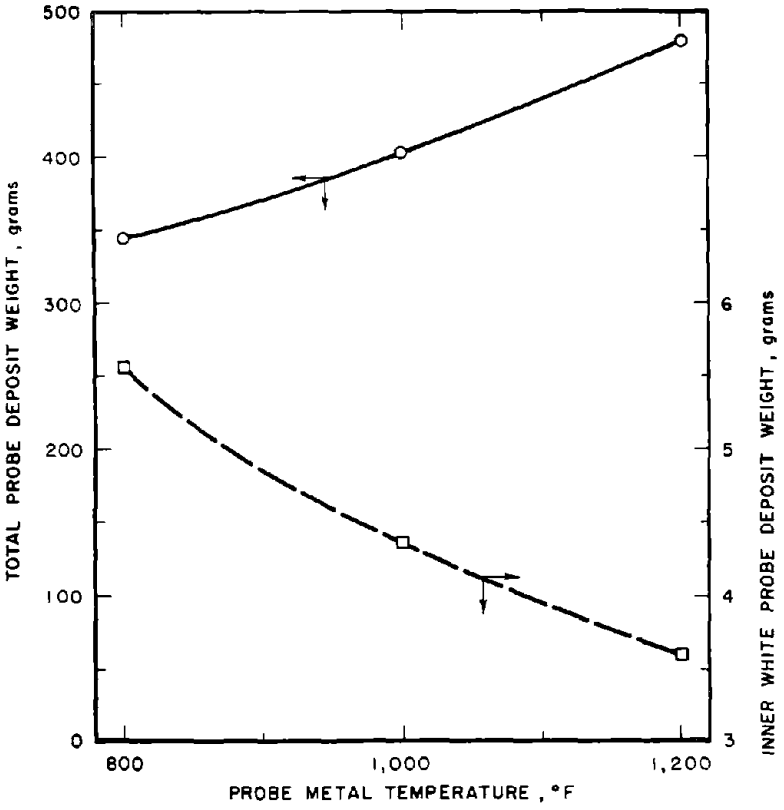

FIGURE 34. - Deposit Rate as a Function of Tube-Metal Temperature.

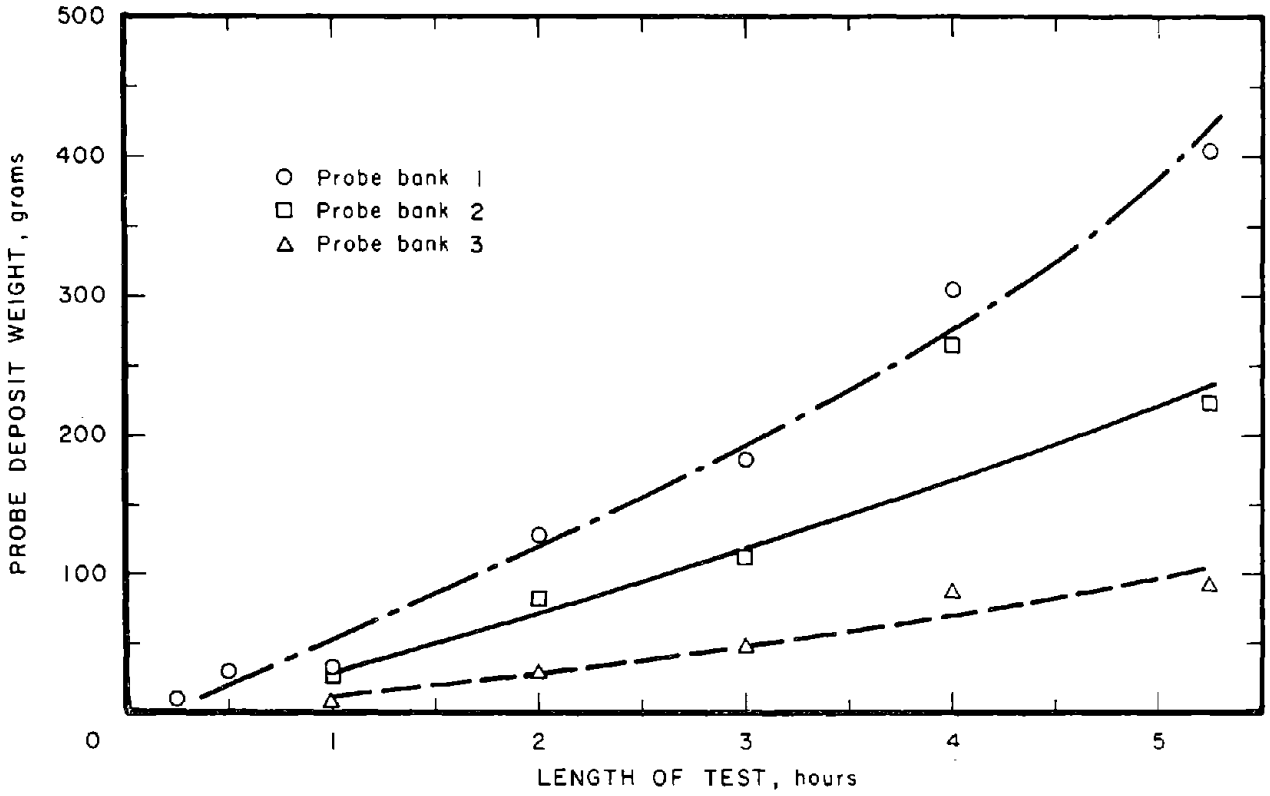

FIGURE 35. - Deposit Rate as a Function of Test Time.

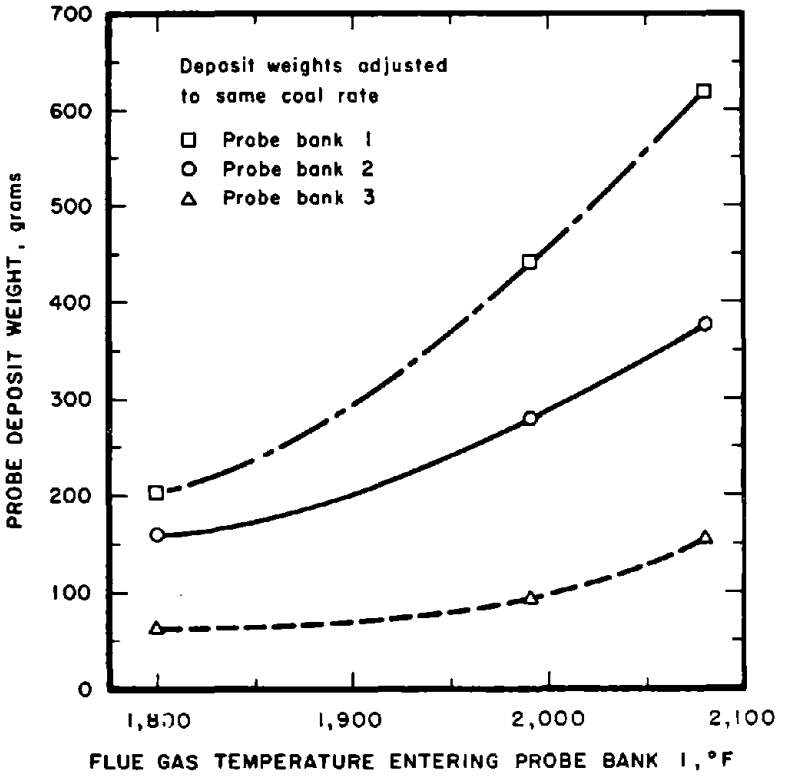

FIGURE 36. - Deposit Rate as a Function of Gas Temperature.

Figure 35 shows the rate at which the deposit builds over a 5-1/4-hr period at standard conditions. These data were obtained by bringing the furnace up to temperature, cleaning the probe banks, and then running the different test periods with a hot furnace, cleaning the probes after each period. As indicated, the fouling rate is nearly linear over the 5-hr test time.

In other tests the gas temperature entering the first probe bank was varied over the range of about 1,800° to 2,100° F and the deposit rate determined. Since the gas temperature change was produced by varying the feed rate, the results were all corrected to the same coal rate before being plotted in figure 36. The effect of increasing gas temperature is very pronounced, as indicated by the threefold increase in the deposit rate over this temperature range. These results are logical since the gas temperature is approaching the ash softening temperature. Obviously, it is important to keep the furnace walls reasonably clean in a commercial boiler so that gas temperatures entering the tube banks are a safe margin below the ash softening temperature.

Air Pollution Studies

The pilot-plant furnace is also being used to obtain data relating to the air pollution aspects of lignite combustion. This work includes determination of sulfur dioxide and sulfur trioxide in the flue gas and a study of the factors affecting electrostatic precipitation of fly ash from low-sulfur coals.

Sulfur Oxide Data

The SO_2 and SO_3 in the 700° F flue gas was determined by the selective condensation[8] technique, and the SO_2 was independently determined using calorimetric indicator tubes. In addition, gravimetric total sulfur determinations

[8] Lisle, E. S., and J. D. Sensenbaugh. The Determination of Sulfur Trioxide and Acid Dew Point in Flue Gas. Combustion, v. 36, No. 7, January 1965, pp. 12-15.

were made occasionally to check against the total sulfur in the SO_2 and SO_3. A continuous infrared SO_2 analyzer having ranges of 0 to 700, 0 to 2,500, and 0 to 5,000 ppm has also been installed.

Selected data on gaseous sulfur oxide emissions from the pilot-plant furnace burning various coals are given in table 8. The sulfur content of the coals ranged from 0.3 to 5.3 percent (on a dry basis), and the resulting SO_2 content in the flue gas ranged from 40 to about 4,000 ppm. The SO_3 concentrations ranged from 3 to 70 ppm. Significantly, no measurable SO_3 has yet been detected when burning North Dakota lignite, even though SO_2 concentrations have been as high as 1,400 ppm. The literature indicates that for bituminous coals burned at normal excess-air levels, the SO_3 is usually 1 to 2 percent of the SO_2; we obtained similar results when burning bituminous coals. The reason for the absence of SO_3 when North Dakota lignites are burned is not clear, although the lower flame temperatures of these high-moisture lignites may be a factor. In addition, the ash from these coals may not have the same catalytic effect for converting SO_2 to SO_3.

TABLE 8. - Selected data on gaseous sulfur oxide emissions from the pilot-plant furnace

Coal burned	Na_2O in ash, percent	Sulfur, percent of moisture-free coal	Sulfur oxides in flue gas		Percent of input sulfur as $SO_2 + SO_3$ in gas	Total alkali in coal ash, percent sum of CaO, MgO, Na_2O, and K_2O	SO_3 concentration in fly ash, percent
			SO_2, ppm	SO_3, ppm			
LIGNITES							
B-1	1.1	1.77	1,400	<1	94	27	9
B-STD	6.3	1.03	460	<1	51	35	11
B-2	9.4	1.24	700	<1	62	36	16
GH-5	9.3	.74	250	<1	40	37	9
V-3	1.4	.32	100	<1	36	51	3
V-1	7.8	.30	40	<1	15	57	8
G-1	3.2	1.47	1,100	<1	82	34	3
S-2	.4	.80	850	<1	100+	24	1
TEX-1	.2	1.86	1,150	6	70	18	1
ALA	.2	4.01	3,000	20	84	23	4
SUBBITUMINOUS							
CEN-1	0.5	0.57	350	<1	66	12	2
CS-1	.3	.84	500	<1	77	23	2
BITUMINOUS							
ILL-1	1.5	5.0	2,900	40	76	10	4
ILL-2	.5	5.3	4,070	70	94	9	1
SS-1	1.1	.74	485	6	94	6	1
ARK-1	.8	2.13	1,000	3	77	6	3

[9] Smith, W. S., and G. W. Gruber. Atmospheric Emissions From Coal Combustion--An Inventory Guide. U.S. Public Health Service, Pub. No. 999-AP-24, April 1966, 112 pp.

Also shown in table 8 is the percentage of input sulfur which is converted to gaseous sulfur oxides. In general, the higher alkali coals tend to show less percentage conversions of the sulfur to gaseous sulfur oxides and a higher percentage of SO_3 in the fly ash collected in the mechanical dust collector. Because of this effect, lignites should show an advantage over most bituminous coals, in terms of sulfur oxide emissions, when the two are compared on an equal sulfur input per million Btu basis.

Electrostatic Precipitation

Because there are currently no electrostatic precipitators operating on North Dakota lignite, and because of known problems in precipitating low-sulfur fuels,[10] a program was started to study electrostatic precipitation in conjunction with the ash fouling studies. Since no commercial units meeting the size requirements could be found, a special unit was designed by Precipitair Pollution Control, Inc., and built and installed by the Bureau of Mines. Figure 37 shows the precipitator with a side panel removed. Some of the principal specifications for the precipitator are given in table 9. As shown in figure 27, all or part of the flue gas can be diverted through the electrostatic precipitator, and the mechanical separator can be either used or bypassed.

TABLE 9. - Specifications for pilot-plant electrostatic precipitator

(Designed by Precipitair Pollution Control, Inc.)

Mechanical data:	
Plate type, parallel gas paths	3
Plate spacing, in	6
Total plate area, sq ft	48
Cross-sectional area at plates, sq ft	3.0
Design capacity, cfm	250
Specific collecting area, sq ft/1,000 cfm	192
Design gas velocity, fps	0.4
Predicted efficiency (maximum), percent	99.6
Electrical data:	
Number of transformer-rectifiers	2
Primary voltage	208
Secondary voltage (negative half-wave)	0-35,000
Secondary amperage	0.035
Output power, kva	1.2

Installation of the electrostatic precipitator was just recently completed and no detailed test results are available; however, preliminary tests indicate that precipitation is being achieved on "Beulah Standard" fly ash at a voltage of 33,000 and with a 400° F gas temperature.

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[10] Ramsdell, Roger G., Jr. Design Criteria for Precipitators for Modern Central Station Power Plants. Proc. Am. Power Conf., v. 30, 1968, pp. 444-449.

FIGURE 37. - Pilot-Plant Electrostatic Precipitator With Side Panel Removed.

The test program planned for the electrostatic precipitator includes investigation of the following variables:

1. Sulfur content of the coal.
2. Ash analysis.
3. Gas velocity.
4. Gas temperature.
5. Electrode voltage.
6. Quantity and size of fly ash.
7. Additives.
8. Specific collecting area.

Summary and Conclusions

The pilot-plant furnace being used to study ash fouling and air pollution problems has proven to be a reasonably good model of a commercial pc-fired boiler. We now have a tool that can be used to evaluate fouling tendencies of coals from new mining areas in advance of commercial experience and a means of evaluating some proposed methods of handling high-fouling coals.

After a 19-month furnace test of coals having widely different ash characteristics, the following conclusions are reached:

1. By far the most important single factor in relative fouling potential of the coals tested is the sodium content of the ash. Fouling rate increases rapidly with sodium content up to about 8 to 10 percent Na_2O in ash. At this level a "saturation effect" seems to occur, and further increases in sodium content up to 25 percent have little effect on the deposit rate.

2. The North Dakota lignite having a 40-percent calcium content in the ash showed significantly lower fouling for the same sodium content than other lignites having a 20-percent calcium content.

3. Next to sodium content, the most important factor in ash deposition rate is the flue-gas temperature at the deposition area.

4. Various chemical additives were tried as a means of reducing deposit rate and strength. Some beneficial effects were noted but none were nearly as effective as reducing sodium content from 6 to 1 percent.

5. The level of excess air and the moisture content of the lignite were found to have little effect on rate of fouling, but increasing tube metal temperature from 800 to 1,200 noticeably increased the fouling.

6. Lack of good reproducibility of deposit rates for some moderate- to high-fouling coals has been a problem and this reduces the possibility of determining significant effects for small variations in ash composition.

7. Air pollution studies showed that for North Dakota lignites the percentage of the input sulfur that appears as gaseous sulfur oxides in the stack gas varies with the sulfur level and alkali content of the coal, but normally it is considerably lower than that for bituminous coals.

8. No measurable SO_3 has been found in the flue gas when burning North Dakota lignites, although SO_2 levels have been as high as 1,400 ppm.

Installation of a pilot-plant electrostatic precipitator has been completed, and a program is planned for studying the variables affecting precipitation of fly ash from low-sulfur coals.

The ash fouling studies will be continued in an effort to find ways and means of reducing the problem resulting from combustion of high-fouling coals. Increased efforts will be made to further understand the ash fouling mechanism.

EXAMINATION OF COAL AND COAL ASH BY X-RAY TECHNIQUES

By W. Beckering,[1] H. L. Haight,[2] and W. W. Fowkes[3]

Introduction

One of the major research programs at the Bureau of Mines Grand Forks Coal Research Laboratory is the study of the mineral constituents in North Dakota lignites and their tendency to form troublesome deposits on heat transfer surfaces in commercial boilers. This paper will discuss laboratory research in the following areas related to the ash fouling program:

1. The physical and chemical nature of the mineral in the coal.

2. The reactions that can occur when the ash is subjected to the high temperatures of the combustion zone.

3. The reactions that may occur as the ash is carried by the gas stream from the combustion zone to the convection section of a boiler.

4. The mechanism by which the ash is transferred from the gas stream to the boiler tube.

The Grand Forks Coal Research Laboratory recently purchased X-ray diffraction equipment, an X-ray fluorescent spectrograph, and an electron microprobe to aid in examining and studying the ash fouling problem. The capabilities of these three instruments, especially the electron microprobe, make it possible to draw conclusions regarding the nature of the mineral matter in the lignite and the chemical composition of the boiler deposits. The X-ray equipment and their capabilities will be described, followed by our work on mineral matter in lignite and the examination of ash deposits.

X-Ray Equipment

The X-ray powder diffraction camera (fig. 38) is mounted on top of the X-ray generator adjacent to the copper X-ray tube. The 114.59-mm-diameter Debye-Scherrer camera is capable of identifying a mineral or crystalline compound uniquely by its diffraction pattern. It will also distinguish between two different crystalline forms of the same compound (alpha quartz and beta quartz, for example) which are impossible to distinguish by an elemental analysis. A hydrate of a compound has a different crystalline structure than does the anhydrous form and therefore can also be distinguished.

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[3]Project coordinator, Grand Forks Coal Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.

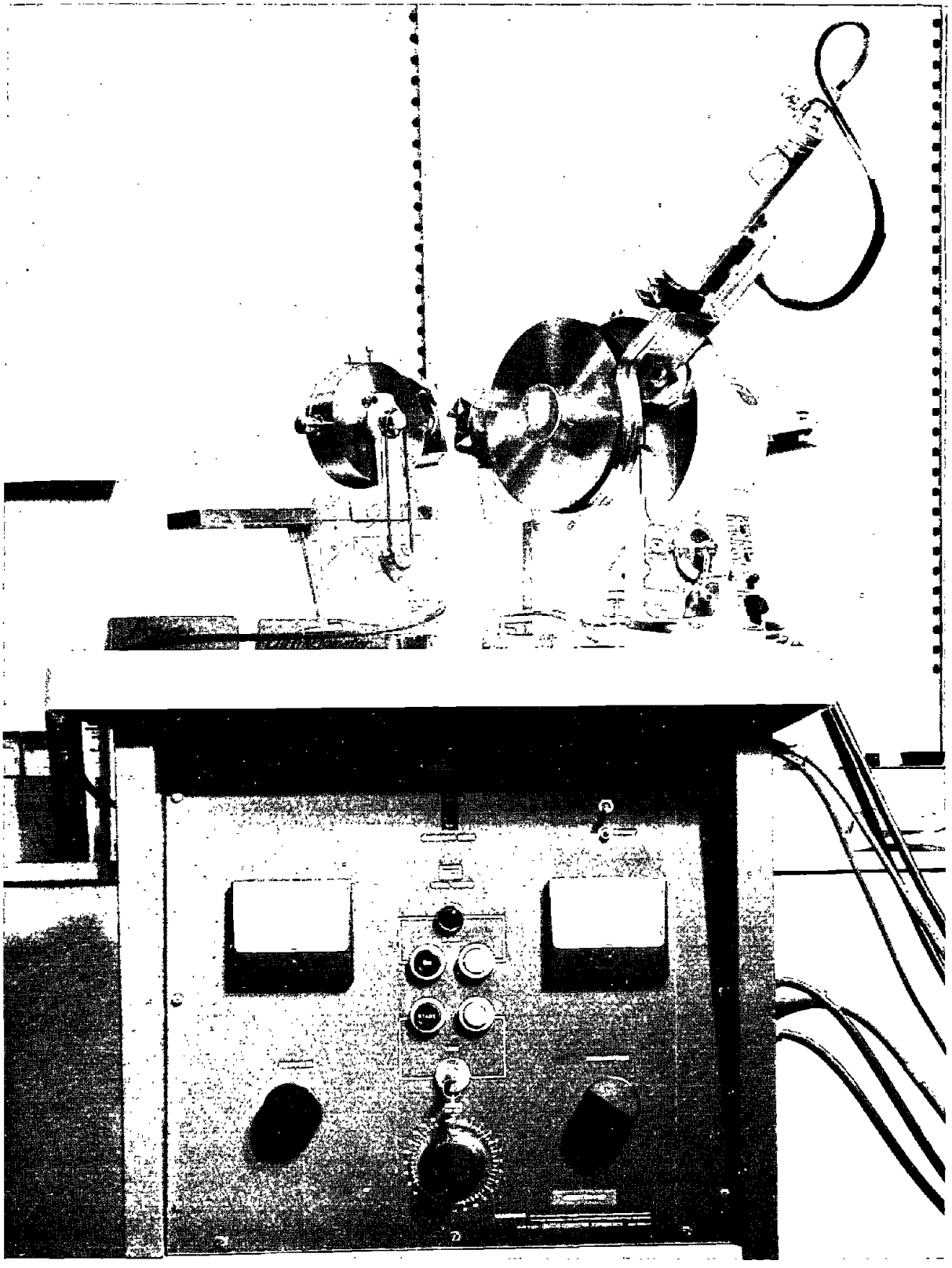

FIGURE 38. - X-Ray Diffraction Equipment.

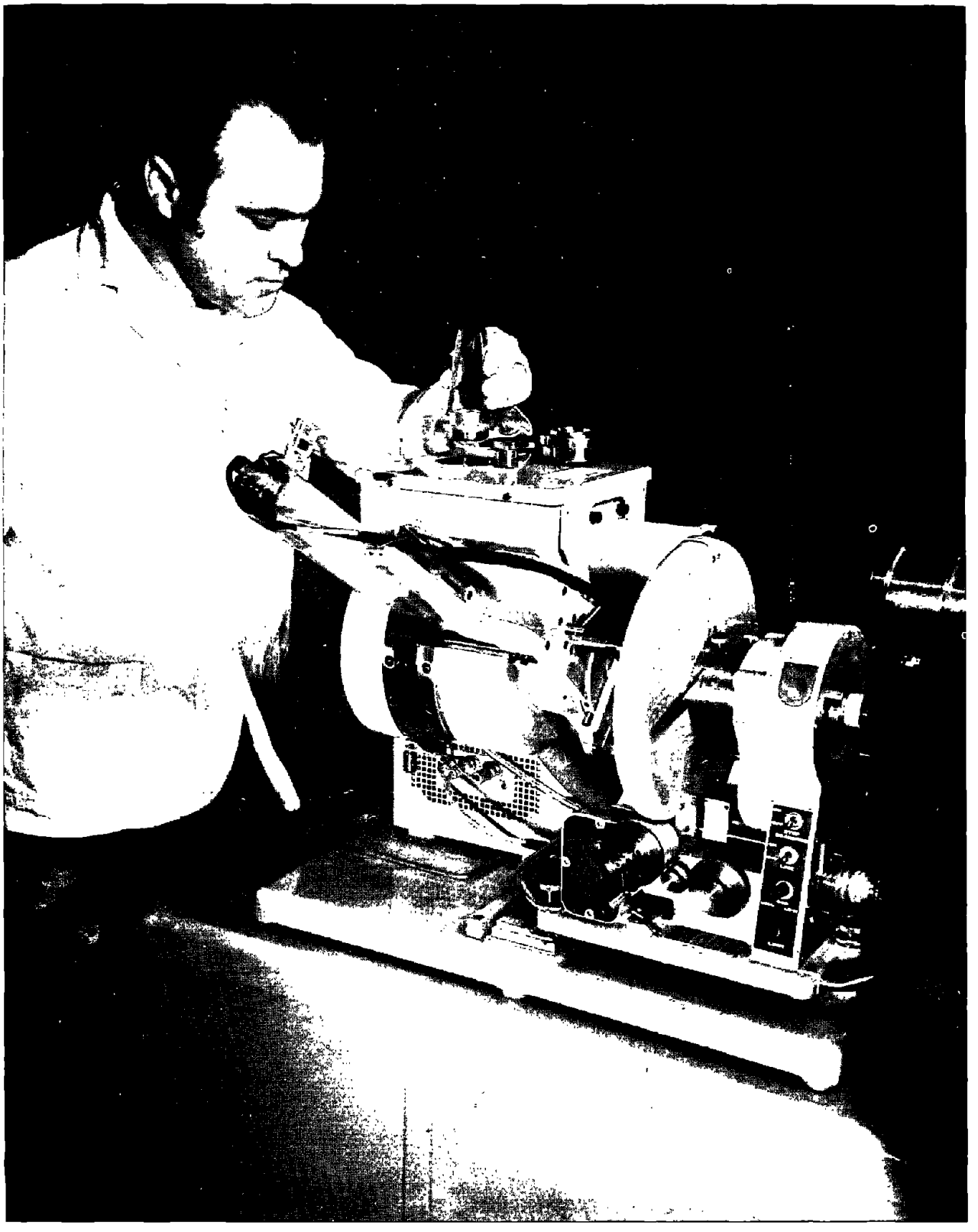

FIGURE 39. - X-Ray Fluorescent Equipment.

The X-ray fluroescent spectrograph (fig. 39) is capable of performing a rapid elemental analysis of ash. It can also analyze a sample of coal directly for the same elements. This makes it unnecessary to ash the sample at elevated temperatures, and therefore eliminates the possibility of volatilizing some of the components. The analysis is performed by radiating the sample with X-rays that excite the atoms in the sample. The atoms in the sample then reemit fluorescent radiation at wavelengths characteristic of the element. After being separated by the analyzing crystal, the different wavelengths strike the detector. The intensity of the output radiation appears in digital form on a readout panel and is directly proportional to the number of atoms of the element in the sample. One of the advantages of X-ray analysis is that it does not destroy the sample. About 3 grams of ash is required for a routine analysis.

Equipment used in conjunction with the electron microprobe is shown in figure 40. This instrument focuses a high-energy electron beam onto a spot less than 1 square micron in area; it possesses the capability of analyzing this small area for all the elements heavier than beryllium (which has the atomic number 4 in the periodic table). The stage holding the sample is

FIGURE 40. - Electron Microprobe Consol.

linked to an electric motor through a reduction gear box so that the sample can be advanced slowly beneath the electron beam. The rate of advance can be varied from 2.6 to 0.052 micron per second. By positioning the detector at the appropriate angle for a certain element, one can monitor the relative concentration of this element as the sample advances beneath the electron beam. For example, the concentration of sulfur in a boiler deposit can be monitored continuously from a point near the tube to the outer edge. The relative concentration of the element is recorded on a strip chart recorder. In addition to analyzing a 1-square-micron area or a narrow strip over the surface of a sample as described above, it is possible by using the beam scanner attachment (on the right side of fig. 40) to analyze a larger square area. The cross-sectional area that is being analyzed appears on the face of one of the oscilloscope tubes in the beam scanner. The largest area that can be analyzed at one setting is 320 microns square. Each of the elements in this cross section can be analyzed consecutively; one can observe the location of the element in this area and also its concentration. In four steps the magnification of the sample area can be varied from X 400 to X 2,400. The field of view will change correspondingly from 320 to 53.3 microns. The depth of analysis varies from 3 to 8 microns.

Figure 41 is a schematic diagram of the electron probe and beam scanner attachment. When the electron beam strikes the sample surface, some of the electrons are absorbed, producing a small amount of sample current; a certain

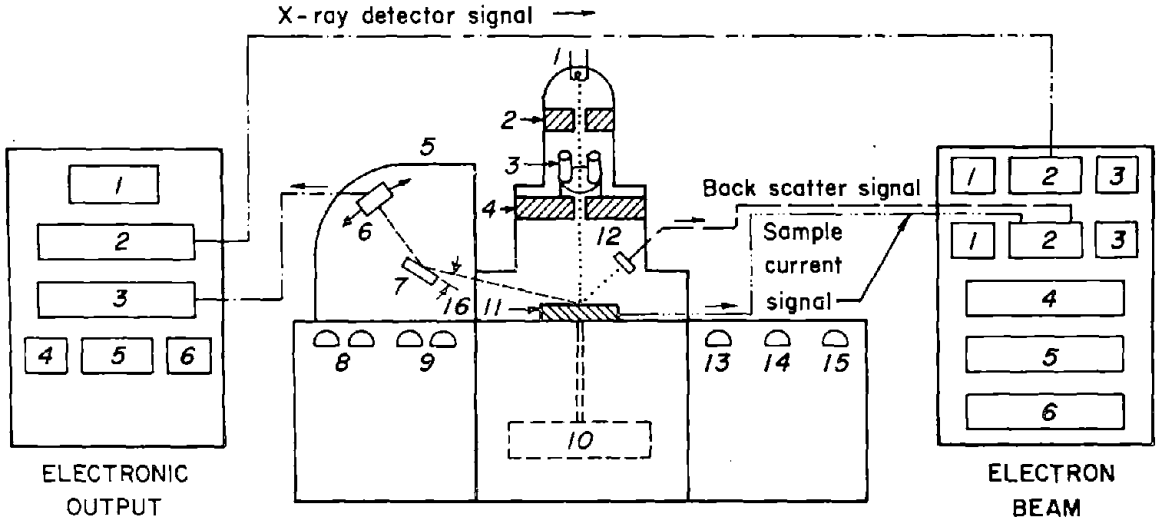

FIGURE 41. - Schematic Diagram of Electron Probe and Beam Scanner.

fraction of the electrons are reflected, producing a backscatter current. By monitoring the backscatter current with the beam scanner, one can have a topographical view of the sample. An example of a backscatter scan of a 200-mesh copper screen is shown in figure 42 at X 400 and X 800 magnification.

Examination of a sample of lignite or a boiler deposit with the electron microprobe requires imbedding the sample in an epoxy resin. This is done under vacuum conditions so that the voids in the sample will become impregnated with resin. In our work, we found Armstrong C-7 resin in conjunction with the Armstrong H-43 activator very satisfactory. After the sample is imbedded in the resin, it is polished by standard methods and the polished surface is then coated with a thin layer of carbon. The carbon layer enables the electrons from the electron beam to bleed rapidly away from the irradiated area of the sample. This is necessary for beam stability.

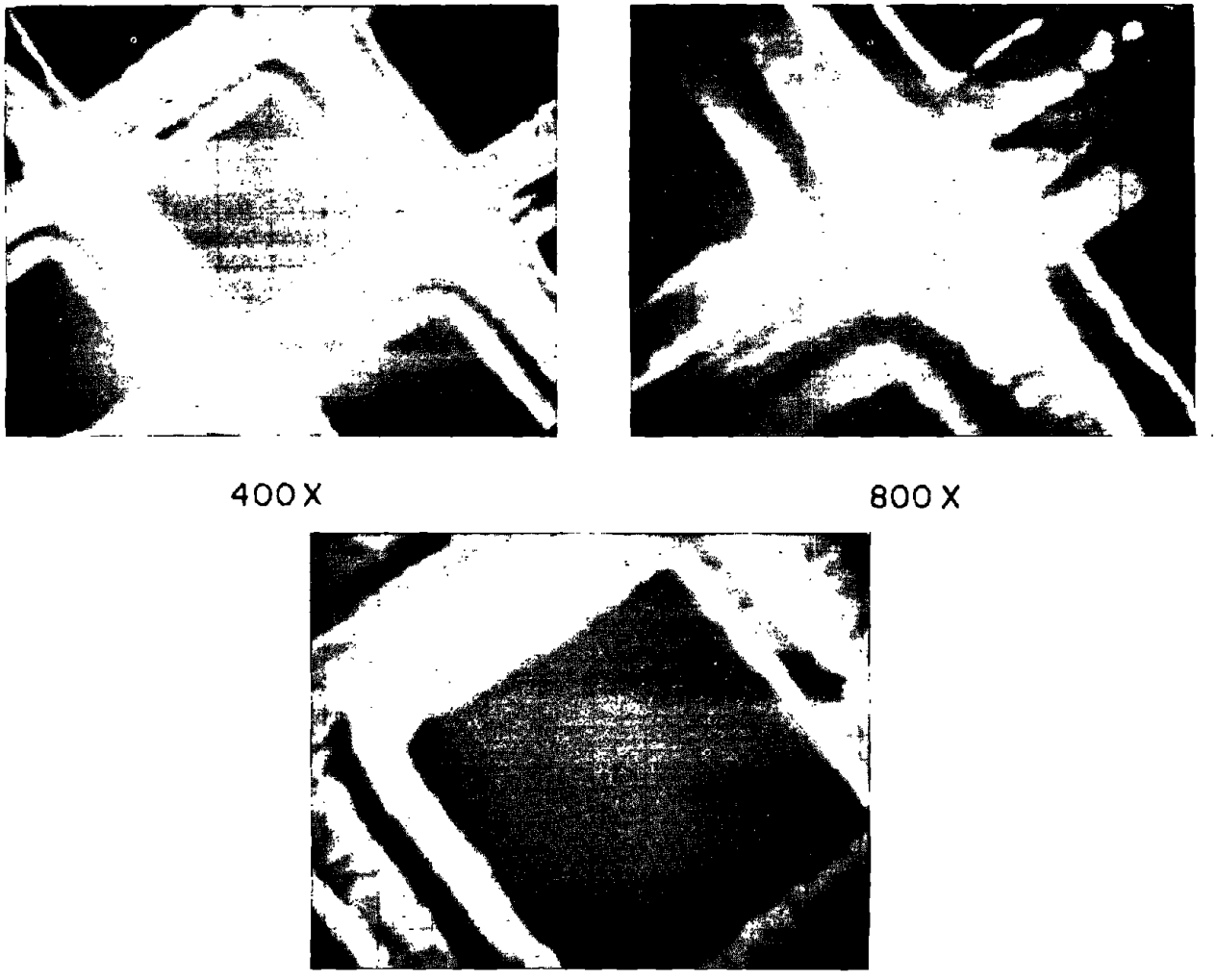

FIGURE 42. - Microprobe Scan of a 200-Mesh Copper Screen.

Mineral Matter in Lignite

In studying the fouling problem of lignites, one has at his disposal the starting material (lignite) and the end product (ash on the boiler tube). What happens between the time the fuel is burned and the ash is deposited on the boiler tube is not yet well known. Therefore, one of the requisites to a good understanding of the entire problem is a thorough study of the lignite as fed to the burner. The electron microprobe makes it possible to examine the lignite in much greater detail than was possible previously.

Earlier work at the Grand Forks Coal Research Laboratory on the separation and identification of minerals in lignite indicated only 12 to 15 percent of the ash could be separated by separation technique in carbon tetrachloride. Results from low-temperature ashing of lignite with microwaves also indicated few silicate minerals present in the lignite. If only a small part of the ash can be separated by usual physical methods, the question arises as to how and in what form does the major portion of the ash occur in lignite.

In an attempt to obtain additional information on this problem, several samples of different lignites were mounted in epoxy resin and examined using the microprobe. The automatic stage drive was set so that the sample advanced beneath the stationary electron beam at a rate of 0.26 micron per second. This procedure analyzes a narrow surface strip of the lignite 1 to 2 microns in width and several millimeters in length. One element at a time was analyzed in this strip. The same area was scanned for each element of interest. The intensity of the X-rays emitted by the element was directly proportional to the concentration of that element in the sample. Figure 43 shows such a plot for the three elements--sodium, sulfur, and silicon--in a high-sodium Baukol-Noonan lignite. The plot of silicon appears on the top of the figure. Each peak in this figure represents a particle containing silicon; actually, most of these peaks represent small grains of sand or quartz in the lignite. The important feature from this plot shows that silicon occurs in the lignite as small particles of minerals (quartz) in the raw lignite. Many of these particles have a diameter of 5 microns or less. The center plot is that of sulfur; the intensity is about 50 percent full scale and nearly uniform across the sample. This indicates that the sulfur concentration is uniform throughout the sample and does not occur as particulate matter like silicon. This can be explained by assuming that all the sulfur in this strip occurs as uniformly distributed organic sulfur.

It is well known that sulfur also occurs as pyrites in lignite. This plot does not contradict the presence of pyrites but merely shows that no pyrites were observed in this narrow strip. A standard analysis for pyrites in this lignite indicated very little present. The plot at the bottom of the figure is the sodium concentration in this same strip. The sodium plot is like the sulfur plot, but somewhat lower in intensity. The uniform distribution of sodium in lignite indicates that it, like sulfur, is not present as particulate mineral matter but is probably distributed throughout the lignite as the sodium salt of a hydroxyl group or a carboxylic acid group in humic acid.

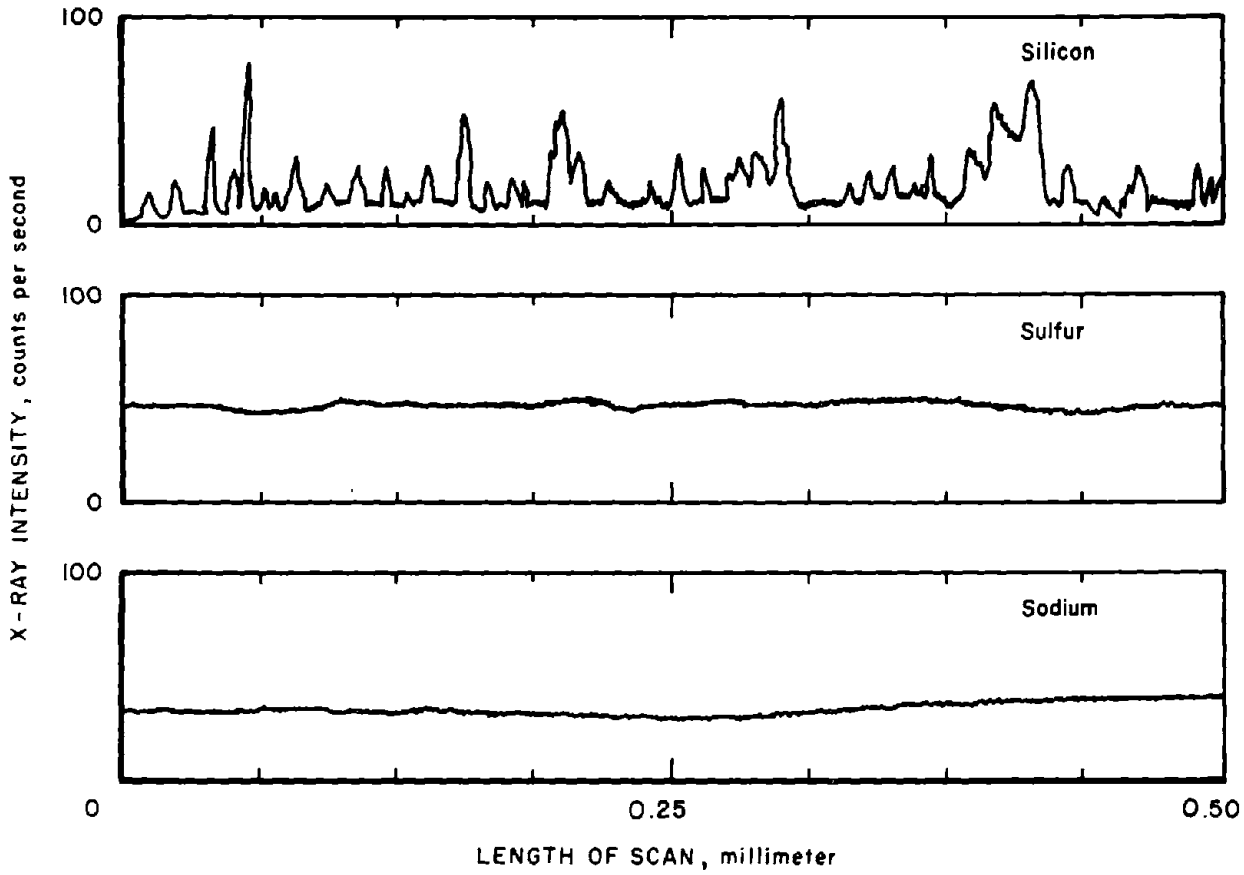

FIGURE 43. - Microprobe Scan of Silicon, Sulfur, and Sodium in Baukol-Noonan Lignite.

A high-sodium lignite was chosen on the assumption that if the sodium exists as a particulate mineral in lignite, the individual particles in this sample would be more numerous and, therefore, easier to locate with the electron microprobe. Other workers[4] have also postulated that sodium is present in this form in German brown coal on the basis of ion-exchange work. However, the present data is the first physical evidence that this is true.

Figure 44 compares the calcium concentration in the same strip of lignite discussed above with a sample of subbituminous coal from Centralia, Wash. Microprobe examination strongly indicates that the calcium in the lignite, like the sodium, is bound organically to the humic acids; therefore, it is uniformly distributed in the sample. The subbituminous coal does not appear to have any calcium present in the area examined. Standard ash analyses, however, indicated as much as 10 percent calcium in the ash of this coal. We can conclude that the calcium occurs as discrete mineral matter, such as calcite, in the subbituminous coal; however, no such mineral particle happened to be in the strip that was analyzed.

[4]Schiffer, A. The Inorganic Constituents of Rhein Brown-Coal and Their Effect on the Fouling of Heating Surfaces of Steam Generators. Z. Deutsch Geol., Ges., v. 118(1), 1968, pp. 125-134.

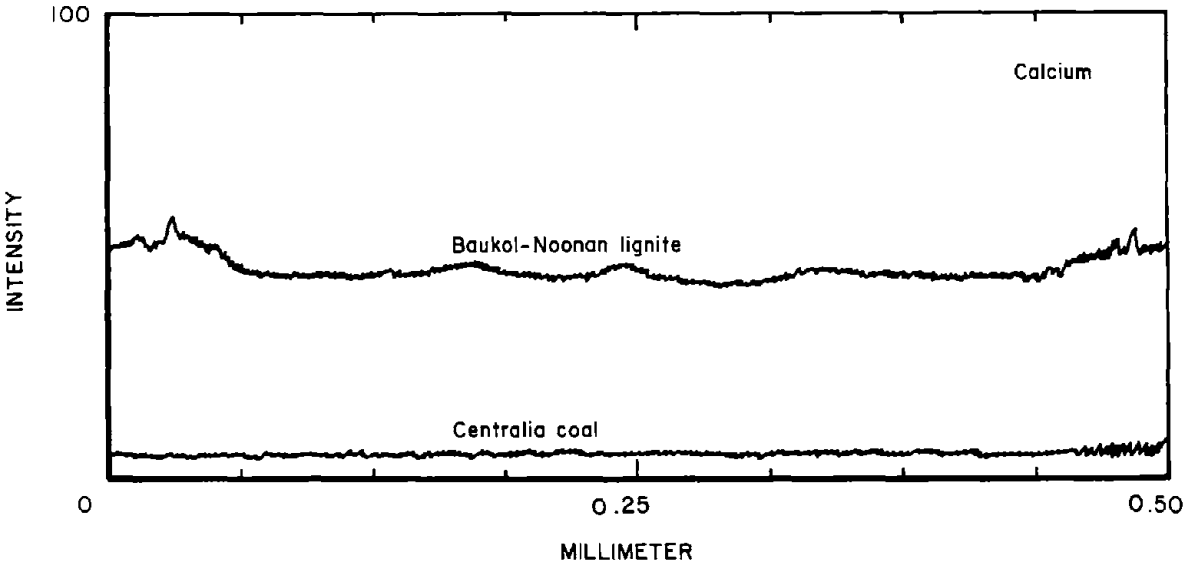

FIGURE 44. - Microprobe Scan of Calcium in Baukol-Noonan Lignite and Centralia Coal.

The same strip of lignite was also analyzed for aluminum, iron, and magnesium. The results indicate that a certain amount of all of these cations is tied up as the salts of humic acids. In some of the work with the electron microprobe we have found, in addition to silicon dioxide in lignite, particulate mineral matter such as magnesium aluminum silicates and aluminum silicates, but these mineral particles were difficult to find.

The time required to perform these analyses with the electron microprobe is considerable, and, consequently, we have only done a very small amount of work in this area. Considerable work on lignite still needs to be done, but it is felt that the results observed thus far will be typical of what is expected in other lignites of the Northern Great Plains area.

Combustion Process

The electron microprobe examination has shed some light on how the ash elements are associated in lignite. Using this information one should be in a better position to understand the combustion process.

In the pulverized-fuel-fired boilers, the coal is crushed so that 70 to 80 percent is smaller than 74 microns or 200 mesh. In the combustion zone these particles are exposed to temperatures of approximately 3,000° F. The behavior of the inorganic constituents at these temperatures will depend on how they are initially associated with the lignite. Some of the material, such as silicon dioxide and silicates that occur as particulate inorganic mineral, may melt at these temperatures and form small fluidlike spheres. These may undergo little, if any, chemical change. Some inorganic minerals, such as calcite and quartz, may decompose into carbon dioxide, calcium oxide, and silicon monoxide. The inorganic material that is tied up as salts of humic acids, which may comprise the bulk of the ash, will likely form the oxides in the

combustion process. These oxides may experience considerable volatilization as well as chemical reaction. It is believed that much of the sodium oxide will volatilize, and some of it may react with the oxides of calcium, aluminum, magnesium, and silicon to form low-melting silicates in the combustion zone. The oxides of calcium, magnesium, and aluminum may react with the small silicon dioxide particles to form high-melting silicates. This reaction may take place between the ash constituents within each particle of lignite fed into the boiler. The organic sulfur compounds will produce sulfur dioxide and a small amount of sulfur trioxide in the combustion process.

Reactions in the Gas Stream

It is assumed that the temperature of the particles in the gas stream will be within 100° F of the temperature of the combustion gases in the stream.[5] Some of the physical and chemical changes that take place in the gas stream are as follows:

1. Volatilization--Because of the turbulent nature and the high temperature of the gas stream, ash particles that have a moderate vapor pressure would volatilize. This would especially occur near the combustion zone where the temperatures are the highest.

2. Dissociation--At these high temperatures a number of molecular species may dissociate into molecules of lower molecular weight. For example,

$$CaCO_3 \rightarrow CaO + CO_2 .$$

It is also likely that Na_2O vapor will dissociate into its individual atoms. It is known that sodium hydroxide will dissociate into sodium, hydrogen, and oxygen at 2,350° F.[6]

$$2NaOH \rightarrow 2Na + O_2 + H_2 .$$

3. Chemical reactions--At the high temperatures of the combustion zone, the atomic and molecular species are in a highly active state and it is unlikely that many chemical combination reactions will take place. The tendency toward dissociation will outweigh the driving force for chemical combinations to occur. However, some refractory silicates may form, such as $2CaO \cdot SiO_2$ (m.p. 2,130° F)[7] and $Al_6Si_2O_{13}$. Some of the other compounds, such as Al_2O_3 and SiO_2, will exist as small liquid or semiliquid spheres. As the gases leave the combustion area, the temperature will drop and a number of chemical reactions and physical changes will occur. The turbulent nature of the gases will cause intimate mixing. One would anticipate that the most basic oxides would combine with the most acidic oxides first. On this basis, sodium oxide should combine with sulfur dioxide giving sodium sulfite, which then readily oxidizes to sodium sulfate:

$$2Na_2O + 2SO_2 + O_2 \rightarrow 2Na_2SO_4 .$$

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[5] Johnson, H. R., and D. J. Littler. The Mechanism of Corrosion By Fuel Impurities. Butterworths and Co., Ltd., London, 1963, pp. 357-365.

[6] Partington, J. R. Textbook of Inorganic Chemistry. Macmillan and Co., Limited, London, 6th ed., 1950, p. 689.

[7] Weast, R. C., editor in chief. Handbook of Chemistry and Physics. The Chemical Rubber Pub. Co., Cleveland, Ohio, 48th ed., 1967, p. B-165.

The sodium sulfate may first exist as a vapor, and as the temperature drops downstream, some of the molecules may condense to form small liquid droplets.

There are probably few chemical addition reactions that take place in the gas stream with particulate matter for the following reasons:

1. Solid-solid, solid-liquid, and liquid-liquid reactions are too slow.

2. Solid-gas reactions would occur but would only be a surface phenomena.

3. Residence time is very short.

The reaction of Na_2O and SO_2 is a gas-gas reaction and should occur rapidly. One would expect CaO to react with SO_2 and it probably does; however, Na_2O is a more basic oxide and therefore would react in preference to CaO with SO_2. At high CaO concentrations, the mass action effect would favor the formation of $CaSO_4$. Pilot-plant studies indicate that increasing the CaO concentration tends to reduce fouling. This may be due to an insufficient amount of SO_2 necessary for significant Na_2SO_4 formation.

Tube Deposit Formation

The examination of a test probe deposit from burning Beulah lignite was accomplished with the electron microprobe by imbedding the deposit in an epoxy resin by a procedure similar to the preparation of the lignite samples described earlier. The imbedded sample was cut at an angle perpendicular to the boiler tube. Microprobe and microscopic examination of several deposits indicated three definite areas (fig. 45). The layer next to the tube, known as the inner white layer, consists of small particles completely surrounding the boiler tube. Electron microprobe analysis and chemical analysis of this area indicate high concentrations of sodium and sulfur. Beneath the bulk of the deposit the thickness of this white inner layer may vary from 1 millimeter or more to an extremely thin layer. X-ray diffraction analysis of the white layer indicated sodium sulfate as one of the constituents in many of the deposits. In one pilot-plant experiment with sodium chloride used as an additive, this layer was approximately 80 percent NaCl. Calcium sulfate and silicon dioxide have also been identified in this area. In some cases, this layer will contain most of the elements that normally occur in ash, with sodium and sulfur predominating.

The second layer on the tube is known as the inner sintered layer. Microprobe examination of this area using the beam scanner indicated the presence of individual ash particles as the main characteristic. Individual particles of silicon dioxide, iron oxide, aluminum silicate, magnesium and calcium aluminum silicates, and several others have been identified.

The outer sintered area comprises the bulk of the deposit. Microscope examination indicates a definite change in physical appearance between the inner and outer sintered layer. Electron microprobe analysis indicated the presence of fewer discrete ash particles. Most of the deposits examined with the beam scanner were large and had an irregular outline with adjacent

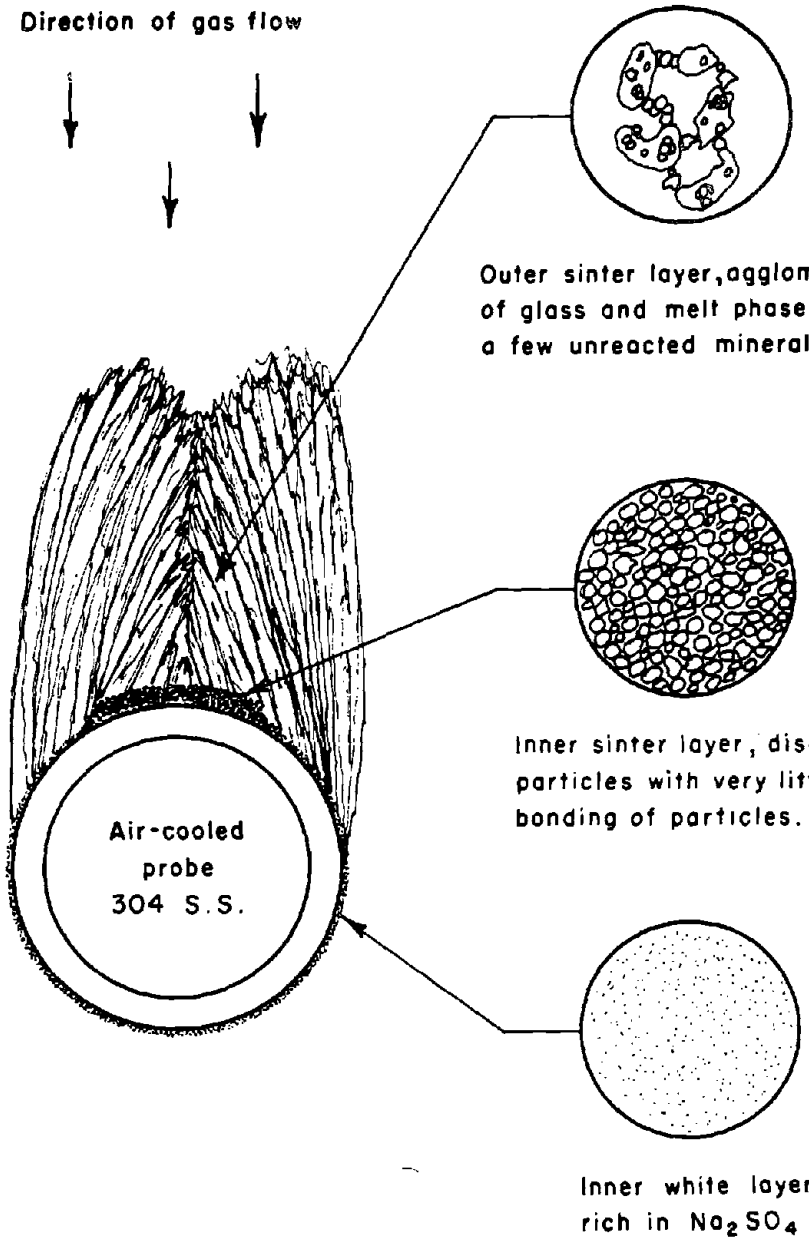

FIGURE 45. - Physical Structure of a Typical Deposit From the Pilot-Plant Furnace Burning High-Fouling Lignite.

deposits joining one another in a random fashion. An elemental analysis of this outer deposit with the microprobe indicated the presence of essentially all the major ash elements in each of the agglomerates. Potassium occurred in the same regions as sodium. Silicon, calcium, aluminum, and magnesium were the predominate elements and were found almost everywhere in the outer deposit except in certain specific particles such as quartz and iron oxide balls. Hollow balls were found in the deposit and some of these had a "ring" containing sodium at a higher concentration level than the surrounding matrix.

Using this information, a probable fouling mechanism is postulated. The initial white layer is formed primarily by the condensation of sodium sulfate vapors into a solid on the tube. This takes place on the entire surface of the tube. During the condensation process, there may be some deposition of small liquid droplets of sodium sulfate.

Before the deposition of Na_2SO_4 on the tube, solid particles strike the tube and bounce off again. Semifluid particles will also strike the tube but do not have a bonding agent to hold them onto the tube. However, once the layer of Na_2SO_4 has formed, it acts as a soft porous mat. Now when the solid or semisolid particles strike the tube they can sink a short distance into

this mat and are held to the tube. The forces holding these new particles are primarily physical forces and therefore the attachment is a weak one. For example, a high-temperature particle striking the Na_2SO_4 layer may cause partial melting of the Na_2SO_4 (m.p. 1,625° F) and thereby promote more intimate contact of the hot particle with the Na_2SO_4. As the deposit slowly builds up, the inner sintered layer is formed. In this region the temperature is intermediate between that of the tube temperature and of the gas stream. The deposit temperature is too low to permit chemical reactions of the ash particles to occur very rapidly. Therefore, we see discrete particles in this region, each of which has its own chemical composition. With additional deposit formation, the temperature of the outer layer rises. The higher temperatures are more conducive to chemical and physical reactions among the silicates deposited on the tube. At the higher temperature, the silicates in the outer layer react with the sodium compounds from the gas stream to form low-melting silicates that fuse with each other. In the lignite, the threshold concentration of sodium necessary to produce these low-melting compounds appears to be about 4 to 5 percent. This sticky, semisolid, low-melting matrix has a high efficiency to retain impacted material so that the solid particles in the gas stream are readily embedded in the soft matrix. This increases the rate of ash formation on the boiler tube. Over a period of time, the atoms and molecules slowly shift around forming more stable silicate compounds. Isomorphic exchange of Mg^{+2}, Ca^{+2}, and Fe^{+2} with each other can readily occur. A similar exchange is possible between Na^{+} and K^{+} or between Fe^{+3} and Al^{+3}. The number of possible silicates that can form with these atoms is extremely high, and one would expect the most stable silicate to form. The resulting compounds are long silicate structures produced by the breaking and making of oxygen-to-silicon bonds in a tetrahedral arrangement. Over a long period, a silicate polymer is formed having strong bonding properties and satisfying all the requirements for a stable compound.[8]

Our work so far has been limited primarily to the study of ash from Beulah lignite. It is obvious that further work is necessary with other lignites. Further studies combining the results from the microscope, electron microprobe, and X-ray diffraction on a variety of deposits are planned. A better knowledge of the chemical and physical properties of lignites and their boiler tube deposits should contribute to a better understanding of the fouling mechanism.

Conclusions

The capability of the electron microprobe to chemically analyze particles as small as 1 or 2 square microns in area makes it very useful to study minerals in lignites and furnace ash deposits.

Electron microprobe examination of a few lignite samples indicates that much of the mineral matter exists as salts of humic acids and that this matter is uniformly distributed in the lignite. In the samples examined, quartz and some silicate minerals were the only discrete mineral particles observed.

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[8] Pauling, L. The Nature of the Chemical Bond. Cornell Univ. Press, Ithaca, N.Y., 2d ed., 1948, pp. 378-401.

A similar examination of ash deposits from a test furnace indicated three layers: a white layer next to the tube, an inner sinter layer, and an outer sinter layer which makes up the mass of the deposit. The inner white layer is generally rich in Na_2SO_4 and completely surrounds the tube. The inner sinter layer is deposited at an intermediate temperature and consists of discrete particles that are loosely bonded to each other. There appears to be little matrix material in this area. The outer sinter layer is formed at a higher temperature level, and the silicates react with sodium compounds from the gas stream to form low-melting compounds. These lower melting compounds fuse with one another to form a highly viscous liquid. Solid particles from the gas stream are readily embedded in this matrix, and thereby promote the growth of large sinter deposits on the upstream edge of the tube. Over a long period of time, large silicate polymers may be formed that have strong bonding properties and satisfy all the requirements for a stable silicate compound.

ASH DEPOSITION RESEARCH ON CANADIAN LIGNITES

By A. D. Winship[1] and F. Bender[2]

Introduction

Combustion Engineering-Superheater, Ltd. (CE-S) began its basic research on deposition of lignite ash in 1964. The bases for the research were the tremendous lignite reserves in Canada's western provinces and the economic attractiveness of this fuel. The research was undertaken to improve the reliability, availability, and predictability of performance of larger capacity lignite-fired units operating at higher pressures and temperatures than current units in Canada. In addition, there exists the possibility, through the better understanding of problems, of reducing the relative size and cost of lignite-fired units when compared with units burning higher rank coals. At the beginning of the study, it was assumed that sufficient practical engineering experience was available to overcome the common problems of high-draft losses, plugging of dust collectors, settling of ash in the ducts, and problems related to pulverizer capacity. Therefore, our research effort was concentrated in the area of ash deposition in the superheater and reheater regions of steam generating units.

Research objectives were to obtain better understandings of basic factors that might affect deposition, such as gas velocity, pulverized fuel fineness, excess air, ash composition, and gas temperature. This was done to (1) improve the operation of lignite-fired units, (2) improve the design criteria for future lignite-fired units, and (3) provide a basis for more economical steam generator designs and for the design of larger units. This paper presents the results of five different full-scale tests on operating utility steam generators with regard to the ash deposition parameters previously mentioned.

During 1968, CE-S obtained a research grant from the National Research Council of Canada to investigate a broader sense of problems associated with low-grade fuel utilization. This program, which is now underway, will study, from a basic research point of view, the mechanism of furnace and superheater ash deposition and luminous, nonluminous, and convection heat transfer. Also, studies of the combustion of pulverized low-grade fuels will be carried out.

The Mechanism of Deposit Formation

The mechanisms and deposition rates were studied by exposing controlled temperature probes in the superheater and reheater regions of utility lignite-fired units under a wide range of operating conditions. The basic deposition mechanisms are (1) thermal and eddy diffusion, (2) condensation of vaporized material, and (3) impingement or inertial impaction.

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Thermal and eddy diffusion has been confirmed by microphotography and composition analysis on probes inserted for short periods of time. Condensation of vaporized materials, as a deposit mechanism, has been verified by operating probes at high temperatures, and by proving the absence of vaporized materials above their condensation temperature by analysis. The area of our greatest research has been that of impingement (or inertial impaction). An attempt was made to isolate the different parameters with an overall objective of being able to predict the rate of deposition in different convection regions of steam generators.

The first stage of deposition buildup (stage 1) produces a uniform thin layer of below-10-micron particles (fig. 46) uniformly around the perimeters of the probe or tube. This layer is formed by thermal or eddy diffusion, or condensation of vaporized materials. It is nonadherent and is easily removed by impingement of other solid ash constituents or by soot blowing action.

Stage 2 is the selective deposition of low-melting-point ash constituents of larger-than-average diameter. Because these constituents are sticky, they adhere to the tube upon impingement and are bonded strongly enough not to be eroded from the surface when struck by other solid particles. After a thin layer of these particles is bonded to the upstream tube face, the rough

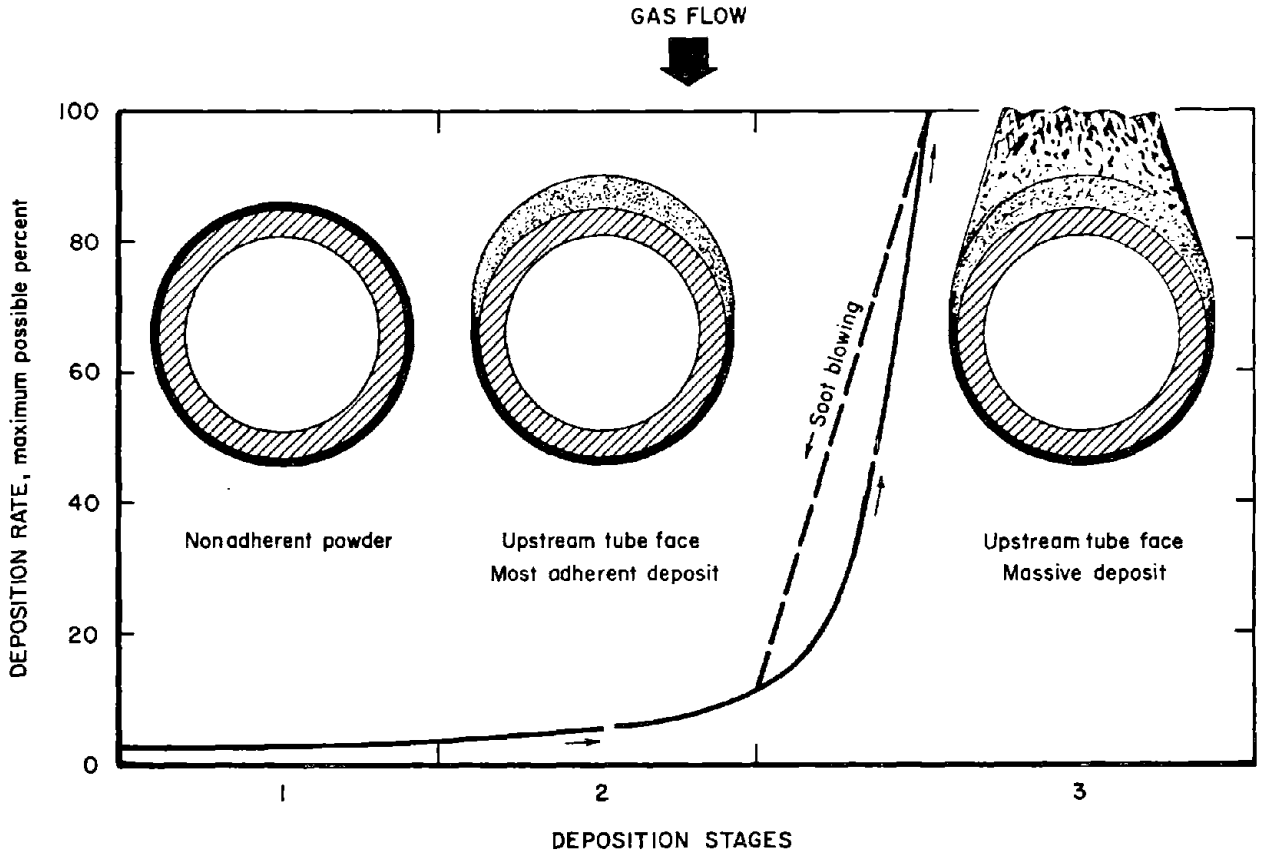

FIGURE 46. - Deposition Stages of Fireside Deposits.

surface (which closely resembles sandpaper) traps all particles that strike it. Due to the insulating effect of the adherent inner layer, the cooling effect of the original tube surface is reduced on the particles approaching the surface. Stage 2 forms the most adherent deposit that normally cannot be removed by soot blowing. This stage is followed by stage 3 of deposition, during which all the particles striking the inner deposit adhere and a rapid, massive buildup occurs. The shape of the buildup varies depending upon the gas temperature and the percentage of low-melting constituents. It may assume the shape shown in figure 47, varying from "A," which represents a small percentage of sticky particles, to "C," which represents the extreme case with a high percentage of particles in a sticky or fused condition. The outer massive deposit can be removed with soot blowing, and the tube is returned to the condition at the end of stage 2 of deposition. This outer massive deposit is very weakly bonded to the inner deposit, and quite frequently falls off due to its own weight.

In some tests, the ash composition and gas temperature conditions have been such that stage 2 has been bypassed, and the massive outer deposit started immediately upon insertion of probes. This occurs when the ash composition contains a high percentage of low-melting-point constituents, and the

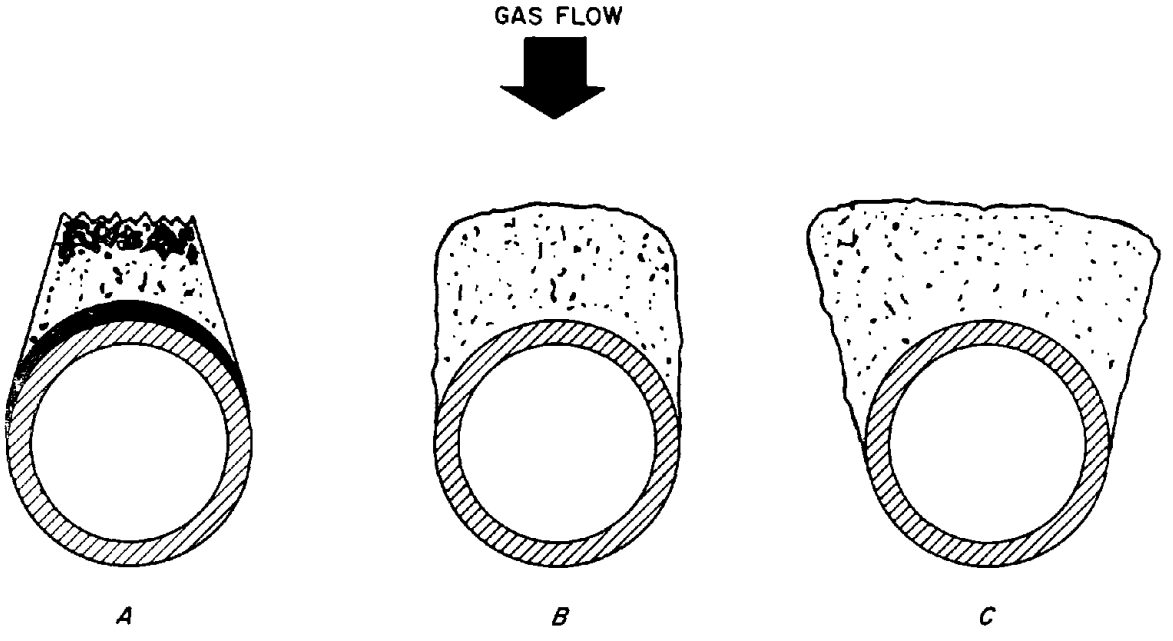

FIGURE 47. - Effect of Melting Point of Constituents on Ash Deposition.

gas and ash temperatures are high. Under this condition, normal soot blowing causes the deposit to break off, exposing a clean tube; however, random nuclei of tightly bonded deposits remain and the adherent inner layer will eventually form.

During the early stages of our testing, carefully cleaned probes were used for each test. However, most of our recent test work has been performed with probes where some stage 2 deposition has already occurred so as to more closely parallel deposition on seasoned tube surfaces. Testing was concentrated mainly in the area of massive stage 3 deposition because this represents the worst or maximum deposition rate condition. Therefore, this stage has a very important effect on the design and operation of a lignite-fired steam generator. In actual operation, as the heating surface located immediately at the furnace outlet becomes fouled, the reduction in heat transfer moves the high-gas temperature region further back into the convection pass, thereby causing stages 2 and 3 deposition to also move further back into the convection pass. In many cases of massive deposition where deposits have been removed and weighed, essentially 100 percent of the particles impinging upon the tube have formed the deposit.

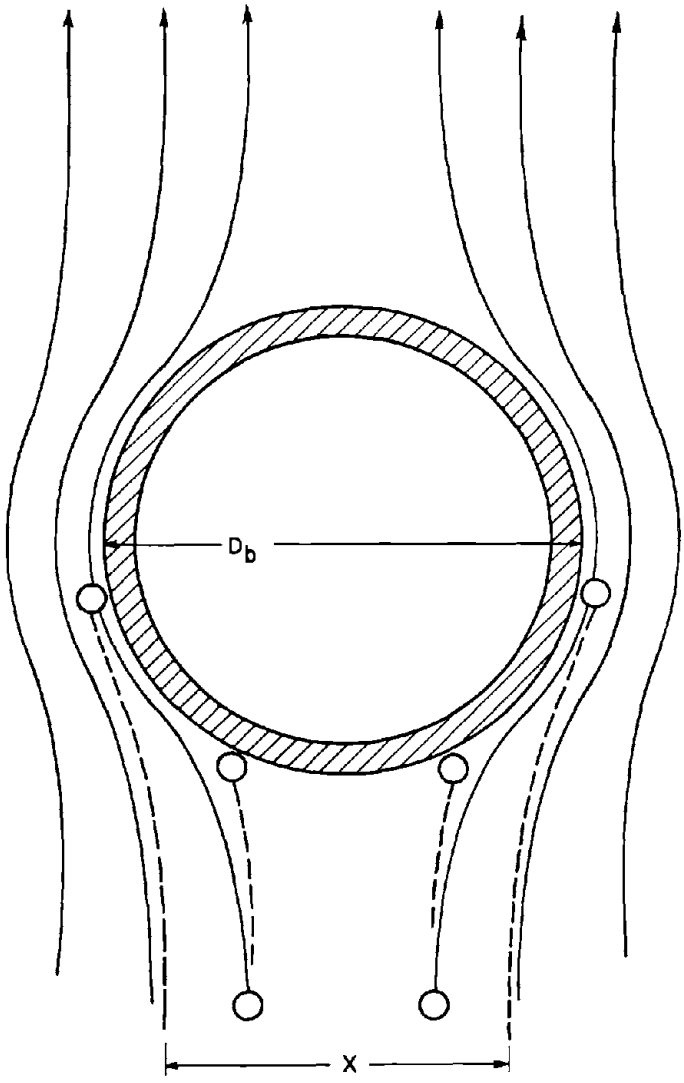

FIGURE 48. - Factors Influencing Impingement on a Tubular Surface.

Figure 48 shows the factors which affect particle impingement on a tubular surface. These parameters are related to the target efficiency determined by other investigators.

Our research work has indicated that the impinging particles are spherical. The fact that the particles striking the tube during stage 3 deposition are the result of physical impingement can be verified by comparing the predicted deposit analysis based on the composition of the ash with the actual deposit analysis. Using the physical impingement theory,

the weight rate of deposit during stage 3 can be calculated with more than sufficient accuracy for any design or operating condition; however, the bulk density of the deposit is not always the same. Hence, the actual physical deposit size cannot be predicted with the same degree of accuracy.

The Effect of Gas Velocity on Massive Deposition Rate

The ash-particle velocity is assumed to be equal to the gas velocity because of the small diameter of the ash particles. Velocity in the installation can be influenced during operation by a variation in unit load, excess air, and, to a lesser extent, gas temperature. Figure 49 shows the particle impingement percentage for a 2-in-diameter tube, for particles with a specific gravity of 2 in the size range normally encountered on lignite units. Because of economic considerations, gas velocities below 30 ft per sec at maximum continuous rating are not normal. As indicated by the impingement relationship, the higher the velocity, the greater the percentage of particles impinging, and hence, during stage 2 or 3, the greater the deposition rate.

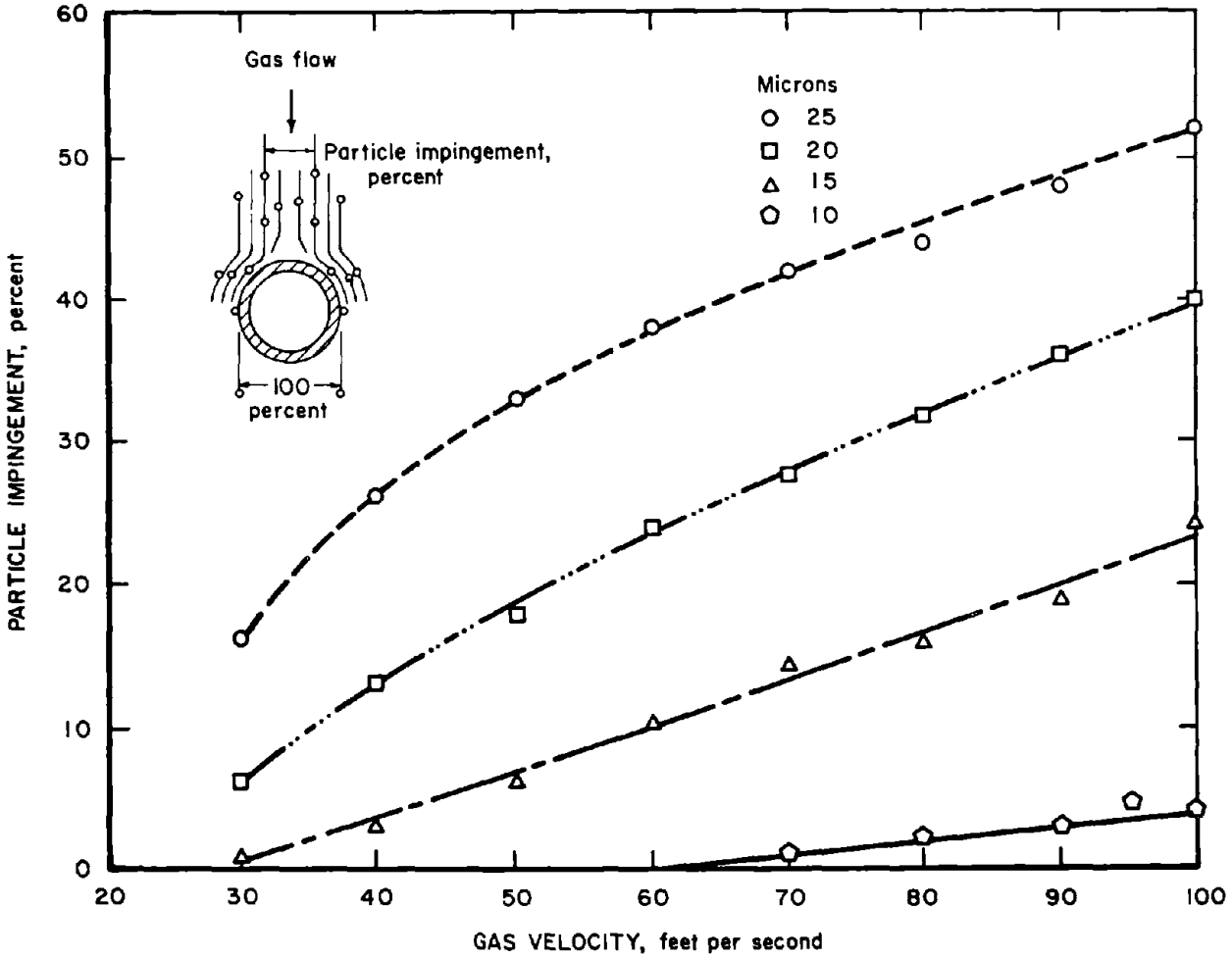

FIGURE 49. - Particle Impingement as a Function of Gas Velocity.

The Effect of Gas Temperature on Deposition Rate

Gas temperature and ash temperature (which is slightly lower) also have an important effect on ash deposition rate. In tests burning lignite with a range of sodium in ash compositions of 2.3 to 12 percent and sulfur contents of 0.25 to 0.8 percent, stage 3 deposition occurred between 1,700° and 2,100° F. The 1,700° F temperature corresponds to the approximate melting point of the lowest melting ash constituent normally found in the gas stream. Once the mass is built up, it continues with about 100 percent of the impinging particles adding to the deposit. The deposit shape is similar to that shown in figure 47. Figure 50 shows the effect of gas temperature (on a clean probe) on ash deposition rate for lignites "A" and "B."

During stage 2, the deposition rate is very low; usually only 1 to 4 percent of the impinging particles remain on the tube surface. Within a narrow band of approximately 100° F with a seasoned surface, the deposition rate

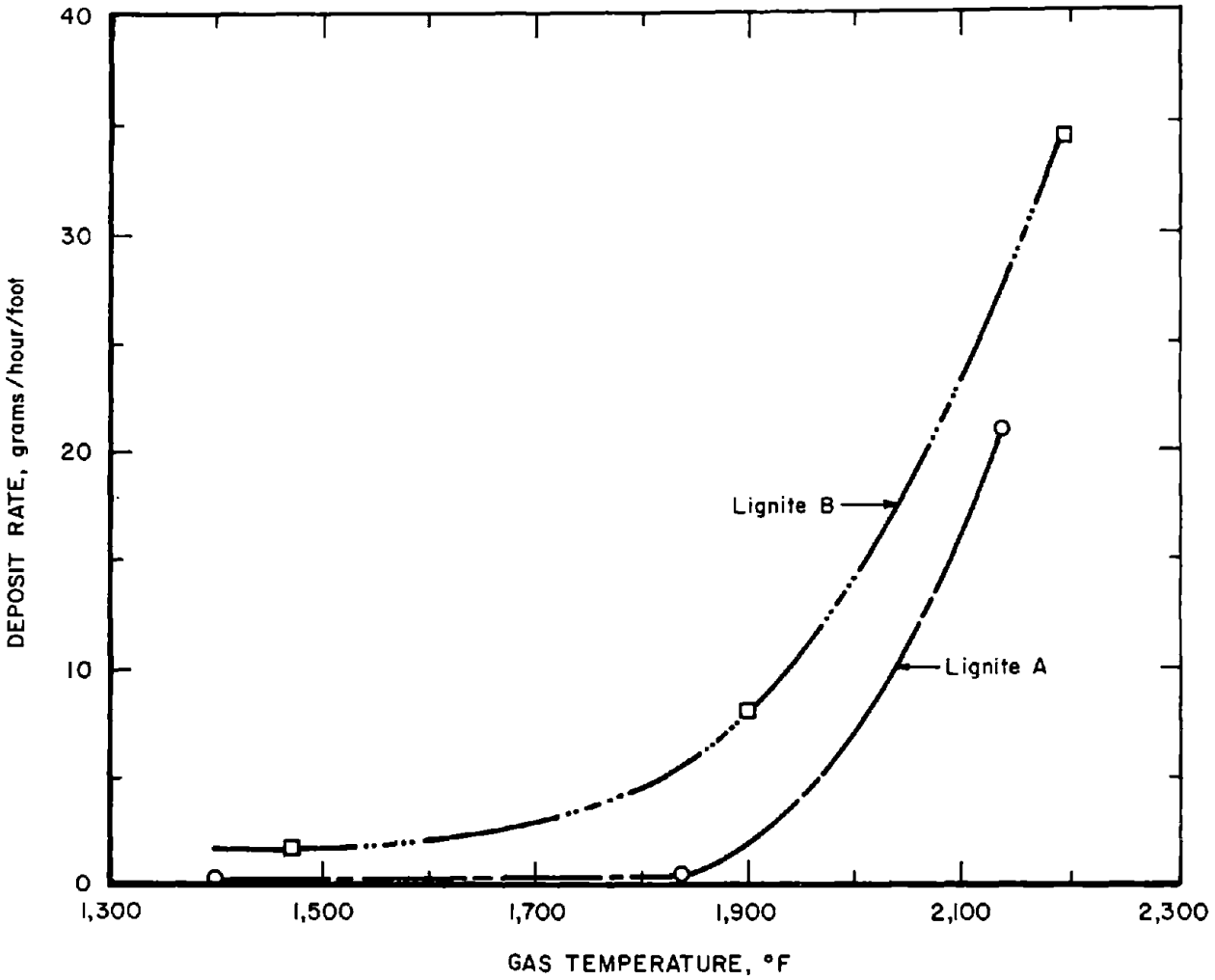

FIGURE 50. - Ash Deposition Rates as a Function of Gas Temperature, Using 4-Hour Probe Exposures.

increases so that between 25 to 100 percent of the impinging particles adhere. Once the insulating effect is increased, all particles striking the surface adhere. Obviously, the transition point from stage 2 to stage 3 deposition is of great importance. The transition temperature varies depending upon the analysis of the lignite. In the past, this temperature has been determined by burning lignite from a new mine in an existing installation.

Effect of Surface Temperature on Ash Deposition Rate

To date, the effect of metal temperature on ash deposition rate has not been pursued to a great extent. Other design considerations, such as the superheat and reheat temperature control range and the economic factors involved with material selection, normally govern this parameter. Lowering the metal temperature, however, lowers deposit rates with lignite firing by retarding stage 2 formation. This is due to the greater degree of solidification of low-melting-point ash particles passing through the tube boundary layer. Once the most adherent layer is fully developed, metal temperature has a much reduced effect; its effect is eliminated completely as deposits increase. At very low temperatures (below saturation temperature), such as occur with high-velocity temperature probes operating at about 200° F, the most adherent layer never appears to form.

Decreasing the metal temperature from 1,000° to 800° F, reduces the 1-hour deposit rate in a 2,000° F gas zone by one-half. In other tests using high ash fusion coals, metal temperature had less influence on deposits than is the case with lignite.

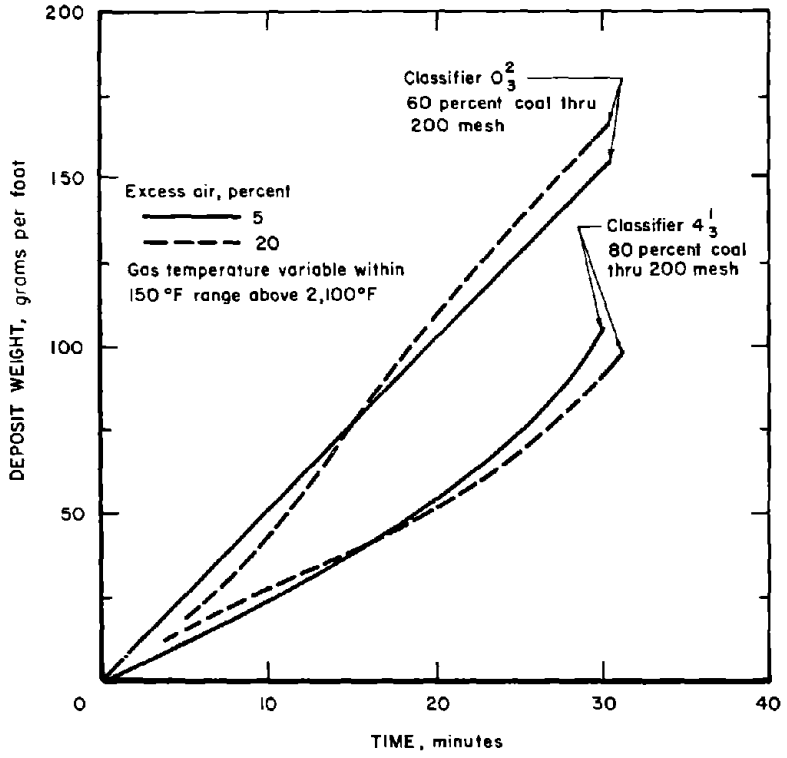

FIGURE 51. - Deposit Weight Versus Exposure Time, Depending on Coal Size.

The Effect of Pulverized Coal Fineness on Ash Deposition Rate

Ash fineness, as indicated in figure 51, has a tremendously important effect on particulate impingement. These tests were run with different pulverizer classifier settings, resulting in coal fineness through 200-mesh screen of 60 to 80 percent. The curves represent six tests, which were later confirmed by reruns. Throughout the test period, the gas velocity varied by 15 percent and the gas temperature varied within a 150° F range, but always remained above

2,100° F. The variation of excess air illustrated in figure 51 was carried out as part of another series of tests. Tests using North Dakota lignite "D" showed similar results. Increasing the fineness from 60 to 80 percent through a 200-mesh screen reduces the deposition in stage 3 by approximately one-half under all conditions.

The above results were not entirely expected since it was assumed that there would not be a constant or reproducible relationship between coal and ash particle size. Also, it was felt that the combustion history of the coal particle and the nature and structure of the ash containment within the coal would affect the ash sizing at the furnace outlet to a greater extent than any of the lignite tests have indicated. Therefore, additional tests will be required to confirm this result. No attempt has been made to experimentally verify this result on any other coal. The economic implication regarding pulverizer sizing and power consumption will limit the usefulness of the relationship between fineness and deposition rate.

The Effect of Fuel Analysis and Ash Composition on Ash Deposition Rate

Table 10 contains the lignite analysis for the major tests reported. The effect of the ash and fuel analysis on deposition rate are limited to lignites within this range.

TABLE 10. - Data on lignites tested in ash deposition work

	Lignite[1]				
	A	B	C	D	E
Proximate analysis, percent:					
Moisture	37.0	37.0	37.0	37.4	36.3
Volatile matter	26.2	24.4	25.4	25.3	24.7
Fixed carbon	28.3	30.0	30.8	30.0	30.1
Ash	8.5	8.6	9.9	6.2	8.9
Sulfur, percent	0.4	0.4	0.3	0.8	0.4
Heating value, Btu/lb	6,600	6,520	6,850	6,820	6,590
Ash analysis, percent:					
SiO_2	38.9	41.0	39.4	22.7	37.4
Al_2O_3	22.2	21.9	23.4	12.2	18.0
Fe_2O_3	4.3	4.2	3.0	14.6	3.6
CaO	21.6	16.3	14.1	28.7	17.5
MgO	4.7	3.2	2.9	11.2	4.6
Na_2O	2.3	9.2	9.0	8.9	5.0
K_2O	0.2	0.3	0.4	0.5	0.3
Ash fusibility, ° F:					
Initial deformation temperature	2,030	2,060	2,150	2,160	2,020
Softening temperature	2,120	2,115	2,250	2,420	2,110
Fusion temperature	2,160	2,190	2,450	2,600	2,250
Relative deposition rate:					
At 1,800° F	-	4	1	-	-
At 2,000° F	1	2	-	8	-
Relative impingement rate[2]	1.5	1.2	1.0	1.6	1.4

[1]A--Sask. Pit No. 5, 1964; B--Sask. Pit No. 8, 1964; C--Sask. Pit No. 7, 1967; D--North Dakota, 1961; E--Sask., 1968.

[2]20-micron ash particles; gas velocity--30 ft per sec.

Formation of the most adherent inner layer, consisting of a high percentage of low-melting-point constituents, was found to be influenced most by the sulfur content of the lignite. Under similar test conditions at gas temperatures below the transition temperature to massive deposition, lignite "C" deposited at one-quarter of the rate of lignite "B" at 1,800° F, while at 2,000° F lignite "B" deposited at one-quarter the rate of lignite "D." (The sodium contents of the ash were approximately constant at 9 percent for lignites "B," "C," and "D.")

Above the transition gas temperature where massive deposition began to occur, the effect of sulfur content decreased over that at lower gas temperatures. Tests carried out indicated relative deposition rates of approximately 2:1 at 2,000° F for lignite "B" (sodium content 9.2 percent) and lignite "A" (sodium content 2.3 percent). Hence, the higher the sodium content of the ash, the higher the deposition rate for a lignite with constant sulfur content. It was further concluded that sodium and sulfur are the most important constituents affecting deposition rate near the transition temperature to massive deposition. The sodium content varied more than the sulfur content for the lignite tested, and hence, would have affected actual operation to a greater extent.

At a gas temperature substantially above the point where massive deposition began to occur (above 2,200° F), there were sufficient molten or sticky ash particles in the lignites tested so that all particles impinging on the probe adhered. At this temperature, the ash or fuel composition of the lignites affected the deposition rate only because of the specific gravity effect on particle impingement. Based upon 20-micron ash particles and a velocity of 30 ft per sec, the deposition rates are listed on a relative basis in table 10. The deposition under these conditions would be proportional to the ash quantity leaving the furnace.

The relative deposition rates indicated in table 10 represent actual probe measurements. Precise comparisons would not be warranted because the results were obtained under conditions where variations in velocity of 10 ft per sec and fineness of 15 percent through 200 mesh occurred. Also, the values have not been corrected for the variation in ash content of the fuel.

In addition to affecting the deposition rate, the composition of the ash has a strong effect on the ease with which the ash can be removed from a tubular surface, the nature and strength of the ash formations, and hence, the size of the deposits removed. These factors have an important practical operating and design significance, but these factors have not been studied extensively in this research program. These tests have shown that fuel and ash analyses are better design and operating guides than ash fusion temperature.

Conclusions

This research has shown that the lignite ash deposition rate can be reduced by varying the following parameters: Reducing the gas temperature; reducing the surface metal temperature; increasing the fineness of pulverized lignite; and lowering the gas velocities.

In the gas temperature region where the most adherent inner layer forms, and below the gas temperature where transition to massive deposition occurs, the lower the sulfur content, the lower the deposition rate. In this temperature region, the sulfur content was found to be the most important fuel constituent affecting deposition.

Near the gas temperature where transition to massive deposition occurs, the sodium content of the ash and fuel sulfur content have an important effect on the deposition rate. The lower the sodium content, the lower the deposition rate.

Substantially above the transition gas temperature, all lignite ash particles impinging on a tubular surface adhere (all lignites tested reached this stage below 2,100° F). The deposition rate is influenced by the impingement parameter of the ash (size and specific gravity) and the quantity of ash.

OPERATIONAL EXPERIENCE WITH LIGNITE AT THE UNITED POWER ASSOCIATION PLANT

By Charles McQuarrie[1] and Justin P. Winkin[2]

Introduction

The Stanton Plant of the United Power Association is located on the Missouri River near large sources of lignite fuel. The turbine generator served by the boiler has a nominal capacity of 175 mw. The boiler (fig. 52) is a natural circulation, balanced draft unit, with a capacity of 1,200,000 lb/hr. It operates at 1,875 psig at the superheater outlet with a 1,005° F primary steam temperature and a 1,005° F reheat temperature. The reheater is located in a parallel pass section; reheat temperature is controlled by gas proportioning dampers. Spray is used to control the final primary steam temperature.

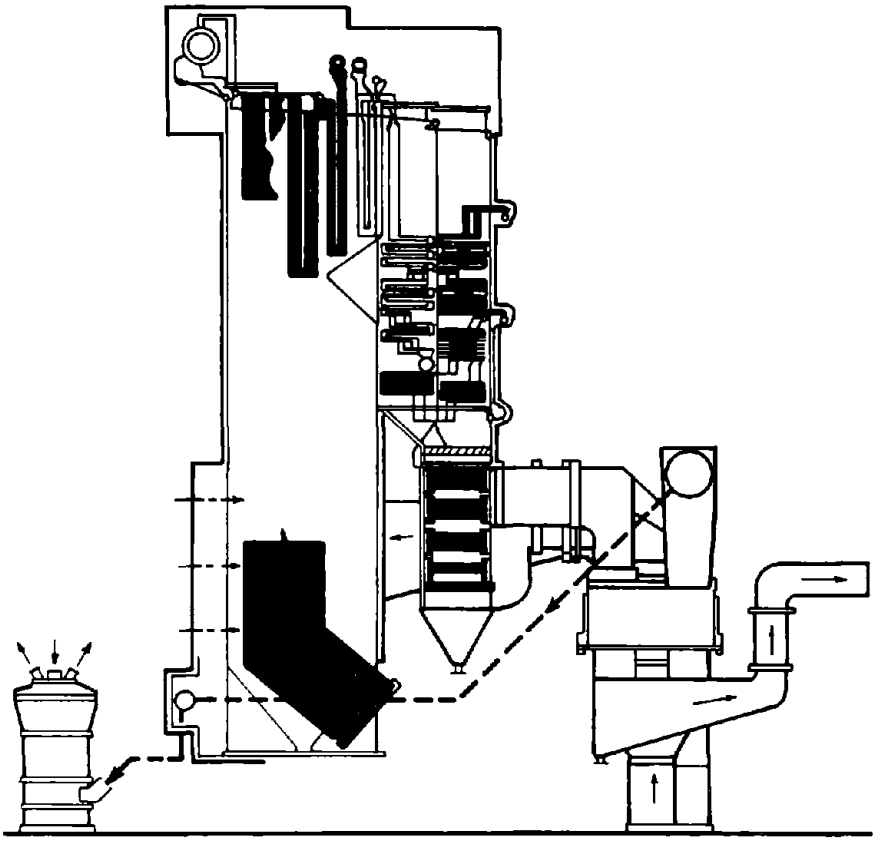

FIGURE 52. - Steam Generator for the United Power Association's Plant, Stanton, N. Dak.

Fuel Characteristics

The lignite comes from strip mines in the area near Beulah, N. Dak. Table 11 shows the actual range in characteristics of the lignite received from this source.

The degree of variation in the gross heating value of the fuel is shown in figure 53. These heating values were obtained from fuel samples taken at the time of shipment from the mine. It may be seen that the values run from as low as 6,570 Btu/lb to as high as 7,370 Btu/lb.

Figure 54 shows the variation of fuel flow as weighted by gravimetric feeders

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[2]Director of Engineering, Equipment Division, Foster Wheeler Corp., Livingston, N.J.

while maintaining a unit output almost constant at a load from 173 to 177 mw. These variations reflect the changes of heating value of the fuel as well as changes in unit efficiency resulting from different moisture content in the fuel. The range of fuel flow is from 238,000 to 272,000 lb/hr. This represents a difference of 14 percent in the fuel fired while maintaining a constant load output.

TABLE 11. - Range in characteristics of lignite fired at United Power Association Plant

Moisture.....percent..	25-40
Proximate analysis, percent, dry basis:	
Volatile matter.....	39-55
Fixed carbon.....	47-52
Ash.....	5-15
Ultimate analysis, percent, dry basis:	
Hydrogen.....	4.5-5.0
Carbon.....	61-64
Nitrogen.....	0.8-1.0
Oxygen.....	19.0-21.5
Sulfur.....	1.0-3.0
Chlorine.....	0.0-0.05
Ash.....	5-15
Heating value.....Btu/lb, as-received..	6,570-7,370
Grindability index.....	40-60
Ash analysis, percent:	
SiO_2.....	15-35
Al_2O_3.....	5-15
Fe_2O_3.....	5-12
TiO_2.....	Trace-0.5
CaO.....	24-31
MgO.....	4-8
Na_2O[1].....	1.5-11.0
K_2O.....	0.1-1.0
SO_3.....	6-20
Ash fusibility, ° F:	
Reducing atmosphere:	
Initial deformation temperature.....	2,210-2,330
Softening temperature.....	2,280-2,410
Fluid temperature.....	2,330-2,430
Oxidizing atmosphere:	
Initial deformation temperature.....	2,190-2,400
Softening temperature.....	2,280-2,470
Fluid temperature.....	2,330-2,500

[1]Normal range 3 to 7 percent.

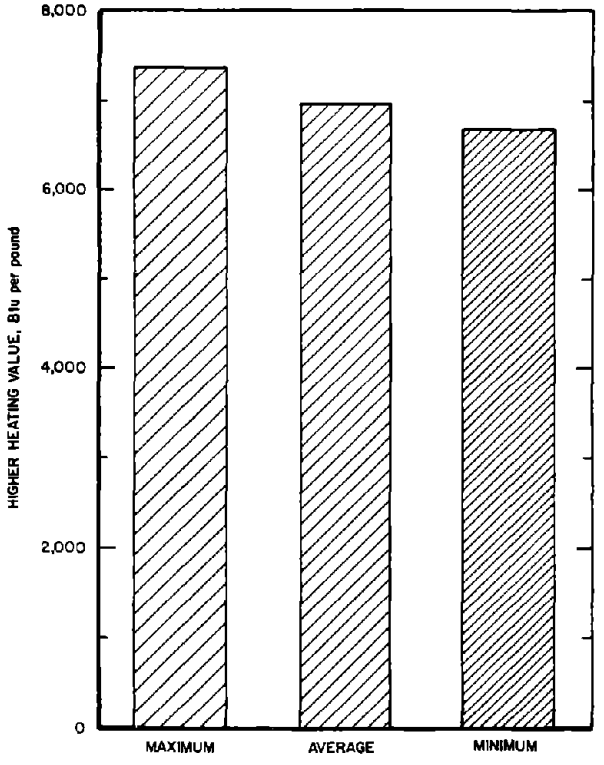

FIGURE 53. - Actual Variation in Gross Heating Value of Fuel.

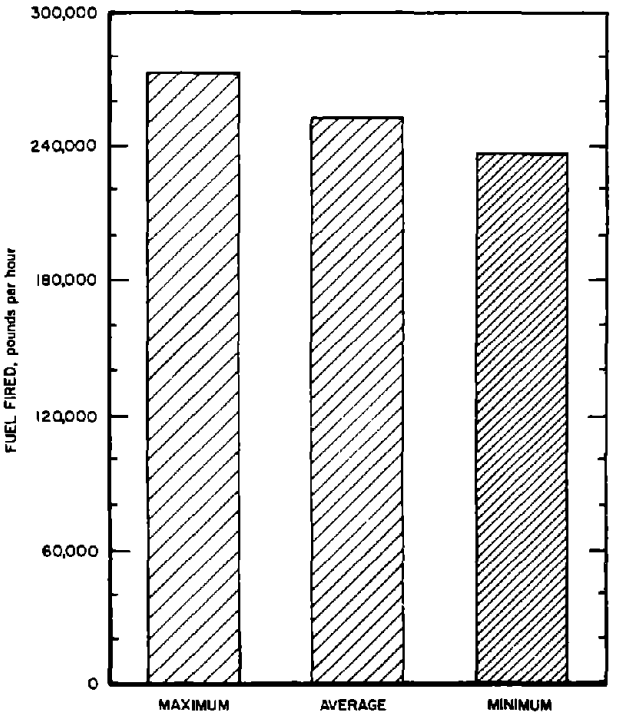

FIGURE 54. - Actual Range in Fuel Fired for a 175-mw Load.

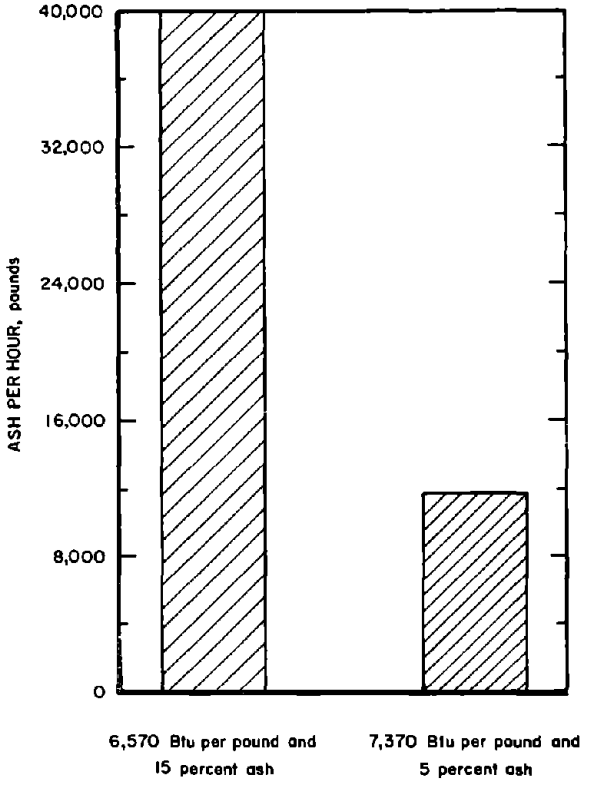

FIGURE 55. - Effect of Heating Value and Ash Content on Total Ash Fired for a 175-mw Load.

Figure 55 shows the combined effect of heating value and ash content on the total ash fired. From the range for heating values and ash content given in table 11, and assuming that the fuel with a heating value of 7,370 Btu/lb contains 5 percent ash and that the 6,570 Btu/lb fuel contains 15 percent ash, total ash quantities to the furnace were calculated. The block chart shows a possible range between 11,900 to 40,000 lb of ash/hr. These data do not take into account differences in steam generator efficiency due to variations in moisture content in the fuel.

Probably the most significant variable in the fuel which effects slagging characteristics of the unit is the sodium content. Measured sodium contents in the ash range from 1 percent to as much as 12 percent (by weight). Because these variations were related to areas of the strip mining operation, it was often possible to predict what the sodium content in the lignite would be depending upon the section of the mine being worked at the time. This information was used to carry out a blending operation at the mine for several months last year. During this period, the sodium content in the ash was kept below about 6 percent pending the installation of more cleaning equipment. It was apparent from this blending operation that the slagging effects of very high sodium lignite deposits could be reduced considerably by blending with fuel from lower sodium sources. The feasibility of doing this on a continuing basis is contingent on the availability of low sodium deposits and the costs of the blending operation.

Another interesting characteristic of lignite fuel is that changes in storage indicate a loss in volatile matter. This is being explored in more detail; however, the operators can recognize a difference in operation when reclaimed fuel appears to cause more slagging than can be associated with the sodium content. This is a problem that deserves more study.

MB Mills

The lignite for the United Power Association boiler is pulverized in three MB-23 mills. These are the largest mills used for pulverizing coal or lignite in operation in this country. Each has a capacity of 105,000 lb/hr of lignite. A similar size MB-23 mill has been operated up to 140,000 lb/hr on bituminous coal. It is interesting to note that the mill system supplied on the United Power Association unit would be capable of supplying enough pulverized coal to operate a 400-mw unit if the fuel were a 13,000 Btu/lb bituminous coal.

Some initial mechanical problems were encountered with the MB mills. These were mostly associated with the nonwearing parts. These difficulties, as well as those associated with initial low fineness conditions, have been overcome. The remaining work involved in modification of these mills is being done during the current annual outage. The operating availability of the MB mills at United Power Association during 1968 was about 97.5 percent.

During the past 5 years, there has generally been an increasing occurrence of explosions in pulverizing equipment. This has occurred on high-volatile bituminous, subbituminous, and lignite fuels. To avoid explosions of this type, a simple, but effective, steam smothering system has been installed

on the United Power Association mills. The arrangement used for injecting the steam is shown in figure 56. As a backup for the steam smothering system, there are provisions for adding carbon dioxide, which is considered more effective in an actual fire.

The smothering steam is used as a purge for about 10 minutes just before starting a mill. It is used when a mill is tripped out without being emptied of fuel and when the mill temperature is high or starts to rise after a normal shutdown. Auxiliary steam at 150 psig is used.

Air Heater Arrangement

The high moisture content of lignite, which is generally in the range of 35 to 40 percent, not including snow or ice introduced during the winter months, requires a large amount of drying be done in the mill as the lignite is being pulverized. To accomplish drying with the extreme of moisture content requires the use of hot air at about 800° F. This compares with about 500° to 600° F air required in a mill when a typical bituminous coal is used.

Figure 57 shows a schematic arrangement of the air heaters on the United Power Association unit. There are two secondary air heaters and a single primary air heater. Regulation of the primary air temperature is required to meet the drying requirements of the lignite in the mills as moisture varies. To obtain this regulation, and at the same time meet the maximum requirement of 800° F air, the flue gas to the primary air heater is taken from between two economizer sections, from the outlet of the two economizer sections, or any combination of the gases from these two points. This provides a wide range of primary air temperature to match the variations in the fuel supply.

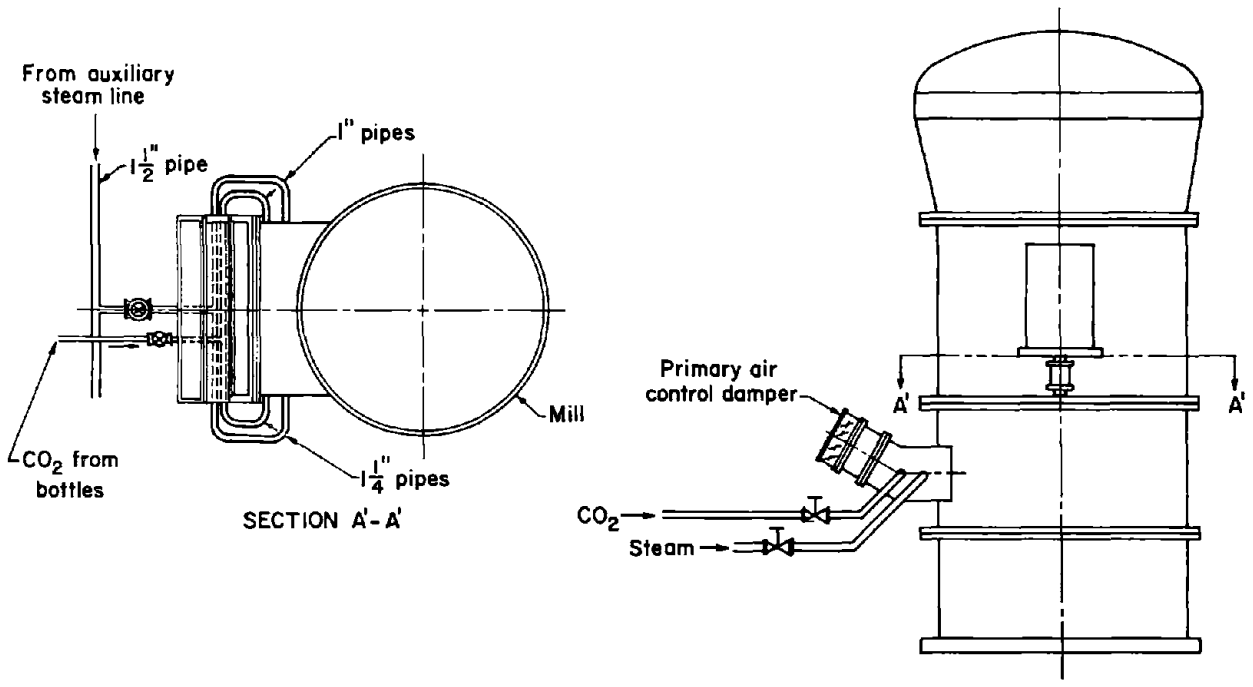

FIGURE 56. - Purge System for MB Mills.

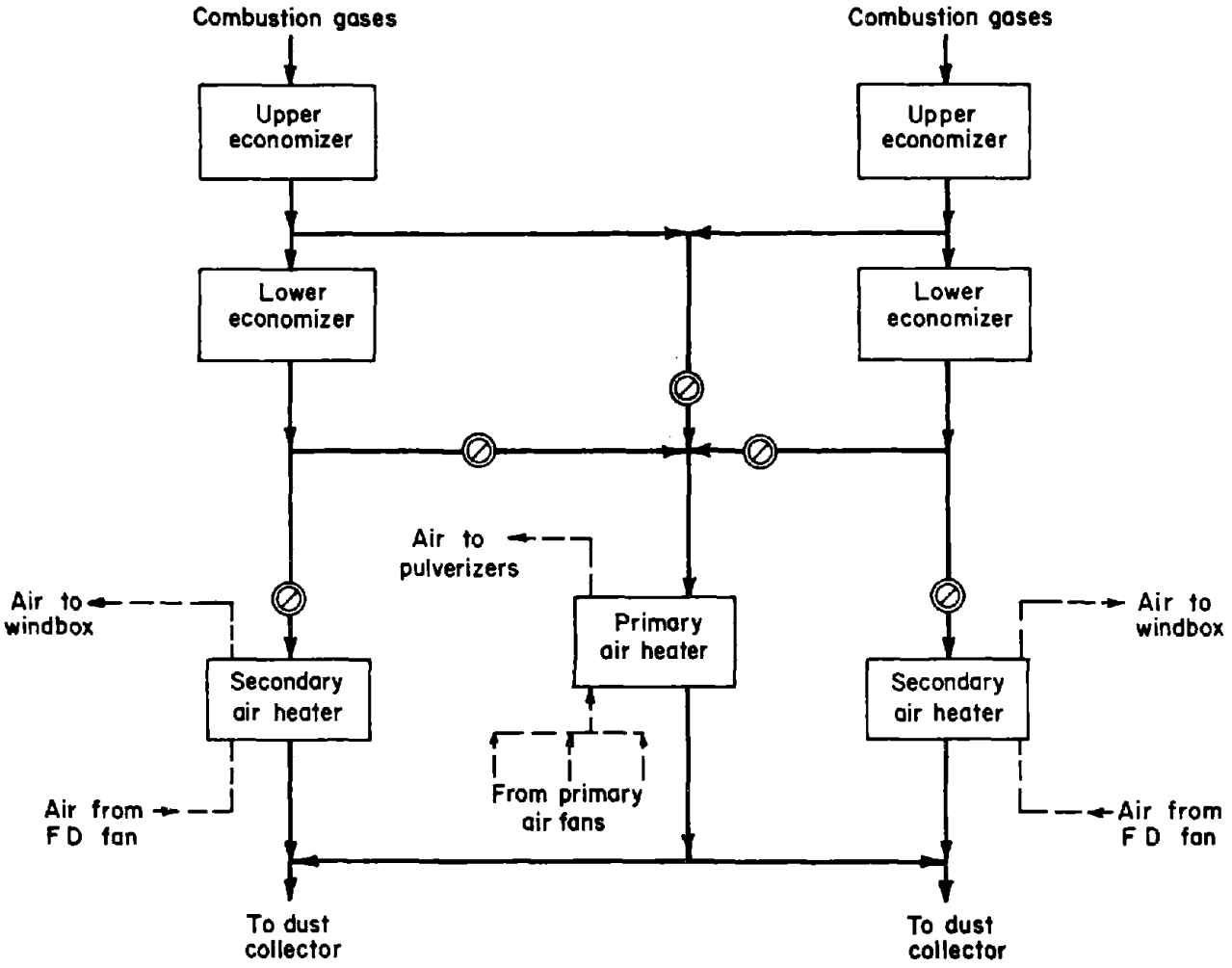

FIGURE 57. - Schematic Arrangement of Air Heaters for the United Power Association Unit.

Problems have been encountered with plugging of the air heaters, which are located in a separate downflow section in back of the boiler. Most of this plugging has been removed during outages of the boiler by water washing with high-pressure jets from a 4,000-psi supply.

An air bypass duct is being installed around the primary air heater during the current annual outage to assure cooling airflow through the primary air heater during boiler startup operations before the mills are placed in service. This change will prevent possible over-expansion of the rotor during startup which could effect the seals.

Use of Water Injection

The United Power Association boiler was furnished with a complement of standard wall blowers using steam as a cleaning medium. When the boiler was operated at partial loads and the sodium content in the lignite was less than about 2 to 3 percent in the ash, the steam-wall blowers could keep the furnace

walls fairly clean. If either load or sodium content were increased, the steam-wall blowers became ineffective. Increasing the number of blowers and increasing the steam blowing pressure made little change.

Use of a water jet for hand lancing was very effective in removing the slag. Foster Wheeler requested Diamond Power Specialty Corporation to review what could be done to inject water through their wall blowers. It was learned, through Diamond, that a means of doing this had been developed in Germany.[3] The German application was inspected by representatives of Foster Wheeler and United Power Association. It was found that the German application of water injection was limited to a single band near the top of the furnace. The study of the German unit showed that the injection of water for a 3-year period had no detrimental effect on the boiler tubes.

The engineers from Foster Wheeler developed a system for cleaning a substantial portion of the heat absorption surface of the furnace section and placed an order with Diamond for 15 water injectors to be used with this system. The water injectors on the German units were located high in the furnace; the water injectors on the United Power Association unit are located in the middle and lower portions of the furnace.

The first test of water injection took place at United Power Association on May 7, 1968. This was on a single injector installed through the rear wall opposite the top row of burners. The deposit in this area at the time was at least 6 in thick. The water injector was able to remove the deposits that the adjacent steam blower had been unable to dislodge.

Water injection cleaning was applied to major portions of the furnace walls after the annual outage about 1 year ago, and this system has been operating ever since.

Hopper Throat Bridging

There have been several occasions when the hopper throat in the furnace has bridged over due to slag falls into the hopper. The tendency for hopper throat plugging has been greatly reduced by the installation of water injectors in the furnace walls and should be eliminated by the additional water injectors that are being added during the present annual outage.

To handle buildups in the hopper throat, a water-cooled ram was proposed by Foster Wheeler and built with the assistance of United Power Association. The ram used a remote operated air cylinder to give a ramming action which broke up the plug by removing the "key from the slag arch." By judicious use of the ram, it has never been necessary to shut the United Power Association boiler down to clear a hopper plug. Further improvements in the ram are being considered to reduce manual operation.

Acknowledgments

We would like to acknowledge the substantial contributions made by Mr. Edward E. Wolter, General Manager of the United Power Association, for his support in the developments listed herein.

We also would like to acknowledge the contributions made by Mr. Ralph Moon, superintendent of the Stanton Plant, and Mr. Donald Cullum, operations supervisor, and their staffs.

[3]McQuarrie, Charles, James W. Locke, Sr., and J. P. Winkin. Water Injection Cleaning of Slag Deposits on a Lignite Fired Boiler. Proc. Am. Power Conf., v. 31, 1969, pp. 284-289.

U.S. GAS DEMAND AND SUPPLY

By Henry R. Linden[1]

Gas Demand

Any forecast of gas demand should be consistent with projections for primary energy consumption. All of the current forecasts to the year 2000 assume that United States gas demand will be met entirely with domestically produced or imported natural gas. Therefore, they do not include allowances in the primary energy requirements for inefficiencies of converting primary energy sources, such as coal, into synthetic pipeline gas. This is also true for petroleum demand which is treated as if it will be supplied entirely from domestic crude oil production and recovery of natural gas liquids, and from imported crude oil and petroleum products. Again, no allowance is made for conversion of primary energy sources such as oil shale and coal to synthetic liquid fuels.

On this admittedly tentative basis, there is reasonably close agreement among current forecasts of total primary energy requirements for the United States, as summarized in figure 58.[2] Apparently, primary energy consumption will rise at an average annual rate of 3.25 percent from 59 quadrillion (10^{15}) Btu in 1967 to 170 quadrillion Btu in the year 2000. Agreement among forecasts of the percentages of the total requirements that will be supplied by the various energy sources is not as good. Reconciliation of these forecasts gives the approximations shown in table 12. The widest deviations from other reported values are for nuclear energy, with advocates and competitors of this form of energy differing widely over its rate of penetration into the electric power generation market.

TABLE 12. - Primary energy consumption forecast

	1970	1975	1980	1985	1990	2000
Total.....quadrillion (10^{15}) Btu..	66	78	93	110	128	170
Percentage:						
Coal.....	21.5	21	19	18	16	12
Dry natural gas.....	31.5	31	30	29	28	25
Petroleum.....	43.0	41	40	39	38	35
Hydropower.....	3.5	3	3	3	3	3
Nuclear.....	0.5	4	8	11	15	25
Total.....	100.0	100	100	100	100	100
Dry natural gas (1,032 Btu/CF basis) trillion CF/yr..	20.1	23.4	27.0	30.9	34.7	41.2

[1]Director, Institute of Gas Technology, Chicago, Ill.

[2]The Oil and Gas Journal. Nuclear Power to Carry Out Big Gains. V. 65, Sept. 18, 1967, pp. 52-54.

Ebasco Services, Inc. 1967 Business and Economic Charts. Ebasco Research Dept., New York, 1967.

World Petroleum. Greater Use of Synthetic Fuels Appears Imminent. V. 39, January 1968, p. 23.

Vogely, W. A. Models of All-Gas and All-Electric Economies, ed. by L. B. Holmes. Proc. Seventh Biennial Gas Dynamics Symposium. Northwestern University Press, Evanston, Ill., Aug. 23-25, 1967, pp. 63-82.

Texas Eastern Transmission Corporation. Competition and Growth in American Energy Markets, 1947-1985. Texas Eastern Transmission Corp., Houston, Tex., 1968, 101 pp.

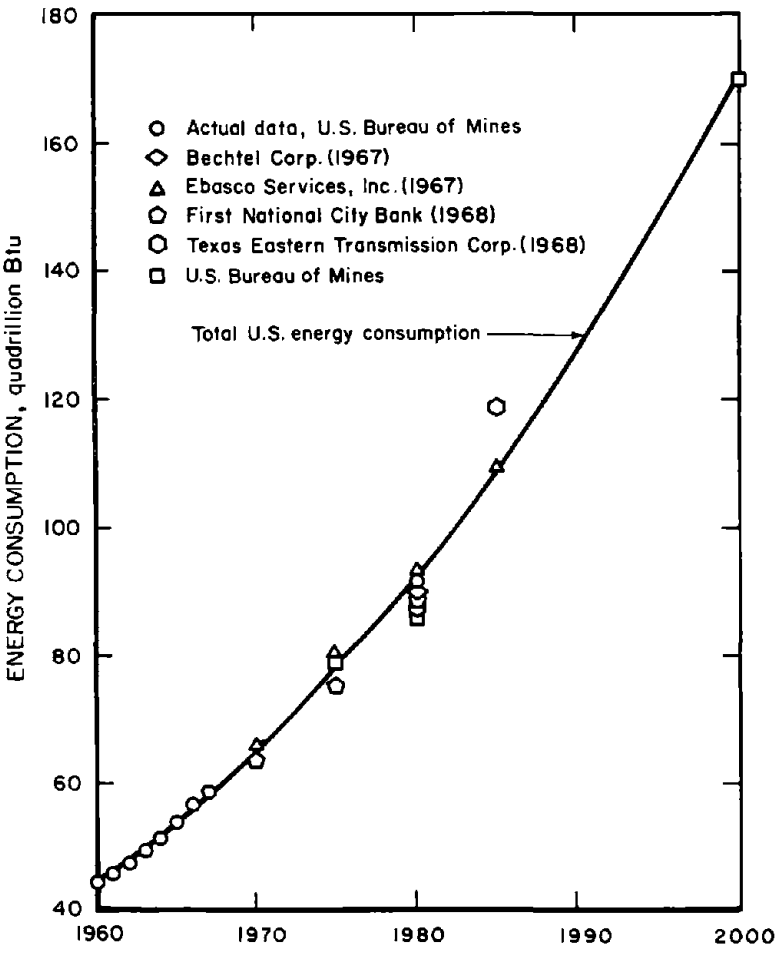

FIGURE 58. - Projection of Total U.S. Energy Consumption to the Year 2000.

The computed quantities of natural gas which correspond to the smoothed total energy requirements, and the reconciled percentage distributions from the various forecasts are also shown in table 12. As shown in figure 59, these computed gas demands agree quite well with the forecast to the year 1990 by the Future Requirements Committee,[3] extended by the most recent Bureau of Mines projection for the year 2000.[4] In contrast, the projection for 1980 by A.G.A.[5] and the projection for 1985 by Texas Eastern Transmission Corporation[6] tend to be relatively high, whereas the projection for 1980 by the Bureau of Mines tends to be low.[7] Thus, only the combined Future Requirements Committee-U.S. Bureau of Mines projections come close to meeting the condition of compatibility with the present overall picture of primary energy requirements. Therefore, they will be used here as the basis for assessing future United States gas demand.

Natural Gas Supply

Many estimates have been made of recoverable natural gas reserves in the United States. These have generally been derived from geologic considerations and have often used crude oil reserve estimates as their basis, with the

[3]Future Requirements Agency. Future Natural Gas Requirements of the United States. University of Denver, Denver, Colo., v. 2, June 1967, 31 pp.
[4]Fourth reference cited in footnote 2.
[5]Gradin, T. I. Private Communication. American Gas Assoc., Inc., 1966 (author's files).
[6]Fifth reference cited in footnote 2.
[7]Office of Oil and Gas, U.S. Department of the Interior. United States Petroleum Through 1980. July 1, 1968, 92 pp. Fourth reference cited in footnote 2.

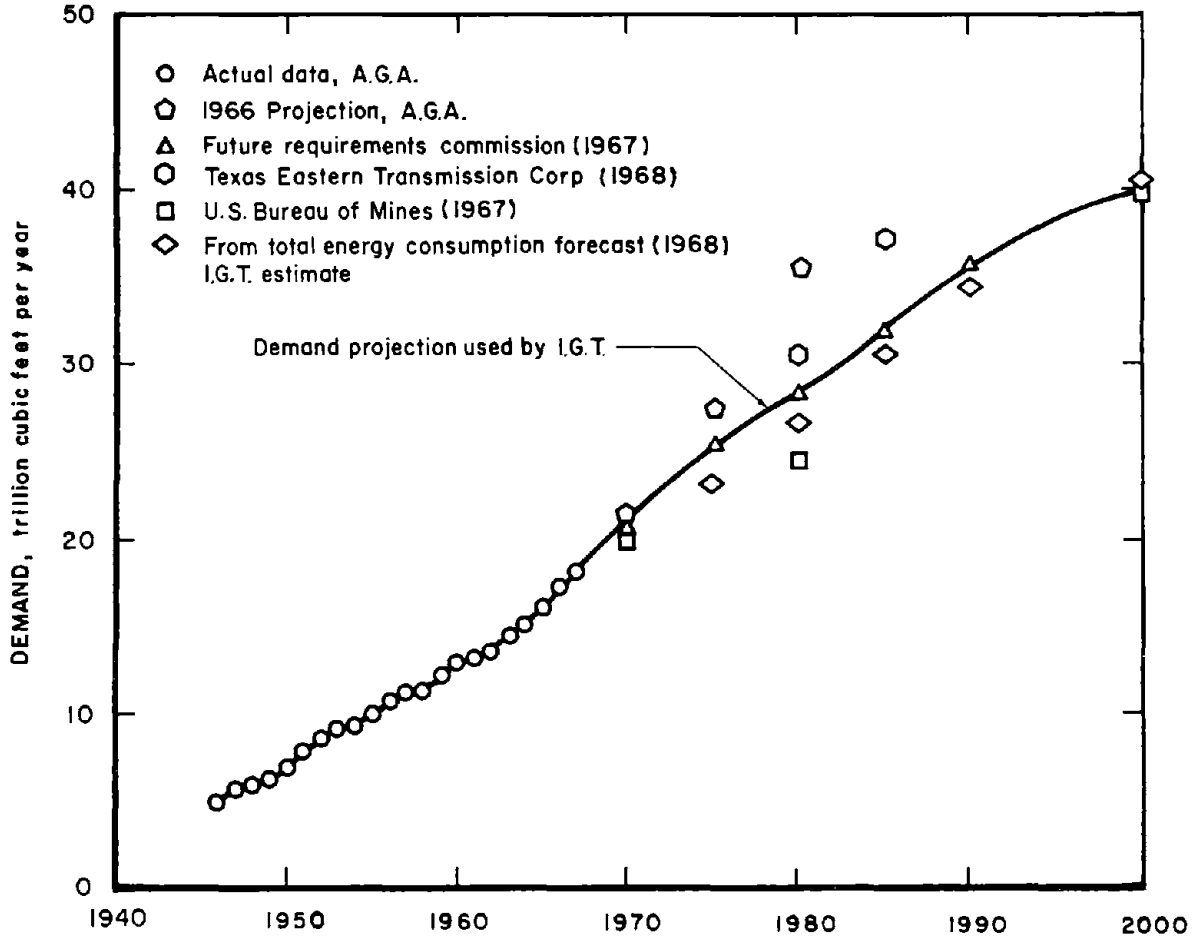

FIGURE 59. - Gas Demand Projections to the Year 2000.

corresponding gas reserves computed from projected gas/oil production ratios.[8] Typical of such geological estimates that also include considerations of economic feasibility are those of the Potential Gas Committee[9] (1,290 trillion cu ft) and the U.S. Geological Survey[10] (2,000 trillion cu ft). The latter estimate specifically excludes the outer continental shelf from 120 to 600 ft of ocean depth, which was recently included to update the corresponding crude oil originally-in-place estimate.[11] A notable characteristic of these geological estimates has been their sharp upward trend over the years as the extent

[8]McKelvey, V. A. Contradictions in Energy Resources Estimates. Proc. Seventh Biennial Gas Dynamics Symposium, ed. by L. B. Holmes. Northwestern University Press, Evanston, Ill., Aug. 23-25, 1967, pp. 13-26.

[9]Potential Gas Committee, Potential Gas Agency. Potential Supply of Natural Gas in the United States as of December 31, 1966. Mineral Resources Institute, Colorado School of Mines Foundation, Inc., Golden, Colo., 1967, 38 pp.

[10]Hendricks, T. A. Resources of Oil, Gas, and Natural Gas Liquids in the United States and the World. U.S. Geol. Survey Circ. 522, 1965, 20 pp.

[11]Work cited in footnote 7.

of actual and inferred reservoirs became better known and as advancing technology allowed the inclusion of potential reserves at greater depths and farther off-shore.

The ultimate reserves are only one of many factors to be considered in gas supply. For the shorter range, the future rates of gas discovery and sustainable production (deliverability) are more important. When the time variable is introduced, geologic considerations alone are no longer sufficient, and changing economic, regulatory, and technologic forces must be considered. In view of the complexity of these variables, the approach must by necessity be empirical. M. A. Elliott and coworkers[12] developed such an approach in the form of a mathematical model of natural gas discovery and production, based on historical data from 1945-46 on, when reliable statistics first became available. The underlying philosophy in using such a model in forecasting is that the historical data reflect the evolution of the same forces, as will be operative in the foreseeable future, and that these forces will affect the behavior of the natural gas supply system the same way in the future as in the past.

The latest version of this model was based on data from 1946 through 1965 and was used to make projections to the year 2000.[13] For the purpose of this publication, it has been updated to (1) include data for 1966 and 1967, (2) correct the pressure base for measuring gas volume from 14.65 to 14.73 psia, and (3) redefine several of the basic variables to make them consistent with corresponding values reported by A.G.A.[14] This results in the following mathematical expressions:

$$P' = 0.00869\ (D')^{1.636} \tag{1}$$

$$R'/p = e^{2.855}\ (R'/P')^{0.1873} - 1 \tag{2}$$

$$R' = (P'/0.00869)^{1/1.636} - P' \tag{3}$$

$$d/p = 11.12\ (P')^{-0.389} \tag{4}$$

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[12] Elliott, M. A. The Role of Gas in Meeting Future Energy Demands. Proc. Pacific Coast Gas Assoc., v. 50, 1959, pp. 26-32.
Elliott, M. A. The Role of Gas in Meeting Future Energy Demands. Midwest Eng., v. 12, May 1960, pp. 8-15.
Elliott, M. A. Future Gas Supply and the Competitive Position. Gas Age, v. 124, October 1959, pp. 21-24.
Elliott, M. A., and H. R. Linden. A New Analysis of U.S. Natural Gas Supplies. J. of Petrol. Technol., v. 20, February 1968, pp. 135-141.
Elliott, M. A. Role of Fossil Fuels in Meeting Future Energy Demands. Proc. Am. Power Conf., v. 24, 1962, pp. 541-562.
Elliott, M. A. Forecasts of Total Energy Requirements and Supply. Proc. Am. Gas Assoc., Inc., Operating Section, Paper No. 64, 1964, pp. 211-217.
Elliott, M. A., and C. G. von Fredersdorff. Natural Gases of North America. AAPG, Memoir No. 9, v. 2, 1968, pp. 2171-2184.

[13] Fourth reference cited in footnote 12.

[14] American Gas Association, Inc., American Petroleum Institute, and Canadian Petroleum Association (joint publication). Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada as of December 31, 1967. Reserves Series, v. 22, May 1968, 309 pp.

where P' = total (cumulated) net production up to the end of any given calendar year. This corresponds to the total (cumulative) annual production values reported by A.G.A., less 35 trillion cu ft for estimated pre-1946 field waste;

D' = total (cumulated) net discoveries up to the end of any given calendar year. This corresponds to the totals of annual discoveries of reserves reported by A.G.A., less 35 trillion cu ft for estimated pre-1946 field waste;

R' = proved net reserves at yearend. This corresponds to the proved reserves reported by A.G.A., less the total gas in underground storage at yearend;

p = annual production, or rate of production, for any given year. This corresponds to the preliminary net production during the year reported by A.G.A.;

e = base of the natural system of logarithms, 2.71828;

and d = annual discoveries, or rate of discoveries, for any given year. This corresponds to the total additions to proved reserves (discoveries, revisions, and extensions) during the year reported by A.G.A.

Equations 1-4 are identical in form to those presented earlier,[15] but incorporate minor changes in the numerical constants. Three of the basic variables have also been labeled with primes (P', D', R') to identify them as "net" values in relation to those reported by A.G.A., as defined above. With equations 1-4, all the variables defined above can be expressed as implicit functions of time by numerical integration with a computer. A summary of the results of these computations for the years 1968-2000 is given in table 13 together with actual data for 1967. A complete presentation of the natural gas discovery and production data predicted by the mathematical model, with superimposed actual data where available, is shown in figures 60-62. The validity of this model (also referred to as the IGT model later in the text) is supported by the excellent fit to the historical data. As noted before, its use here to forecast domestic natural gas discovery and production is based on the assumption that changes in the economic, regulatory, and technologic environment will continue to be of the same evolutionary nature as in the past. Any revolutionary changes in these environmental factors would, of course, invalidate the forecast.

It is of interest that the mathematical model described above also predicts ultimate gas reserves. This corresponds to the solution of equation 1 when P' = D', that is, when total production equals total discoveries. The value obtained in this manner is 1,740 trillion cu ft, which is within the range of current geologic estimates (table 14). It has, however, no direct geologic significance but, rather, indicates what the total quantity of economically recoverable gas would ultimately be if historical trends continue.

[15] Fourth reference cited in footnote 12.

TABLE 13. - U.S. natural gas supply projections based on updated IGT model (1968-2000)

End of year	Trillion cubic feet					(R'/p) Proved net reserves to annual production ratio, years
	(D' + 35) Total discoveries[1]	(P' + 35) Total production	(R') Proved net reserves[2]	(p) Annual production	(d) Annual discoveries	
1967 (Actual)[3].....	619.73	330.20	289.53	18.38	21.80	15.75
1968.....	645.66	348.76	296.91	18.71	22.52	15.87
1969.....	668.53	368.20	300.33	19.45	22.86	15.44
1970.....	691.71	388.38	303.33	20.18	23.19	15.03
1971.....	715.20	409.29	305.91	20.91	23.48	14.63
1972.....	738.97	430.93	308.04	21.63	23.77	14.24
1973.....	762.99	453.27	309.72	22.34	24.02	13.86
1974.....	787.25	476.31	310.94	23.04	24.26	13.49
1975.....	811.71	500.04	311.68	23.72	24.47	13.14
1976.....	836.36	524.42	311.94	24.39	24.65	12.79
1977.....	861.17	549.45	311.72	25.03	24.81	12.45
1978.....	886.11	575.10	311.01	25.65	24.94	12.13
1979.....	911.15	601.34	309.81	26.24	25.04	11.81
1980.....	936.27	628.14	308.12	26.80	25.12	11.50
1981.....	961.43	655.48	305.95	27.33	25.16	11.19
1982.....	986.62	683.31	303.31	27.83	25.18	10.90
1983.....	1,011.79	711.60	300.19	28.29	25.17	10.61
1984.....	1,036.92	740.32	296.61	28.71	25.13	10.33
1985.....	1,061.99	769.41	292.57	29.10	25.06	10.06
1986.....	1,086.95	798.85	288.11	29.43	24.97	9.79
1987.....	1,111.79	828.57	283.22	29.73	24.84	9.53
1988.....	1,136.47	858.55	277.92	29.98	24.68	9.27
1989.....	1,160.97	888.72	272.25	30.17	24.50	9.02
1990.....	1,185.25	919.05	266.20	30.32	24.28	8.78
1991.....	1,209.28	949.47	259.82	30.42	24.04	8.54
1992.....	1,233.05	979.94	253.11	30.47	23.76	8.31
1993.....	1,256.51	1,010.40	246.11	30.46	23.46	8.08
1994.....	1,279.65	1,040.81	238.84	30.41	23.14	7.86
1995.....	1,302.43	1,071.10	231.33	30.29	22.78	7.64
1996.....	1,324,83	1,101.23	223.60	30.13	22.40	7.42
1997.....	1,346.83	1,131.14	215.69	29.91	22.00	7.21
1998.....	1,368.39	1,160.78	207.62	29.64	21.57	7.01
1999.....	1,389.51	1,190.09	199.42	29.31	21.11	6.80
2000.....	1,410.15	1,219.02	191.13	28.93	20.64	6.61

[1] Includes 35 trillion cu ft of estimated pre-1946 waste.

[2] Excludes gas in underground storage; as of Dec. 31, 1967, 292.91 trillion cu ft proved reserves less 3.38 trillion cu ft in storage.

[3] American Gas Association, Inc., American Petroleum Institute, and Canadian Petroleum Association (joint publication). Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada as of December 31, 1967. Reserves Series, v. 22, May 1968, 309 pp.

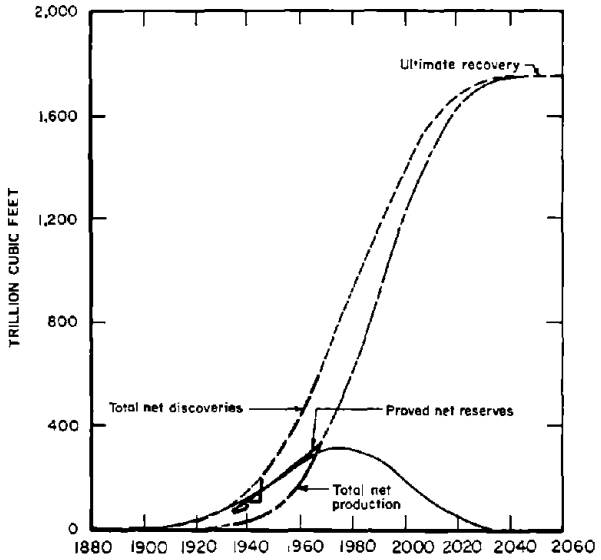

FIGURE 60. - Calculations From the Natural Gas Model for Discoveries, Reserves, and Production.

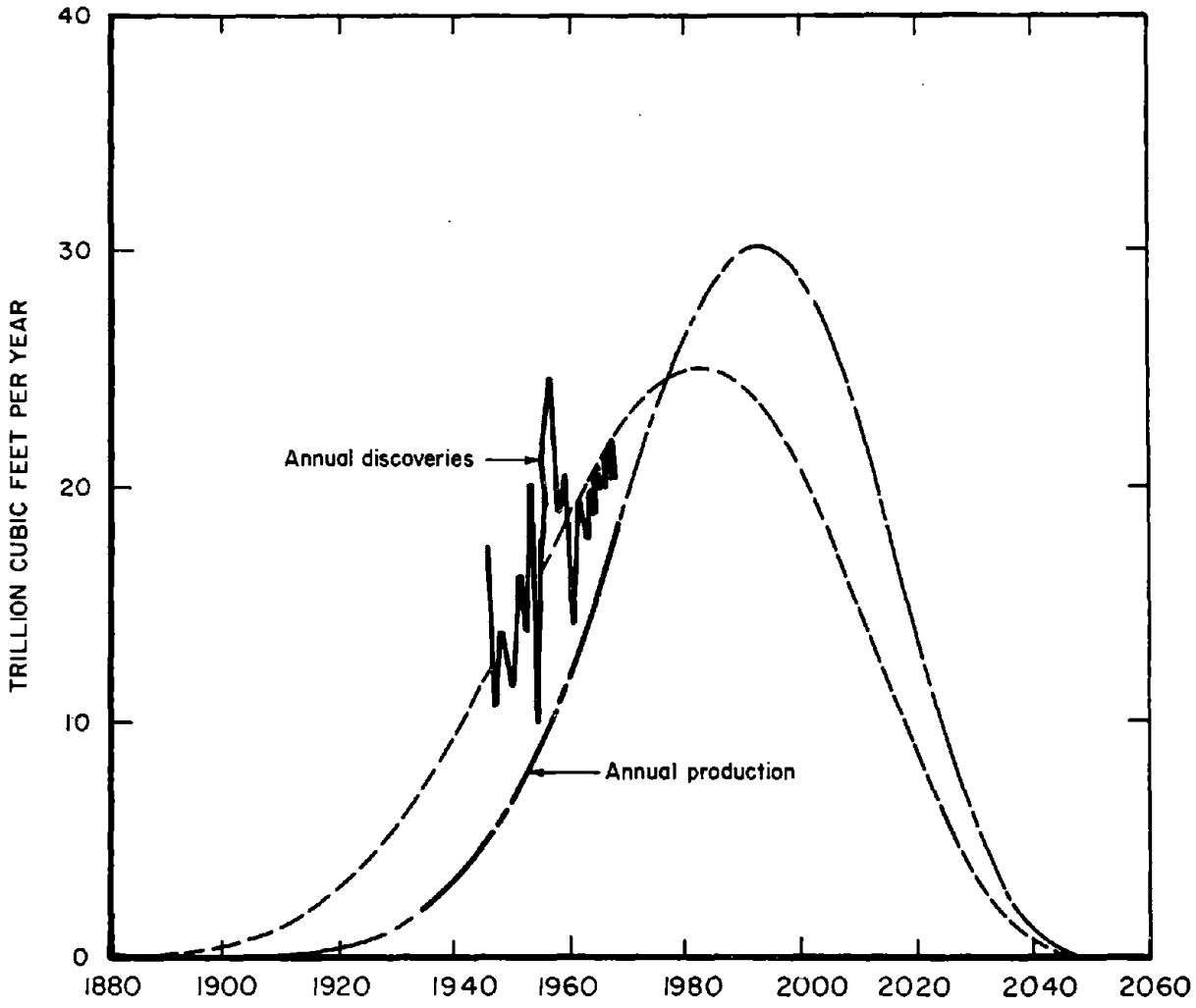

FIGURE 61. - Annual Discoveries and Annual Production as Predicted From the Natural Gas Model.

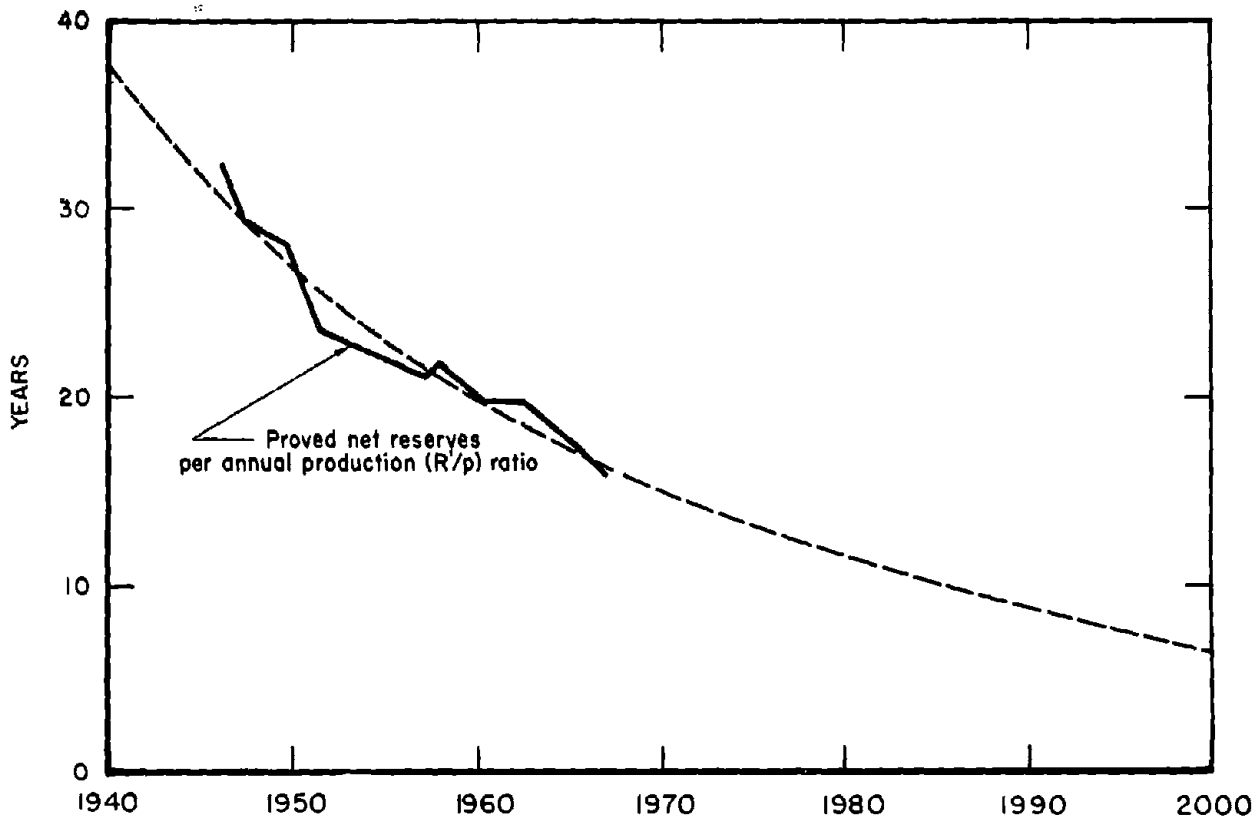

FIGURE 62. - Proved Net Reserves/Annual Production Ratio Predicted From the Natural Gas Model.

TABLE 14. - Ultimately recoverable natural gas reserves, trillion cubic feet[1]

Source	Potential Gas Committee,[2] Dec. 31, 1966	IGT, this study, Dec. 31, 1967	U.S. Geological Survey,[3] 1965
Proved reserves[4]	286	293	-
Future discoveries	690	1,152	-
Total remaining recoverable.	976	1,445	-
Produced to date	314	[5]295	-
Ultimately recoverable	1,290	1,740	2,000

[1]All gas volumes at 60° F and 14.73 psia.
[2]Potential Gas Committee, Potential Gas Agency. Potential Supply of Natural Gas in the United States as of Dec. 31, 1966. Mineral Resources Institute, Colorado School of Mines Foundation, Inc., Golden, Colo., 1967, 38 pp.
[3]Hendricks, T. A. Resources of Oil, Gas, and Natural-Gas Liquids in the United States and the World. U.S. Geol. Survey Circ. 522, 1965, 20 pp.
[4]Including gas in underground storage.
[5]Excluding 35 trillion cu ft of pre-1946 field waste.

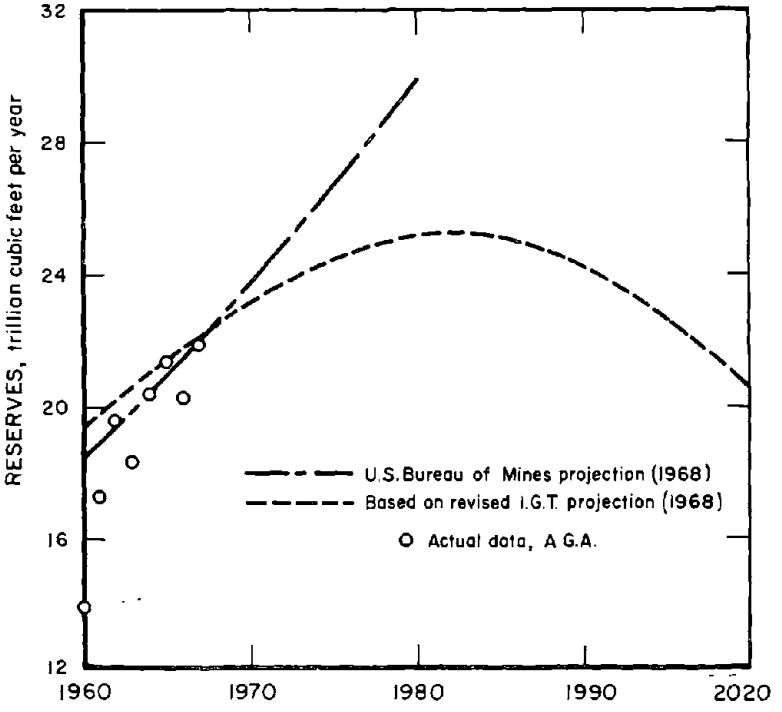

FIGURE 63. - Gross Additions to Proved U.S. Natural Gas Reserves.

Balance of Gas Supply and Demand

Although annual discoveries (gross additions to proved reserves) of natural gas in the United States are on a general upward trend and are currently 22 trillion cu ft per year, most forecasters do not expect them to increase substantially in the foreseeable future. For example, as shown in table 13, the updated IGT model of natural gas discovery and production in the United States projects that discoveries will level out at about 25 trillion cu ft annually in the late 1970's and during the 1980's, then decline to about 21 trillion cu ft by the year 2000. This adds up to a new supply for the period 1968-2000 of about 790 trillion cu ft. Experts who usually reflect the producer's viewpoint, such as Radford L. Schantz of Foster Associates,[16] are relatively more pessimistic.

In contrast, the recent forecast by the U.S. Department of the Interior[17] is much more optimistic (fig. 63). It assumes an increase in gas discoveries of 2.2 percent per year over the period 1965-80, reaching about 30 trillion cu ft in 1980. If this rate of increase were extended to the year 2000, annual discoveries would reach 46 trillion cu ft at that time, for a total over the period 1968-2000 of about 1,100 trillion cu ft.

Adding proved reserves of roughly 290 trillion cu ft to these forecasts of new gas discoveries brings total United States supplies for the rest of the century to nearly 1,100 trillion cu ft (IGT) and possibly as high as 1,400 trillion cu ft (U.S. Department of the Interior). This is approximately the same range as that of two estimates of total remaining recoverable natural gas supply: Potential Gas Committee--980 trillion cu ft; IGT--1,450 trillion

[16] Schantz, Radford L. Economic Evidence Pertaining to Natural Gas Supplies in the United States and in the Other Southwest Area. Foster Assoc. Inc., Washington, D.C. (Official Stenographic Report before the Federal Power Commission in the matter of Area Rate Proceedings, Federal Power Commission Docket No. AR 67-1, Exhibit No. 4, p. 923; also pp. 1035-1104, Direct Testimony, Jan. 10, 1968.)

[17] Work cited in footnote 7.

cu ft (table 14). Only the 1965 estimate by the U.S. Geological Survey suggests that economically recoverable natural gas supplies will not be exhausted around or soon after the end of the century.

These forecasts of potential natural gas supply can now be compared with the demand projection shown in figure 65, which adds up to a total requirement of 1,030 trillion cu ft for the period 1968-2000. It should be noted here that this estimate of demand is probably conservative compared with the much higher A.G.A. and Texas Eastern Transmission Corporation forecasts.

Yet, these higher forecasts probably do not include the effects of such new markets as gas fuel cells, use of liquefied natural gas as a transport fuel, etc. They also may not fully reflect the impact of air quality control on the fuel market. Even this minimum anticipated gas demand exceeds the total remaining supply estimate by the Potential Gas Committee and would nearly exhaust the proved reserves plus new discoveries projected by IGT.

Obviously, the probable discrepancy between projected supply and demand can only be accommodated in the following four ways:

1. Rapid increase in exploration and drilling activity to provide new supplies in the amount projected by the optimistic U.S. Department of the Interior forecast, coupled with an increase in net pipeline imports from Canada and Mexico from the present 0.5 to 1.5 trillion cu ft by 1980. As shown in table 15, this would result in maintaining sufficient proved reserves to stabilize the proved net reserves to annual production (R'/p) ratio at about 10 years beginning in 1990. There is, of course, a question as to the feasibility of this approach, both in regard to adequacy of total natural gas resources (that is, sufficient natural gas deposits to allow discoveries of 1,100 trillion cu ft of new gas in 32 years compared with total discoveries to date of 620 trillion cu ft), and in regard to maintaining a competitive price level for gas while providing sufficient economic incentives to the producers to step up their discovery rate.

2. Rapid depletion of domestic natural gas reserves. This would mean that, on the basis of the Future Requirements Committee-U.S. Bureau of Mines demand forecast and the IGT discoveries forecast, little gas would be left by the year 2000 if supplemental sources of gas are not developed by then (figs. 64-66).

3. Restriction of gas sales to the levels which can be sustained by domestic natural gas production. On the basis of IGT's updated model, this would mean a gradual increase from the 1967 production of 18.4 trillion cu ft, to a maximum of about 30.5 trillion cu ft in the early 90's, followed by a slow decline (fig. 66). This would be accompanied by a gradual decline in the proved net reserves to annual production ratio from the 1967 level of 16 years to about 7 years by the year 2000 (fig. 64).

4. Development of supplemental sources of gas, including greatly increased pipeline imports from Canada, importation of liquefied natural gas (LNG) and production of synthetic pipeline gas from coal.

TABLE 15. - Optimistic forecast of conventional natural gas supply based entirely on U.S. production and pipeline imports, 1968-2000[1]

Year	Trillion cubic feet					Proved net reserves to annual production ratio, years
	Total U.S. gas demand[2]	Net pipeline imports[3]	Domestic natural gas production	Gross additions to proved reserves[4]	Proved net reserves at end of year[5]	
1968.....	19.5	0.5	19.0	23.0	293.5	15.4
1969.....	20.5	.5	20.0	23.5	297.0	14.9
1970.....	21.5	.5	21.0	24.0	300.0	14.3
1975.....	25.5	1.0	24.5	26.7	311.9	12.7
1980.....	28.6	1.5	27.1	29.8	324.1	12.0
1985.....	32.0	1.5	30.5	33.2	337.6	11.1
1990.....	36.0	1.5	34.5	37.0	349.9	10.1
1995.....	38.5	1.5	37.0	41.3	367.2	9.9
2000.....	40.4	1.5	38.9	46.0	396.6	10.2
Total 1968-2000.....	1,030.2	42.0	988.2	1,095.3	-	-

[1]All gas volumes at 60° F and 14.73 psia.

[2]Estimated from Future Requirements Agency, Future National Gas Requirements of the United States: University of Denver, Denver, Colo., v. 2, June 1967. Also, Vogely, W. A., Models of All-Gas and All-Electric Economies: The Seventh Biennial Gas Symposium, Northwestern University, Evanston, Ill., Aug. 23-25, 1967, with necessary interpolations from figure 65 (p. 131 of this publication).

[3]Estimated.

[4]Extended on same basis (2.2 percent per year increase to year 2000) from 1965-1980 projection of Office of Coal and Gas. United States Petroleum Through 1980. U.S. Department of the Interior, July 1, 1968.

[5]Based on 289.5 trillion cu ft of proved reserves less gas in underground storage as of Dec. 31, 1967.

At present, there are no indications that there will be sufficient change in the economic, technological, or regulatory environment to stimulate the needed large increase in gas discoveries. On the other hand, gas demand has been increasing at a consistently higher than predicted rate because of acquisition of new markets in which natural gas is a superior fuel or process feed. Air quality control certainly can be expected to accelerate this trend. Restriction of gas sales is, therefore, not a feasible solution to the supply problem. Consequently, the middle 1970's is the most conservative estimate of the time when average United States natural gas discoveries will equal United States production. At that time, proved net reserves would start to decline and the ratio of proved net reserves to annual production would continue its nearly linear drop from the 1967 level of 16 years to approach exhaustion by the year 2000 (figs. 64-65). This again cannot be accepted because of its effect on investor and consumer confidence. Thus, the only rational course is

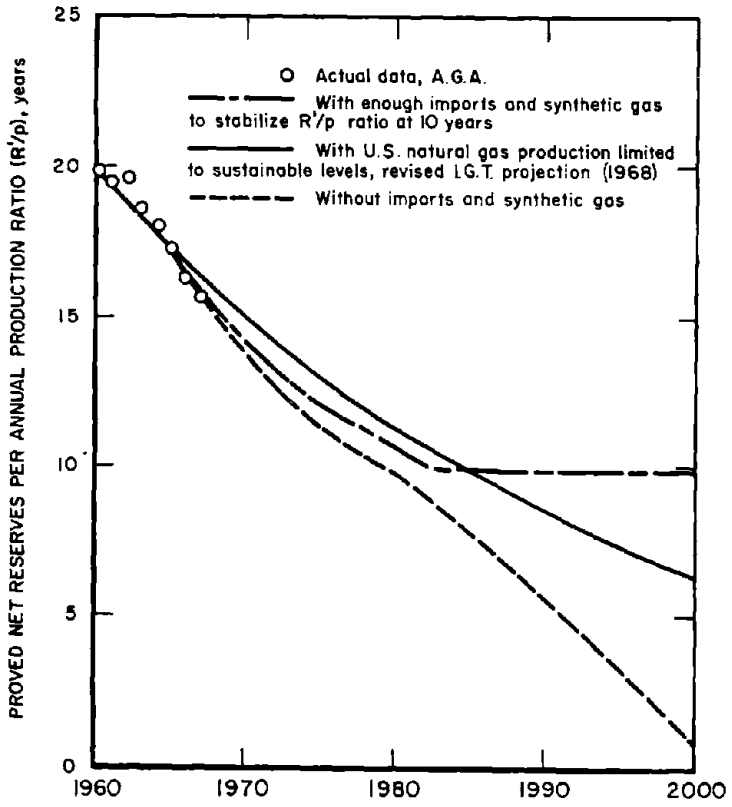

FIGURE 64. - Proved Net Reserves/Annual Production Versus Years on Various Bases.

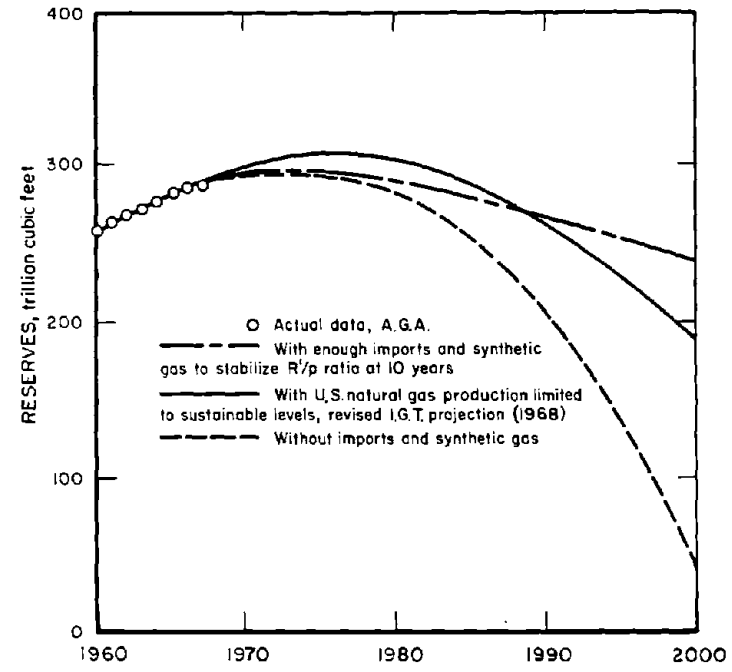

FIGURE 65. - Proved Net U.S. Natural Gas Reserves Versus Years on Various Bases.

to attempt to change these trends by means of gas imports and synthetic pipeline gas from coal.

Sources of Supplemental Gas

Walter Levy, well-known petroleum industry consultant, has estimated that the present imports of Canadian gas of less than half a trillion cu ft per year could be stepped up to about 1.3 trillion cu ft by 1975.[18] Similarly, Radford L. Schantz estimates the Canadian import potential at 1.35 trillion cu ft by 1980.[19] This would be a small but important increment in reducing the gas shortage.

Importation of LNG also looks promising. If all of the importation projects presently under discussion would materialize, they would amount to 1.5 trillion cu ft per year.[20] In view of attaining about 900 trillion cu ft of proved gas reserves outside of the United States, mostly in underdeveloped countries, and the rapid increase of these reserves, there is every reason to be highly optimistic

[18] Oil and Gas Journal. Canada Destined for Major Role as Gas Supplier for U.S. Markets. V. 65, June 19, 1967, pp. 98-102.

[19] Reference cited in footnote 16.

[20] Lofstrom, J. R., and T. J. Joyce. LNG--The Fuel With a Future. Gas Scope. Inst. of Gas Technol., Chicago, Ill., No. 6, Apr. 28, 1968, pp. 1-6.

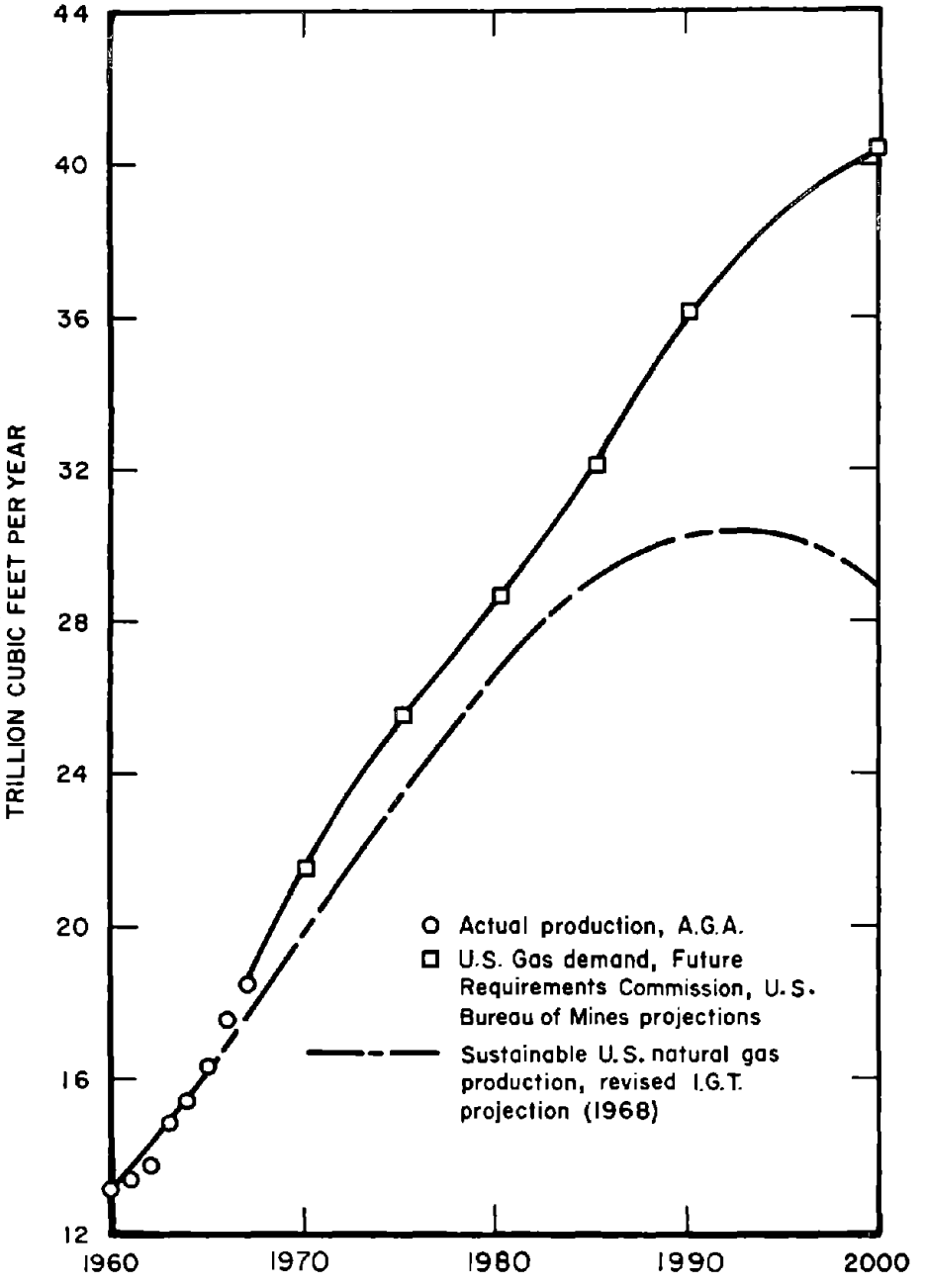

FIGURE 66. - U.S. Gas Demand and Sustainable U.S. Production Versus Years.

about this source of supply. LNG production, transportation and storage technology, and economics are improving rapidly as a result of the many international projects under way and the many more in the construction and planning stages. Estimated costs of imported LNG, for example from Venezuela to the eastern seaboard, are about 40 cents per mcf--not too far above the cost of pipeline gas from the Gulf coast. A total LNG import potential of several trillion cu ft per year can thus be visualized.

However, synthetic gas from coal is the most realistic long-range source of supplemental gas. The supply of minable coal, after allowing for coal requirements for conventional purposes to the year 2000, is enough to produce 11,000 trillion cu ft of natural gas equivalent. About $20 million is now committed and has been spent by A.G.A., the Office of Coal Research, and private companies at IGT alone, to develop and improve the coal gasification process. About as much has been and is being spent at the U.S. Bureau of Mines, Consolidation Coal Company, Bituminous Coal Research, Inc., and others, again largely with Office of Coal Research support. With the present level of funding, it should be possible to build the first commercial plant by the middle 1970's and to make a significant impact on gas supply in the early 1980's.

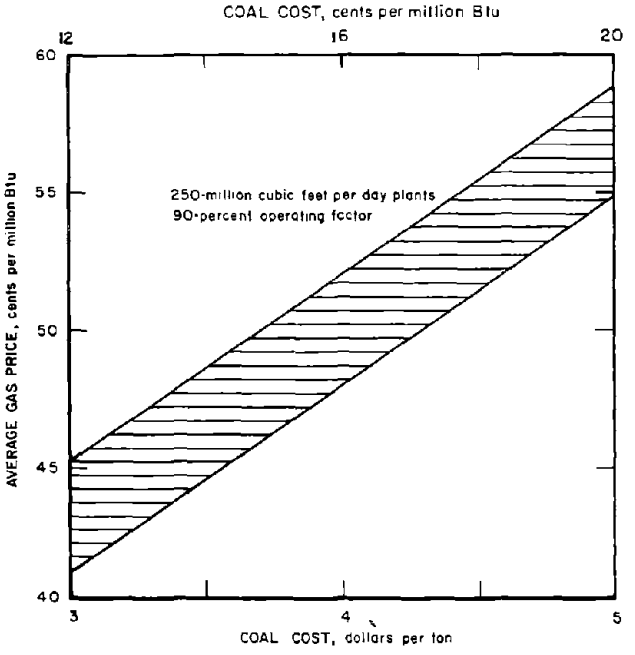

FIGURE 67. - Average Gas Price Depending on Cost of Coal.

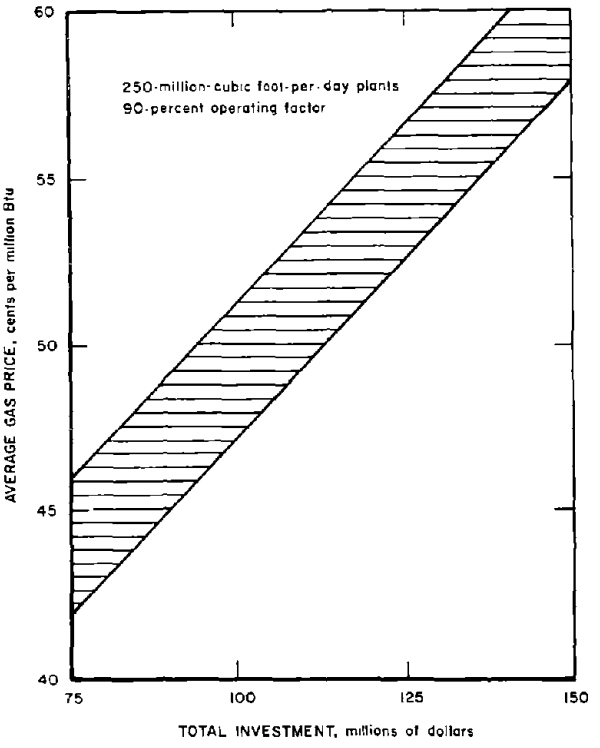

FIGURE 68. - Average Gas Price Depending on Total Investment.

The estimated 20-year average selling price for synthetic pipeline gas from the preferred bituminous coal gasification processes is presently 50 cents per million Btu with $4-per-ton coal. The corresponding gas price for $1.50-per-ton lignite is about 40 cents per million Btu. Substantial reductions in these gas prices are possible by using lower cost, low-grade coals (such as high-sulfur bituminous coals), and process improvements leading to lower investment costs. The approximate effect of these variables on gas price is shown in figures 67-68.

Requirements for Supplemental Gas

After the preceeding assessment of natural gas supply and demand, and of technical and economic feasibility of supplemental gas sources, an estimate of the quantities of supplemental gas required can be made. The following assumptions were used for this purpose:

1. United States gas demand will be that estimated by the Future Requirements Committee to the year 1990, as extended to the year 2000 by means of the most recent U.S. Bureau of Mines estimate for that year. As noted before, these estimated demands are quite conservative for 1980 and beyond.

2. Net natural gas imports by pipeline from Canada and Mexico are assumed to increase from the present 0.5 trillion cu ft per year to 1.5 trillion cu ft by 1980, and then remain at that level.

3. Gross additions to United States natural gas reserves (discoveries) are assumed to follow the updated IGT model projection, that is, to peak at 25.2 trillion cu ft per year in 1981-1983 and then decline slowly to 20.6 trillion cu ft per year in 2000.

4. United States natural gas production will be used to meet the total demand less net pipeline imports from Canada and Mexico, until the proved net reserves to annual production (R'/p) ratio drops to 10 years. At that time, domestic production will be restricted to maintain the R'/p ratio at 10, and excess demand will be met with synthetic pipeline gas from coal and imported LNG. An R'/p ratio of 10 years is probably the lowest average level that will allow sufficient lead time to develop replacements for depleting supplies.

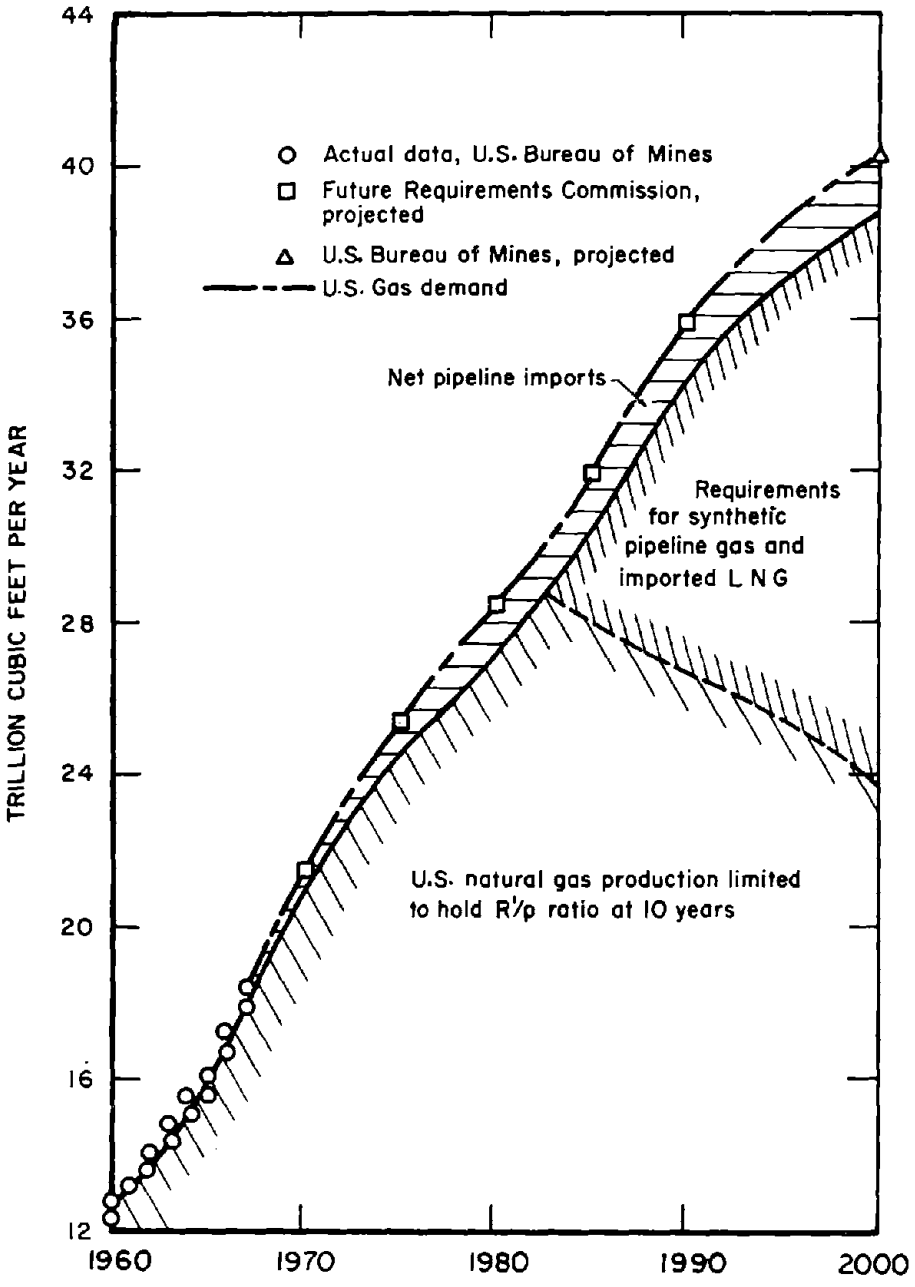

FIGURE 69. - Source of Natural Gas To Meet U.S. Future Demand.

As shown in table 16 and figure 69, on the basis of the above conservative assumptions for gas demand, and what seem to be reasonable assumptions of new natural gas supply, it would be necessary to provide supplemental gas in increments averaging 0.83 trillion cu ft per year beginning in 1983, to a total of 15 trillion cu ft per year by the year 2000. Annual capital investment to make available this quantity of synthetic pipeline gas and/or imported LNG would average $1 billion (table 16).

TABLE 16. - Realistic forecast of U.S. gas supply including requirements for supplemental gas, 1968-2000[1]

Year	Trillion cubic feet					Proved net reserves to annual production ratio, years	Required synthetic gas from coal and LNG imports, trillion cu ft	Total investment in synthetic pipeline gas and LNG imports,[7] billion dollars
	Total U.S. gas demand[2]	Net pipeline imports[3]	Gross additions to proved reserves[4]	Domestic natural gas production[5]	Proved net reserves at yearend[6]			
1968.....	19.5	0.5	22.5	19.0	293.0	15.4	0	0
1969.....	20.5	.5	22.9	20.0	295.9	14.8	0	0
1970.....	21.5	.5	23.2	21.0	296.1	14.1	0	0
1975.....	25.5	1.0	24.5	24.5	302.1	12.3	0	0
1980.....	28.6	1.5	25.1	27.1	296.0	10.9	0	0
1985.....	32.0	1.5	25.1	28.1	280.5	10.0	2.4	3.1
1990.....	36.0	1.5	24.3	26.8	267.5	10.0	7.7	10.0
1995.....	38.5	1.5	22.8	25.5	254.7	10.0	11.5	15.0
2000.....	40.4	1.5	20.6	23.9	239.5	10.0	15.0	19.5
Total 1968-2000.....	1,030.2	42.0	787.1	837.1	-	-	151.1	-

[1]All gas volumes at 60° F and 14.73 psia.
[2]Estimated from Future Requirements Agency, Future National Gas Requirements of the United States: University of Denver, Denver, Colo., v. 2, June 1967. Also, Vogely, W. A., Models of All-Gas and All-Electric Economies: The Seventh Biennial Gas Symposium, Northwestern University, Evanston, Ill., Aug. 23-25, 1967, with necessary interpolations from figure 65 (p. 131 of this publication).
[3]Estimated.
[4]From updated IGT mathematical model of U.S. natural gas discovery and production.
[5]Computed on basis that proved net reserves to annual production ratio does not fall below 10 years.
[6]Based on 289.5 trillion cu ft of proved reserves less gas in underground storage as of Dec. 31, 1967.
[7]On assumption of $1.3 billion investment required per trillion cu ft per year of synthetic pipeline gas or LNG delivered.

Impact of Supplemental Gas on Primary Energy Consumption Projections

In table 17, the data of table 12 are adjusted to gas consumptions corresponding to the Future Requirements Committee-U.S. Bureau of Mines projections. Although this slightly distorts the reconciled primary energy consumptions in favor of gas for the period 1970-90, it allows us to assess the effects of synthetic gas production from coal on the basis of the same gas demands used throughout this study.

TABLE 17. - Impact of synthetic pipeline gas from coal on primary U.S. energy consumption projections[1]

	1967[2]	1970	1975	1980	1985[3]	1990[3]	2000[3]
Total energy consumption, quadrillion (10^{15}) Btu..	59.179	[4]66	[4]78	[4]93	[4]110 (112)	[4]128 (134)	[4]170 (182)
Gas consumption, trillion cu ft:							
Dry natural gas.....	17.885	[5]21.5	[5]25.5	[5]28.6	[5]32.0 (29.6)	[5]36.0 (28.3)	[5]40.4 (25.4)
Synthetic pipeline gas from coal.....	-	-	-	-	- (2.4)	- (7.7)	- (15.0)
Consumption, percent:							
Coal.....	21.9	21.0	19.5	18	17 (20.5)	15 (25)	12 (26.5)
Dry natural gas.....	31.2	33.5	33.5	31.5	30 (27)	29 (22)	24.5 (14.5)
Petroleum (incl. natural gas liquids).....	42.8	41.5	40	39.5	39 (38.5)	38 (36)	35.5 (33)
Hydropower.....	4.0	3.5	3	3	3 (3)	3 (3)	3 (3)
Nuclear.....	.1	.5	4	8	11 (11)	15 (14)	25 (23)
Total.....	100.0	100.0	100.0	100.0	100 (100)	100 (100)	100.0 (100)
Coal consumption, million tons.....	495	530	580	640	710 (880)	730 (1280)	780 (1840)

[1]Heating value of dry natural gas and synthetic pipeline gas--1,032 Btu/cu ft, and heating value of coal--26.2 million Btu/ton, in accordance with U.S. Bureau of Mines practice.
[2]From Department of Statistics, American Gas Association, Inc., 1968 Gas Facts. A Statistical Record of the Gas Utility Industry, 1967 Data (U.S. Bureau of Mines Preliminary Data), New York, 1968, 256 pp. (table 13, p. 20, and table 14, p. 21).
[3]Values in parentheses based on updated IGT projection for supplemental gas requirements (table 16), and on the use of 70 million tons of coal per trillion cu ft of synthetic pipeline gas produced.
[4]Taken from table 12 and figure 64.
[5]See footnote 2, table 15.

If we assume that the natural gas supply deficiencies projected in figure 69 and table 16 are met entirely with pipeline gas from coal, the anticipated decline in the share of the primary energy market for coal would be dramatically reversed. By the year 2000, coal consumption would exceed 1,800 million tons, corresponding to over 26 percent of total primary energy demand, while natural gas (including pipeline imports) would supply less than 15 percent of primary energy consumption. There would also be an increase in total energy requirements due to the inefficiencies in converting coal to gas, very conservatively estimated at 56 percent (or 70 tons of coal per million cu ft of 1,032 Btu per cu ft pipeline gas). The reason for this relatively low efficiency value is that no credit for byproduct fuels and energy is taken.

It should be noted that a reversal of the trend toward a declining market share for coal may occur earlier than indicated. Large-scale synthetic gas production from coal may start sooner than 1983 in view of the conservatism of the demand projections used here. Further, synthetic liquid fuels may create a significant new market for coal. Offsetting

this would be importation of liquefied natural gas from overseas to meet a portion of the supplemental gas requirements.

Conclusion

Although there are now on record independent forecasts of natural gas supply (U.S. Department of the Interior, 1968) and demand (Future Requirements Committee, 1967) that are compatible through 1980, if these forecasts are extended to the year 2000, there still appears to be a high probability of inadequate gas supplies beginning in the middle 1970's. The reason is that some recent forecasts project much higher gas demands than the Future Requirements Committee, and most forecasts project much lower gas discovery rates than the U.S. Department of the Interior. There is yet no evidence that forces capable of correcting the static supply situation are being mobilized. Further, recent experience has shown a consistent trend of growth in gas use that is higher than projected growth rates. For example, the effects of the present effort on air pollution abatement favors natural gas over other fossil fuels. This could lead to its extensive use in new applications (such as stationary fuel cells and, in liquid form, as transport fuel). However, this use may not yet be reflected in current forecasts. The alternatives of (a) rapidly depleting available natural gas supplies to meet all market demands without concern for the future, or (b) restricting the use of natural gas, appear to be unacceptable. The only practical alternative, therefore, seems to be to rapidly develop supplemental sources of pipeline-quality gas in the form of imports from Canada and as liquefied natural gas from overseas: also, synthetic gas from coal. These sources appear to be both technically and economically feasible and capable of meeting any reasonable projections of gas shortages to the end of the century at a relatively small premium over conventional supply.

LIGNITE FLY ASH UTILIZATION

By Oscar E. Manz[1]

Introduction

Since 1967 there has been significant support for research into the utilization of lignite fly ash. This is caused in part by the successful fly ash symposium held in Pittsburgh in 1967 as well as the ever growing problem of fly ash disposal from lignite powerplants.

The Civil Engineering Department of the University of North Dakota has been doing research with lignite fly ash from Otter Tail Power and Basin Electric plants. The research has been concerned with developing fly ash-based brick and stabilizing soil and other aggregates by the addition of fly ash.

In contrast to bituminous fly ash, the high lime content (20 to 35 percent) of lignite fly ash has proven very beneficial; it has been possible to produce both unfired and fired dry-pressed brick that contains only fly ash and complies with ASTM specifications for grade SW fired brick. Also, minimal shrinkage and warpage have resulted. Further work is continuing with fired brick and ceramic glazing.

The use of up to 50 percent fly ash in mixtures involving granular material or naturally fired shale (scoria), plus sufficient water to produce a 3-in slump, have produced a 7-day compressive strength of 675 psi, a 28-day strength of 1,155 psi, and a 90-day strength of 2,100 psi.

Another phase of the investigation has indicated the feasibility of using Basin lignite fly ash as filler in asphaltic concrete.

This paper will report on lignite fly ash research exclusive of that found in either the author's previous paper[2] or the Proceedings of the 1967 Pittsburgh Fly Ash Symposium.[3]

In addition to work being done at the University of North Dakota, some other research organizations in the United States are also involved in lignite fly ash research.

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[2]Manz, O. E. Utilization of Lignite Fly Ash. Paper in Technology and Use of Lignite. Proceedings: Bureau of Mines-University of North Dakota Symposium, Bismarck, N. Dak., Apr. 29-30, 1965, comp. by James L. Elder and Wayne R. Kube. BuMines Inf. Circ. 8304, 1966, pp. 66-78.

[3]Faber, John H., John P. Capp, and John D. Spencer (compilers). Fly Ash Utilization. Proceedings: Edison Electric Institute-National Coal Association-Bureau of Mines Symposium, Pittsburgh, Pa., Mar. 14-16, 1967. BuMines Inf. Circ. 8348, 1967, 345 pp.

Other Research on Lignite Fly Ash

The Civil Engineering Department of North Dakota State University at Fargo, N. Dak.,[4] has published a report of their investigation of lignite fly ash as a mineral filler in bituminous concrete. It was found that the fly ash obtained from the Otter Tail Power Company's Hoot Lake plant at Fergus Falls, Minn., was suitable for use in asphaltic concrete.

The Virginia Polytechnic Institute at Blacksburg, Va.,[5] is conducting research involving the agricultural potential of fly ash (including both bituminous and lignite). This soil fertility research is designed to give needed applied and basic information regarding fly ash application to soil.

A pilot plant in operation at Morgantown, W. Va.,[6] has been involved with production of full-sized bricks made from eight different fly ashes, one of which was fly ash from a Montana lignite. It was reported that a common problem involving the use of fly ash is the presence of soluble minerals such as sulfates of potassium, magnesium, sodium, and calcium. The addition of hydrochloric acid was advantageous with some fly ashes, but produced no measurable improvement when used with lignite fly ash.

An extensive report by Minnick[7] deals with reactions of calcium and magnesium oxides and hydroxides with pulverized coal fly ash. A total of eight fly ashes were investigated, including four lignite fly ashes. A number of the fly ashes, particularly the lignite fly ashes, form complex silicates and calcium sulfoaluminates in a relatively short time when cured in the presence of moisture.

Lignite Fly Ash Research at the University of North Dakota

Since publication of the author's "Utilization of Lignite Fly Ash" in 1966, two more Master of Science theses involving use of lignite fly ash in concrete have been completed by Civil Engineering students at the University of North Dakota.[8]

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[4] Brahma, S. P. Use of Lignite Fly Ash as a Mineral Filler in Bituminous Concrete. North Dakota State University, Fargo, N. Dak. Engineering Experiment Station Series, No. 13, August 1968, 26 pp.

[5] Martens, David C. (Assistant Professor of Agronomy, College of Agriculture, Virginia Polytechnic Inst., Blacksburg, Va.). Personal communication, Jan. 17, 1968, 1 p. (available from author).

[6] Shafer, H. E., Jr., C. F. Cockrell, and J. W. Leonard. A New and Low Cost Method for Making Structural Materials From Problem Fly Ashes and From Fly Ashes Likely to Originate From Certain Potential Air Pollution Control Processes. Coal Research Bureau, West Virginia University, Tech. Rept. No. 34, 1968, 20 pp.

[7] Minnick, L. J. Reactions of Calcium and Magnesium Compounds With Pulverized Coal Fly Ash. Pres. at Annual Meeting of AIME, New York, Feb. 25-29, 1968, American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, 1968, 50 pp.

[8] Fuller, Roger G. Effects of Lignite and Bituminous Fly Ashes on the Durability and Flexural Strength of Lightweight Concrete. M.S. Thesis, University of North Dakota, 1967, 65 pp. (available from the University of North Dakota library).

Abdulgani, Noufal J. Effect of North Dakota Fly Ash on Air-Entrained and Non-Air-Entrained Structural Concrete. M.S. Thesis, University of North Dakota, 1966, 129 pp. (available from the University of North Dakota library).

In the work, "Effects of Lignite and Bituminous Fly Ashes on the Durability and Flexural Strength of Lightweight Concrete," the aggregate used was a sintered bituminous fly ash material. Both a lignite fly ash and a bituminous fly ash were used in the concrete as a replacement for cement at values of 0, 10, 20, 30, and 40 percent (by weight). No replacement was used with the control mix: cement factors of 4-1/2, 6, and 7-1/2 were used. Table 18 contains information on the properties of both fly ashes.

TABLE 18. - Analysis of fly ash obtained from combustion of North Dakota lignite and Michigan bituminous coal

Item	Federal Specifications SS-P-570B[1]	ASTM C618-68T[2]	North Dakota lignite fly ash	Michigan bituminous fly ash
Sum of SiO_2, Al_2O_3, and Fe_2O_3 weight-percent..	[3]75	[3]70.0	51.0	87.2
MgO.....do.....	[4]5.0	-	6.9	0.9
Na_2O.....do.....	[4]2.0	[4]1.5	3.8	0.3
CaO.....do.....	-	-	29.5	2.7
SO_3.....do.....	[4]4.0	[4]5.0	6.7	0.8
Loss on ignition.....do.....	[4]6.0	[4]12.0	1.4	5.3
Retained on No. 325 sieve....do.....	-	-	13.7	20.8
Surface area.....cm^2/cm^3..	[3]6,500	[3]6,500	5,476	6,227
Specific gravity.....	-	-	2.78	2.35

[1]Federal Specifications. Pozzolan (for use in Portland Cement Concrete). SS-P-570B. U.S. Government Printing Office: 0-342-512(3568), Apr. 18, 1969, 13 pp.

[2]American Society for Testing and Materials. Tentative Specifications for Fly Ash and Raw or Calcined Natural Pozzolans, for Use in Portland Cement Concrete. C618-68T in 1969 Book of ASTM Standards: Part 10, Concrete and Mineral Aggregates. Philadelphia, Pa., October 1969, pp. 384-389.

[3]Minimum.

[4]Maximum.

The following conclusions, concerning the effects of a Michigan bituminous coal fly ash and a North Dakota lignite fly ash on structural lightweight concrete, are based on the results of tests performed on the mixes discussed in this investigation.

1. The addition of fly ash has a negligible effect on the durability of concrete for low cement factors. However, with high cement factors, the durability factor is sharply reduced.

2. At all cement factors investigated, concrete incorporating up to 30 percent fly ash had strength equal to or greater than that of the control mix.

3. Although both fly ashes exhibit similar trends, the bituminous coal fly ash produces concrete of slightly higher durability, and the lignite fly ash produces concrete of slightly higher flexural strength.

The North Dakota lignite fly ash reported in table 18 was used in an investigation involving air-entrained and non-air-entrained structural concrete. Three control mixes were used with cement factors of 4-1/2, 6, and 7-1/2 sacks per cu yd. For each control mix, four additional mixes were made, in which fly ash was used as a partial replacement of cement by weight at values of 10, 20, 30, and 40 percent.

Test results given in table 19 indicate that the ratios of air-entrained to non-air-entrained values of durability increase with increasing fly ash replacements. Except for the 20-percent addition, the ratios of the compressive strengths show a similar increase and ratios of the moduli of rupture decrease for all fly ash replacements.

TABLE 19. - Summary of results for air-entrained and non-air-entrained concrete

Cement factor, sacks/cu yd	Percent of fly ash in non-air-entrained concrete					Percent of fly ash in air-entrained concrete				
	0	10	20	30	40	0	10	20	30	40
DURABILITY FACTOR, PERCENT OF CONTROL MIX										
4-1/2.....	100	95	66	53	53	100	100	98	106	103
6.....	100	75	33	29	21	100	114	116	118	120
7-1/2.....	100	100	88	52	50	100	75	82	92	107
Average.....	100	87	62	45	41	100	96	99	105	110
MODULUS OF RUPTURE, PERCENT OF CONTROL MIX										
4-1/2.....	100	112	109	102	114	100	95	97	91	94
6.....	100	99	97	100	108	100	96	97	95	100
7-1/2.....	100	108	99	119	112	100	109	114	105	104
Average.....	100	106	102	107	111	100	100	103	97	99
COMPRESSIVE STRENGTH, PERCENT OF CONTROL MIX										
4-1/2.....	100	95	84	61	78	100	99	98	98	101
6.....	100	99	98	107	91	100	100	87	87	92
7-1/2.....	100	103	109	114	113	100	110	91	89	94
Average.....	100	99	97	94	94	100	103	92	91	98

Since June 1, 1967, the author has been director of a lignite fly ash research project sponsored by the Otter Tail Power Company of Fergus Falls, Minn. Another less extensive project was under contract with Basin Electric Power Cooperative, Stanton, N. Dak., during the summer and fall of 1968. The title of the Otter Tail project is "The Use of Hoot Lake Lignite Fly Ash as a Soil Stabilizer and in the Manufacture of Fly Ash-Based Structural Products." The Basin project was entitled, "Use of Basin Lignite Fly Ash for Bituminous Concrete Filler, for Road Base Stabilizer (with scoria) and in the Manufacture of Brick."

The Hoot Lake plant of Otter Tail Power Company at Fergus Falls, Minn., has three generating units. The major portion of the present research with fly ash-based structural products has involved fly ash and bottom slag from only the No. 2 unit. Chemical analyses of 10 fly ash samples obtained at the dust collector of unit No. 2 over a 4-year period are given in table 20. However, the soil stabilizing portion of the project has involved the use of a

mixture of fly ash and bottom ash as obtained from a collecting silo at the Hoot Lake plant.

TABLE 20. - Chemical constituents of lignite fly ash from Otter Tail Power Company's No. 2 unit, Fergus Falls, Minn.

(Percent)

	Date of sample									
	8-13-65	6-13-67	8-22-68	12-18-68	12-19-68	12-30-68	1-17-69	1-27-69	2-3-69	2-17-69
SiO_2....	20.0	25.7	20.7	24.1	24.1	24.5	22.9	21.9	25.0	25.1
Al_2O_3...	12.4	13.2	13.3	13.1	13.1	12.9	12.8	12.8	12.9	12.8
Fe_2O_3...	14.5	14.7	13.5	14.8	13.7	15.4	15.8	16.6	16.4	15.4
Total	46.9	53.6	47.5	52.0	50.9	52.8	51.5	51.3	54.3	53.3
MgO.....	11.2	9.0	9.2	7.3	7.7	7.3	8.1	8.5	8.5	6.9
Na_2O....	5.7	4.2	5.8	3.7	3.4	2.9	2.1	1.2	1.5	1.4
K_2O.....	.3	.3	.3	.4	.3	.3	.3	.3	.4	.5
CaO.....	26.1	27.1	26.0	28.4	29.2	29.5	30.6	32.0	30.3	28.4
TiO_2....	.3	.4	.4	.5	.5	.5	.5	.3	.4	.6
P_2O_5....	.2	.5	.5	.5	.6	.6	.6	.6	.5	.5
SO_3.....	7.7	6.2	8.3	5.2	5.4	5.1	5.4	4.2	3.9	3.1
Loss on ignition (800° C)	1.0	.3	.4	.1	.3	.0	.1	.3	.2	.2

An investigation of lignite ash in combination with portland cement was carried out. Initially, test cylinders were made of 95 percent ash and 5 percent cement, and 90 percent ash and 10 percent cement. Sufficient water was added to produce maximum dry density when a compactive effort of 12,200 ft lb per cu ft was used. However, the results were unfavorable due to the fact that within a few hours after removal from the molds, the test specimens expanded and cracked severely. Additional water was added to subsequent batches resulting in mixtures that had to be poured like regular concrete. There were no further problems with expansion or cracking. Table 21 summarizes the compressive strength values, as well as wet-dry and freeze-thaw losses of the various test cylinders. There is a marked increase in strength between 7 and 28 days of curing.

TABLE 21. - Summary of test results using lignite ash[1] and cement mixtures

	Test			
	95-5	90-10	95-5	90-10
Compressive strength, psi:				
7-day.....	439	456	34	292
28-day.....	753	1,336	226	1,785
90-day.....	1,368	2,552	378	1,957
7-day wet-dry cycle....percent..	0 (loss)	4 (loss)	Failed-soaking	2 (loss-1st cycle)
7-day freeze-thaw cycle...do....	0 (loss)	19 (loss)	Failed-2d cycle	Failed-2d cycle
28-day freeze-thaw cycle..do....	0 (loss)	1 (loss)	22.2	2 (loss)
Moisture.....do....	18.8	18.4	22.5	22.1

[1]Mixture of fly ash and bottom ash.

A method of using lignite ash in combination with sandy soils or pit-run aggregates was developed. The ash and pit-run material were mixed to a desirable workability (±2-in

standard concrete slump). The percentage of ash investigated was 10, 20, 25, 30, 40, and 50 percent. Two pit-run aggregates (A-1-b, rounded and angular) and a North Dakota scoria were investigated and the compressive strength, flexural strength, absorption qualities, and freeze-characteristics were determined after curing for 7, 28, and 90 days. The results given for the A-1-b angular soil (table 22) are very favorable and could provide for less costly subbase construction for roadways, parking lots, and driveways. Also, an actual test slab of 50 percent ash and 50 percent simulated pit-run material was laid in the entrance to one of the University of North Dakota parking lots. Figure 70 shows the mixing and laying operations for the test slab.

TABLE 22. - Results of physical tests using a mixture of lignite ash[1] (minus No. 4 U.S. mesh) and A-1-b soil (angular)

Lignite ash, percent	Soil, percent	Water, percent	Compressive strength, psi			Flexural strength, psi		
			7-day	28-day	90-day	7-day	28-day	90-day
20	80	12.5	38	203	867	41	152	267
25	75	12.8	188	351	1,047	94	142	325
30	70	12.8	312	581	1,367	127	184	340
40	60	14.4	525	1,082	1,900	148	227	383
50	50	16.5	675	1,155	2,100	186	252	388

[1]Mixture of fly ash and bottom ash.

The mixture used in the test slab was made up of 50 percent ash (minus 1/2-in) and 50 percent simulated pit-run material. The simulated pit-run material was composed of 50 percent existing parking lot surface material and 50 percent of minus 3/4-in washed aggregate. Fifteen percent water was added to produce a mixture that had a 4- to 5-in slump. Entrained and/or entrapped

FIGURE 70. - Laying of Test Slab Using Lignite Ash Concrete.

air was 8 percent. This combination yielded a mixture with a density of 137 lb per cu ft.

Compressive and flexural strength up to 7-day age were as follows:

Age (days)	Strength (psi)	
	Compressive	Flexural
1.....	62	-
4.....	243	-
7.....	745	168

The fly ash research project with Otter Tail Power Company, Fergus Falls, Minn., has been largely concerned with utilization of fly ash in the manufacture of bricks. Initial investigations involved approximately the same proportions of ingredients as used by the Coal Research Bureau of West Virginia University;[9] namely, 72 percent fly ash, 25 percent bottom ash, and 3 percent (dry weight) sodium silicate. However, it was discovered that bricks containing sodium silicate had lower strengths than those with none. Also, mixing was simplified in the small laboratory muller by the elimination of sodium silicate. Various combinations of fly ash and bottom ash were checked, with the final selection of a 55 percent fly ash, 45 percent bottom ash (minus 16-in mesh) combination.

Forming of full-size bricks is accomplished in a steel mold similar to that used at West Virginia University. A unit pressure of 2,300 psi is provided by a Riehle 60,000-lb hydraulic testing machine. Best results are obtained with about 12.5 percent water in the mix. The bricks made with fly ash from Otter Tail Power Company's No. 2 unit can be handled without damage immediately after forming, and can be placed directly into a drying oven at 212° F with no subsequent cracking or warping. Firing to cone 3 (2,106° F) in a Harper electric kiln has produced bricks meeting ASTM grade SW. Table 23 contains the grade SW specifications, as well as selected test results of bricks made from No. 2 unit fly ash. Barium chloride in varying amounts was used in some of the mixes. Early in the work with fly ash from the No. 2 unit, the presence of white efflorescence was observed on the surface of bricks and cylinders that had dried after being immersed in water. The white efflorescence has been analyzed as sodium sulfate and it has been determined that approximately a 12-percent addition of either barium chloride or barium carbonate would be required to prevent its formation. Referring to table 23, the fired strength increases with increasing amounts of barium chloride, but severe cracking develops with a 12-percent addition. In the clay brick industry, additions of barium carbonate in excess of 1 percent are considered uneconomical.

The high lime content (25 to 30 percent) of fly ash from the Otter Tail No. 2 unit is responsible for a pozzolanic reaction and has resulted in compressive strengths of 2,700 to 3,100 psi for unfired bricks after drying at

[9] Turner, C. W. The Status of Fly Ash Brick. Brick & Clay Record, v. 150, No. 6, June 1967, pp. 55-57.

212° F for 24 hr. In addition to passing the grade SW compressive strength limit of 2,500 psi, these unfired bricks also meet the boiling adsorption and saturation coefficient requirements. Also, there is less efflorescence produced by the unfired brick than that with fired brick.

TABLE 23. - Test results from bricks made with lignite ash from unit No. 2, Otter Tail Power Co.

Brick[1]	Cold water adsorption, percent	Boiling water adsorption, percent	Saturation coefficient	Compressive strength, psi	Modulus of rupture, psi
ASTM specification[2] grade SW (individual)...	-	20.0	0.80	2,500	-
75 percent fly ash, 25 percent bottom slag: 4 percent $BaCl_2$, 2,106° F (cone 3).....	9.2	11.4	.89	2,487	656
55 percent fly ash, 45 percent slag:[3] 4 percent $BaCl_2$.....	8.3	10.9	.76	5,168	579
1 percent $BaCl_2$.....	9.3	11.7	.80	3,462	491
7 percent $BaCl_2$.....	6.8	10.7	.64	5,560	725
12 percent $BaCl_2$[4].....	-	-	-	-	-
4 percent $BaCl_2$, 1 day moist, curing at 70° F	8.6	11.0	.78	366	45
4 percent $BaCl_2$, 6 days moist, curing at 70° F	9.5	11.4	.83	1,829	228
4 percent $BaCl_2$, 1 day 212° F.....	8.6	11.0	.78	2,712	205
4 percent $BaCl_2$, 6 days 212° F.....	8.2	10.3	.80	2,837	361
0 percent $BaCl_2$, 1 day 212° F.....	7.7	10.1	.76	3,086	319

[1] Entries include composition of mix, firing temperature, and curing time where applicable.

[2] American Society for Testing and Materials. Standard Specifications for Building Brick. (Solid Masonry Units Made From Clay or Shale.) C62-66 in 1968 Book of ASTM Standards: Part 12, Mortars; Clay and Concrete Pipe and Tile; Masonry Units; Asbestos-Cement Products. Philadelphia, Pa., February 1968, pp. 54-60.

[3] All bricks comprising 55 percent fly ash and 45 percent slag fired to 2,106° F (cone 3).

[4] Bricks cracked and warped in drying oven.

The feasibility of ceramic glazing is being investigated in an attempt to find an economical means of preventing the formation of efflorescence on the surface of the brick. Trials with several conventional glazes used for clay brick resulted in adsorption of the glaze into the interior of the fly ash brick. Applications of a ceramic engobe to seal the surface, prior to glaze application, has produced a fair looking surface. However, with the cooperation of some of the commercial producers of ceramic coatings and glaze materials, it is hoped that a satisfactory impervious ceramic surface can be produced.

In the fall of 1968, two brick panels were made, one containing fired brick and the other unfired. These are being exposed to the elements on the roof of one of the buildings at the University of North Dakota. One possible drawback is that the bricks may need wetting to quench high absorption, as was also observed by a mason at West Virginia University.[10]

The unlimited variety of ceramic color combinations is an added incentive to continue the ceramic glazing feasibility of lignite fly ash brick. The small cost of glazing a brick is more than offset by the increased selling price.

A less extensive project has been conducted using ash from the Basin Electric Power Cooperative plant near Stanton, N. Dak. Analyses of three samples of fly ash is given in table 24.

TABLE 24. - Chemical analyses of fly ashes from the Basin Electric Power Cooperative's plant, weight-percent

Item	Sample		
	68-5	68-12	68-40
SiO_2	26.4	36.2	28.2
Al_2O_3	10.5	12.3	11.0
Fe_2O_3	12.4	10.2	11.0
Total	49.3	58.7	50.2
MgO	7.4	6.4	7.5
Na_2O	7.9	6.9	8.1
K_2O	.5	.8	.5
CaO	26.9	23.4	28.2
TiO_2	.4	.5	.5
SO_3	4.3	1.6	3.4
Total accounted for.	96.7	98.3	98.4

At the Basin Electric powerplant, both dry fly ash and wet bottom ash are available. The bottom ash is very glassy and cellular, resulting in brittleness and low crushing strength. Several different combinations of fly ash and bottom ash were tried but the data in table 25 indicates that there is a

[10]Brick & Clay Record. Pilot Brick Plant Burns Ashes to Brick. V. 154, No. 2, February 1969, p. 46.

marked decrease in strength when the percentage of bottom ash is increased from 10 to 20 percent. Therefore, because of the undesirable features of using bottom ash, only fly ash was used in brick tests and other experiments. A very pleasing brick, meeting the grade SW specifications, was made from fly ash No. 68-5 (with 4 percent $BaCl_2$) and fired to 2,106° F (cone 3). Bricks made from the previous mix and dried at 212° F for 24 hr did not meet the 2,500 psi minimum compressive strength.

TABLE 25. - Test results from bricks made of Basin fly ash No. 68-5

Brick	Cold water adsorption, percent	Boiling adsorption, percent	Saturation coefficient	Compressive strength, psi	Modulus of rupture, psi
ASTM grade SW[1]...	-	20.0	0.80	2,500	-
100 percent ash,[2] 4 percent $BaCl_2$, 2,106° F.....	4.3	7.5	.58	4,794	150
90 percent ash,[2] 10 percent slag, 4 percent $BaCl_2$, 2,106° F.....	8.1	11.0	.73	5,003	388
80 percent ash,[2] 20 percent slag, 4 percent $BaCl_2$, 2,106° F.....	10.2	14.0	.73	2,788	590
100 percent ash,[2] 4 percent $BaCl_2$, 1 day 212° F....	12.0	14.2	.84	1,672	89
100 percent ash,[2] 0 percent $BaCl_2$, 1 day 212° F....	13.1	17.9	.72	1,314	112

[1]American Society for Testing and Materials. Standard Specifications for Building Brick. (Solid Masonry Units Made From Clay or Shale.) C62-66 in 1968 Book of ASTM Standards: Part 12, Mortars; Clay and Concrete Pipe and Tile; Masonry Units; Asbestos-Cement Products. Philadelphia, Pa., February 1968, pp. 54-60.

[2]Mix composition, firing temperature, and curing time where applicable.

When the supply of fly ash No. 68-5 was depleted, samples 68-12 and 68-40 were obtained. However, bricks made from these have cracked and warped during drying at 212° F. Since the chemical analyses do not indicate pronounced variations, further study of the physical properties of these fly ashes is in progress. This involves hydrometer analyses, blaine fineness, and specific gravity determinations. However, since the blaine fineness is extremely difficult to determine on coarse materials, it may be necessary to use a different technique for measuring fineness.

A series of tests were performed with cylinders cast from fly ash and scoria (naturally fired shale) mixes and from fly ash and minus 3/4-in gravel. The summary of results for the fly ash and scoria is given in table 26. A comparison with the results presented in table 22 for lignite ash and an A-1-b soil indicates that much lower strengths result when fly ash is used.

TABLE 26. - Results of physical tests on brick made of Basin fly ash and scoria

Component, percent			Compressive strength, psi			Flexure strength, psi		
Fly ash	Scoria	Moisture	7-day	28-day	90-day	7-day	28-day	90-day
20	80	19.5	22	52	94	([1])	([1])	([1])
30	70	17.5	93	128	304	42	77	232
40	60	17.3	161	210	642	58	134	338
50	50	17.1	110	208	650	71	125	357
60	40	20.1	219	393	712	67	119	335
70	30	20.1	261	379	446	84	144	217
80	20	20.0	271	408	603	81	106	255
90	10	20.8	172	229	501	72	110	210

[1]Broke in handling.

The third phase of the Basin project involved the feasibility of using fly ash as a mineral filler in asphaltic concrete. An aggregate was used that met the limits for class 20 aggregate in the 1965 North Dakota Highway Department Manual.[11] A comparison was made with fly ash, limestone dust, and crusher dust. These fillers were added on a basis of 5.33 percent by volume, which is 15 percent by weight for the fly ash. The results that follow indicate that Basin fly ash No. 68-5 is satisfactory as a mineral filler:

	Limestone	Fly ash	Crusher dust	Specifications[12]
Optimum asphalt, percent..	5.9	5.7	6.1	-
Air voids, percent.....	4.8	3.2	4.6	3 to 5
Stability, lb.....	2,160	1,540	2,080	500 min
Flow in 0.01 in.....	10.8	9.1	10.8	8 to 18

The North Dakota State Highway Department has recently included a special provision[13] for using fly ash as a mineral filler. Basin fly ash meets the mineral filler specifications.

[11]North Dakota State Highway Department. Standard Specifications for Aggregates for Bituminous and Asphaltic Construction. Section 810 in 1965 Standard Specifications for Road and Bridge Construction, Bismarck, N. Dak., January 1965, pp. 412-414.

[12]Work cited in footnote 11.

[13]North Dakota State Highway Department. Special Provision, Section 812, Aggregate for Hot Mix Asphaltic Concrete Pavement, and Mineral Filler. December 1967, 2 pp.

Potential of Utilization of Lignite Fly Ash

Despite the fact that lignite fly ash does not meet either the ASTM[14] or Federal[15] specifications for fly ash, it has several possible uses where compliance with existing specifications is of little consequence. The high lime content (25 to 30 percent) of lignite fly ash causes a built-in pozzolanic reaction; the resulting strength values far surpass those obtainable with bituminous fly ash alone.

The use of lignite ash with either stone aggregate or scoria has potential use in highway subbase and base sections. Conventional concrete paving equipment could be used to mix and lay down "Ashcrete"[16] (ash and aggregate).

The role of lignite fly ash as mineral filler will depend on promotional efforts of the fly ash producers. Laboratory tests indicate that both Otter Tail Power No. 2 unit fly ash and the Basin fly ash appear to be satisfactory as mineral filler. In North Dakota there is a potential mineral filler market of more than 175,000 tons per year. The Basin powerplant near Stanton produces about 50 thousand tons of fly ash per year.

Perhaps the most exciting potential use of lignite fly ash is for fly ash-based structural products. It appears that the best method of forming the various shapes is by applied pressure of at least 3,000 psi. Whether bottom ash is required will depend on the particular fly ash. Approximately 12 percent mixing water is required. The very minimal warping and linear shrinkage (under 1.0 percent at 2,106° F based on the original dimensions) will allow 1-in-thick panels to be formed. In some applications, the 1-day strength of 3,000 psi for specimens cured at 212° F is a distinct advantage of fly ash structural units.

However, the efflorescence problem must not be overlooked. This problem is less pronounced on the unfired units than those that are fired. Efflorescence should not be a problem for interior exposed units or others not subjected to wetting and drying. Where there is wetting and drying, the surface must be sealed with either a ceramic glaze or other material, such as a methylacrylic resin.

Based on economic studies by the Coal Research Bureau at West Virginia University,[17] fly ash brick can be manufactured at a cost considerably less than that for clay brick and marketed at a price to compare with that of the highest quality competitor. A plant capable of producing 500,000 bricks per week from ash would call for a capital investment of about $600,000. Standard size face brick can be produced in such a plant for as low as $20 per thousand, depending on local market and labor costs. The cost for lignite fly ash brick may be even lower since sodium silicate is not required. The small cost of ceramic glazing is returned many times by as much as a 100-percent increase in price over that for an unglazed brick. A 500,000-brick plant would consume about 40,000 tons of fly ash and bottom ash per year. The Basin Electric powerplant near Stanton, N. Dak., could easily supply a large brick plant with fly ash. There is every confidence that the efflorescence problem will be resolved by ceramic glazing.

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[14] American Society for Testing and Materials. Tentative Specifications for Fly Ash and Raw or Calcined Natural Pozzolans, for Use in Portland Cement Concrete. C618-68T in 1969 Book of ASTM Standards: Part 10, Concrete and Mineral Aggregates. Philadelphia, Pa., October 1969, pp. 384-389.

[15] Federal Specifications. Pozzolan (for Use in Portland Cement Concrete), SS-P-570B. Apr. 18, 1969, 13 pp.

[16] Term adopted by ash researchers at the University of North Dakota.

[17] National Ash Association Newsletter. Ash at Work. V. 1, No. 1, 1969, 6 pp.

THE USE OF LIGNITE PRODUCTS AS PLANT GROWTH STIMULANTS

By Philip G. Freeman[1]

Introduction

Although oxidation decreases the fuel value of coal, it increases the content of extractable alkaline humic matter. In the Dakota-Montana lignite areas, there are deposits of coal in various stages of oxidation which total millions of tons, while in adjoining agricultural areas, millions of acres are cultivated comprising soil and crops that could benefit from judicious application of these oxidized coals.

The active ingredient of mildly oxidized coal that has the greatest effect on plant growth appears to be the humus or humic acid fraction. Humus in the soil has a threefold function: (1) physical modification of soil structure and texture enabling increased moisture retention and aeration; (2) chemical fixation of soil minerals and their retention in an exchangeable form available for plant growth, increasing the buffering properties of the soil, and chelating of metal ions under alkaline conditions; and (3) biological stimulation of growth by serving as a substrate for micro-organisms as well as direct plant growth stimulation by supplying a slow release of auxin, amino acids, and organic phosphates. It has been estimated[2] that prairie soil loses up to 50 percent of its native humus in the first 3 years of cultivation under temperate climatic conditions. The quality of humus declines even faster since the most active portions are degraded first. Further decomposition eventually brings cultivated soil to an equilibrium humus content far below that of the virgin soil. This is the condition of most agricultural soil today.

Most soil scientists and agronomists agree that humus serves important functions in the soil. They further agree that humus reserves in present-day intensively cultivated soils are severely depleted. In spite of this, and in spite of the fact that coal-derived humus is essentially the same as the black or brown humus extracts from soil, there is reluctance to accept coal humus as a worthwhile soil additive. Part of this is due to unfounded belief that only "fresh" humus--that is, humus clearly derived from recently decayed organic matter--has a beneficial effect. Although it is essential that crop residues be returned to the soil, and although sugars and proteins from these sources certainly have a beneficial effect, these do not constitute humus. Furthermore, only a small part of this organic matter will ever become humus and then only after long residence in the soil.

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[1]Research chemist, Grand Forks Coal Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.

[2]Kononova, M. M. Problema pochvennogo gumusa i sovremennyye zadachi ego izucheniya (Soil Organic Matter, Its Nature, Its Role in Soil Formation and In Soil Fertility). Pergamon Press, Inc., New York, 1961, pp. 273-333.

Waksman, Selman A. Humus, Origin, Chemical Composition, and Importance in Nature. The Williams and Wilkins Co., Baltimore, Md., 1938, 2d ed., pp. 7-8, 254-260.

Coal humus is not merely organic matter that must be converted to humus, it is concentrated and rich in both organic and mineral substances essential to plant growth. The chemistry of humus is so confused that literally hundreds of definitions exist ranging from vague generalizations to terse oversimplifications. Since the nature of humus or humic acids is so complex, it is not possible to show chemically that soil humus and coal humus are completely identical. It then becomes necessary to demonstrate the utility of coal-derived humus as a plant growth stimulant at the practical level by field testing and at the theoretical level by attempting to unravel the biochemical mechanisms involved.

Many forms of mildly oxidized coal are available; they can generally be classified by stages of oxidation eventually ending in the humification of the starting material. In the case of lignite, the ultimate product of natural oxidation appears to be soft, loose textured, earthy material called leonardite.[3] This material usually occurs at lignitic outcrops or at shallow depths overlying or grading into the parent lignite seam.

Partially oxidized lignite, often associated with storage piles, but also occurring in intact seams, is sometimes called slack lignite. The humic acids recovered from slack lignite are usually less degraded than leonardite humic acids, and thus have an apparent higher molecular weight.

Since these two fairly well-defined substances represent the most abundant sources of naturally occurring coal humates, they were chosen as the subjects of the investigations reported here. Table 27 compares some of the chemical properties of a typical leonardite, slack lignite, and lignite.

TABLE 27. - Some chemical properties of a typical lignite, slack lignite, and leonardite, percent maf[1]

Property	Baukol-Noonan lignite	Beulah slack lignite	Gascoyne leonardite
Oxygen in source material.....	19.9	24.8	28.4
Humic acids extracted.....	5.0	28.4	84.3
Oxygen in extracted humic acids...	25.3	30.4	31.1

[1]Moisture- and ash-free.

Field Applications of Lignite-Derived Humates

Potato Test Plot

The plot used consisted of four 200-foot rows for each of three treatments: leonardite, slack lignite, and control. Two unfertilized guard rows

[3]Fowkes, W. W., and C. M. Frost. Leonardite: A Lignite Byproduct. BuMines Rept. of Inv. 5611, 1960, 12 pp.
Frost, C. M., J. J. Hoeppner, and W. W. Fowkes. Source and Some General Properties of Humic Acids From Lignitic Materials. J. Chem. and Eng. Data, v. 4, No. 2, 1959, pp. 173-176.

were planted on each side of the test plot. Pulverized leonardite and slack lignite (1 ton per acre) were admixed with 10-20-10 fertilizer (200 pounds per acre) and applied in the row at the time of seeding. Control rows received only fertilizer. Kennebec potatoes were seeded using a commercial style two-row planter. The seed was cut mechanically and treated with fungicide prior to planting. The plot was cultivated at intervals during the growing season and the vines were killed chemically at the appropriate stage of growth. Harvesting was done by hand after the tubers were lifted with a one-row digger. An attempt was made to duplicate as much as possible the normal procedures used in commercial potato cultivation to demonstrate that no extraordinary means were required to make use of coal humates.

Table 28 gives the weight yield of potato from each 800 feet of row. The unfertilized guard row gave the lowest yield as would be expected. The other three treatments each received 10-20-10 fertilizer at 200 pounds per acre. The small increase in yield owing to slack lignite treatment is probably not significant, although the pigmentation of the vines during growth appeared to be superior to control. The large increase in yield from the leonardite-treated rows is very significant and correlates with apparent greater vigor of vine growth and pigmentation during plant development. This was only a single test and will have to be repeated before the magnitude of the stimulatory effect is well enough established to permit reliable predictions.

TABLE 28. - Comparative yields of field grown potatoes (variety Kennebec), summer 1968

Treatment	Potato yield		Specific gravity
	Hundred-weight per acre	Percent of control	
Guard rows.....	126.4	70.6	-
Control.....	179.0	100.0	1.087
Slack lignite[1]...	195.8	109.4	1.089
Leonardite[1].....	229.9	128.4	1.088

[1] 1 ton per acre row application.

Each group of potatoes was graded by Federal-State inspectors but no significant differences were found. Taste test, chipping quality, and sugar assay were identical for all three treatments. Since yield was based on weight, it was possible that increases in weight would be nullified by greater water content; however, specific gravity of the tubers was essentially identical for all three groups. Apparently, there is no detrimental effect from the treatments on quality or processing characteristics of the crop. It should be reemphasized that the increased yield reported here was obtained from a single test, using a single potato variety, growing in a single soil type. Generalizations from such limited data are extremely risky and confirmation of these results will have to await more extensive testing.

Soybean Test Plot

The effect of leonardite on the growth of soybeans was of particular interest because of the highly variable response of this plant to fertilization. Alkaline soil conditions and short growing season are further limiting factors for this plant in the Northern Great Plains area. Since cultivation under these conditions is at best a marginal undertaking, any dependable form of growth stimulation could easily make the difference between crop failure or success.

In this limited pilot study, two rows of soybeans (Merit variety) were planted by hand. One row was treated with 1 ton per acre of leonardite in the row while the other row was untreated and served as the control; neither were fertilized. Half of each row was inoculated with bacterial culture to induce nodulation while the other half was left untreated. It was then possible to compare the effect of leonardite on soybean growth under both inoculated and uninoculated conditions. The results, given in table 29, indicate remarkable leonardite stimulation. Bean yield was almost three times control when uninoculated and almost twice control when inoculated. Again, these results are very limited and require much more study and verification before much trust can be given them. However, results from laboratory studies support fundamental nutrient uptake effects on the part of leonardite-derived humic acids that go far in explaining the increased growth.

TABLE 29. - Response of soybeans to leonardite (1 ton per acre, row application)

	Uninoculated		Inoculated	
	Control	Leonardite	Control	Leonardite
Average plant height...inches..	14.1	19.6	17.4	18.8
Bean yield....grams/25-ft row..	103.0	292.0	169.0	313.0
Bean yield.....percent..	100.0	283.4	164.7	303.9
Nitrogen in beans.....do.....	6.6	7.1	6.2	6.9

Laboratory Investigations

It had been observed throughout previous growth tests that one of the principal effects of coal-derived humus was a darker pigmentation in the treated plants than in the control plants. A convenient way to study pigment development on a quantitative basis is with algal cultures. When grown in the dark under normal nutrient conditions with 1 percent glucose, these single-celled plants develop green pigmentation in proportion to the amount of available iron. They continue to respire and do not die; most higher plants will die when deprived of light.

To study the effect of coal-derived humus on pigment development, a water-soluble humic acid (WSHA) fraction of naturally oxidized lignite (leonardite) was prepared. Preparation of WSHA is described in detail in a previous

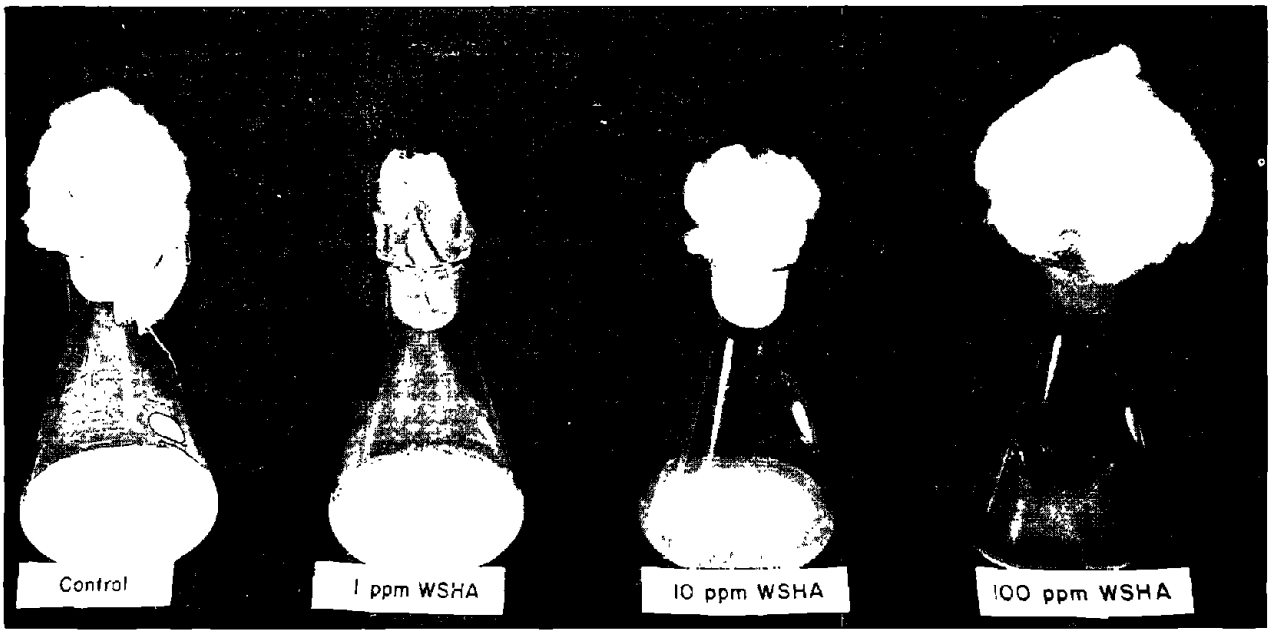

FIGURE 71. - *Chlorella* Cultures.

publication.[4] This material was added to a standard nutrient solution in concentrations of 1, 10, and 100 parts per million (ppm). Each nutrient was sterilized, then inoculated with a wild strain of Chlorella vulgaris, a common single-celled alga. After 90 hours of growing in the dark, the algal cultures had produced pigment roughly in proportion to the concentration of WSHA in the nutrient medium[5] (figs. 71-72).

Pigment production is often correlative to iron availability, for example, chlorosis (yellowing due to lack of green pigment) can be induced by using iron-free growth media. As a direct measure of iron uptake, the algal cultures were supplied with a tracer, isotope Fe^{59}. The amount of iron taken up by the Chlorella in the various cultures could then be determined by spinning out the cells and measuring the residual radioactivity of the nutrient. The amount of Fe^{59} taken up by the plant cells was in direct proportion to the WSHA concentration in the nutrient (fig. 73).

This made it increasingly clear that at least one of the main functions of WSHA in promoting plant growth was an ability to supply iron to the plant. In the case of Chlorella, it might also be assumed that, since a close correlation exists between pigment production and iron uptake, the two go hand in hand. Further evidence is necessary, however, to determine the extent of this effect on higher plants. To do this, the Fe^{59} isotope was again used in hydroponic nutrient solution with a soybean variety (PI-54619-5-1). This soybean

[4]Freeman, P. G., and W. W. Fowkes. Coal-Derived Humus: Plant Growth Effects. BuMines Rept. of Inv. 7203, 1968, 16 pp.

[5]Brown, C. J. Effect of Coal Derived Humic Acid on Growth and Chlorophyll Content of Chlorella Vulgaris. M.S. Thesis, University of North Dakota, January 1969, 35 pp.

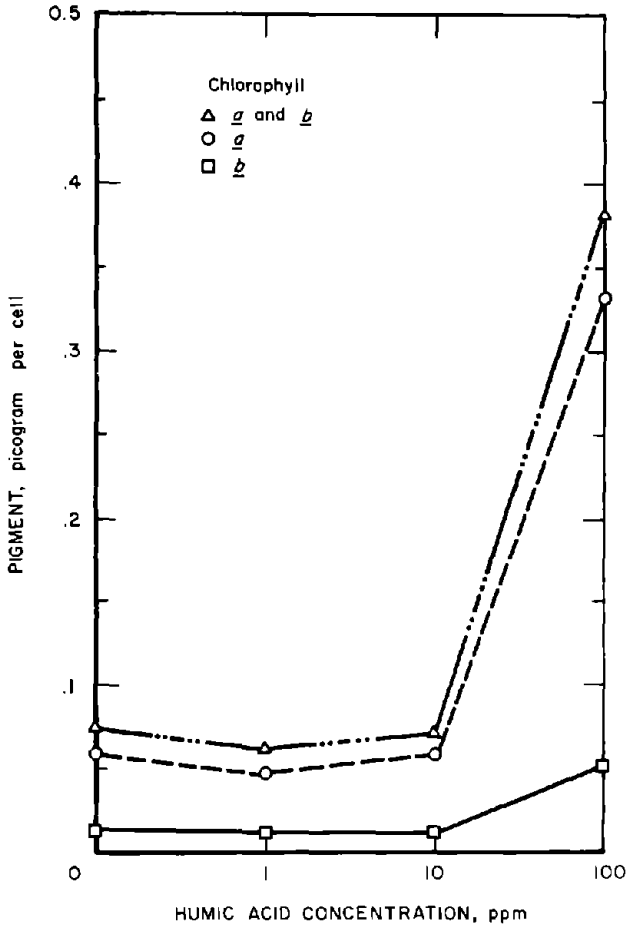

FIGURE 72. - Pigment Production by Wild-Type *Chlorella* in Dark Grown Cultures.

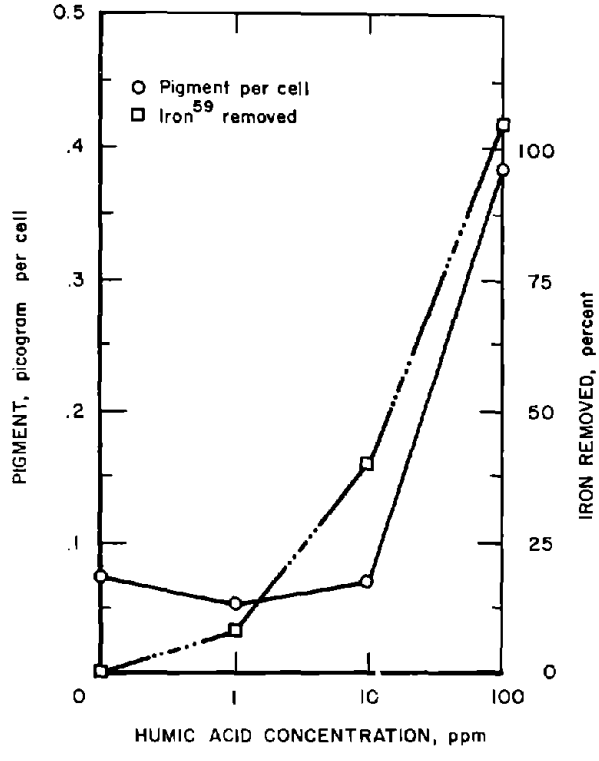

FIGURE 73. - Comparison of Pigment Accumulated by Wild-Type *Chlorella* in an Iron-Free Media to Iron^{59} Taken From Media.

is highly inefficient in its ability to absorb and translocate iron.[6] Plants were grown in two identical nutrient solutions until the second trefoil began to develop, Fe^{59} (2μc) isotope was then added to each nutrient, 100 ppm WSHA was added to one, and the other served as control. After 8 days of continued growth, the two plants were removed from the isotope-nutrient, mounted, and placed on X-ray film for autoradiography (figs. 74-75).

The autoradiographs demonstrate not only greater uptake of iron from the humic acid treated nutrient, but also more effective transport to the aerial portions of the plant. Regular photographs also indicate superior size, symmetry, and color of leaves on the treated plant.

[6]Brown, J. C. Genetic Variants as Factors Affecting the Nutrition and Physiology of Plants. Ch. in Isotopes in Plant Nutrition and Physiology. Internat. Atomic Energy Agency, Vienna, Austria, 1967, pp. 413-420.

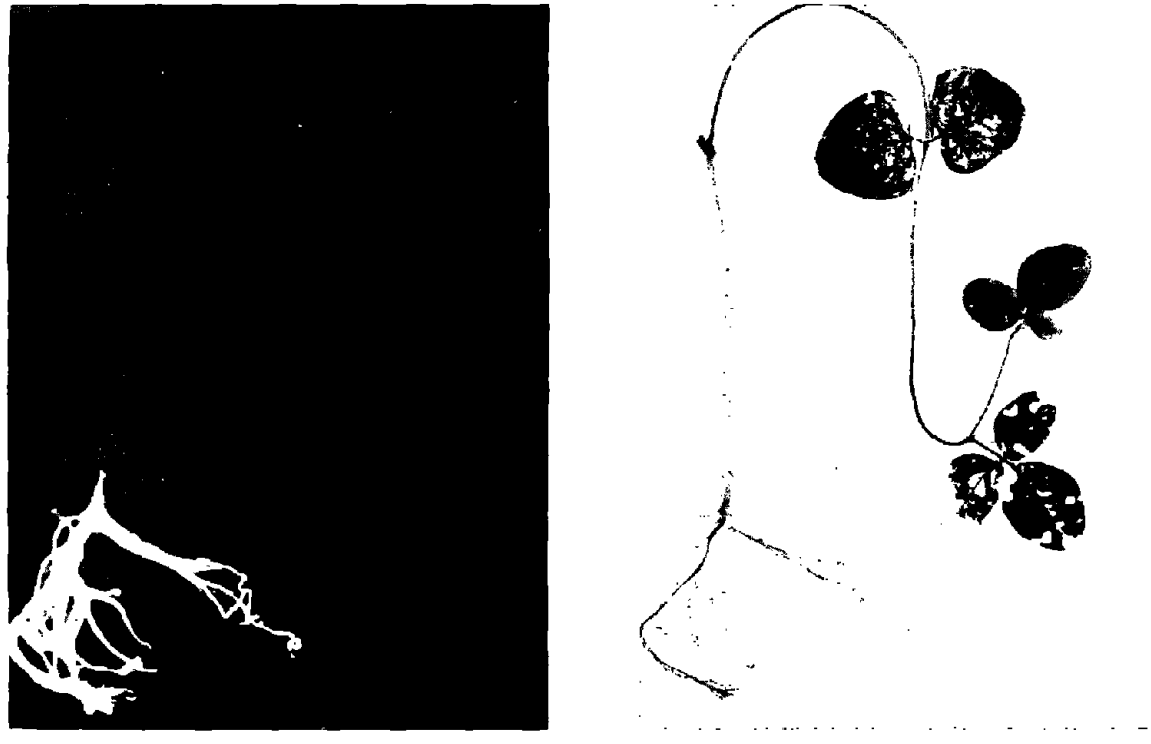

FIGURE 74. - Matched Photo and Autoradiograph, Control Soybean.

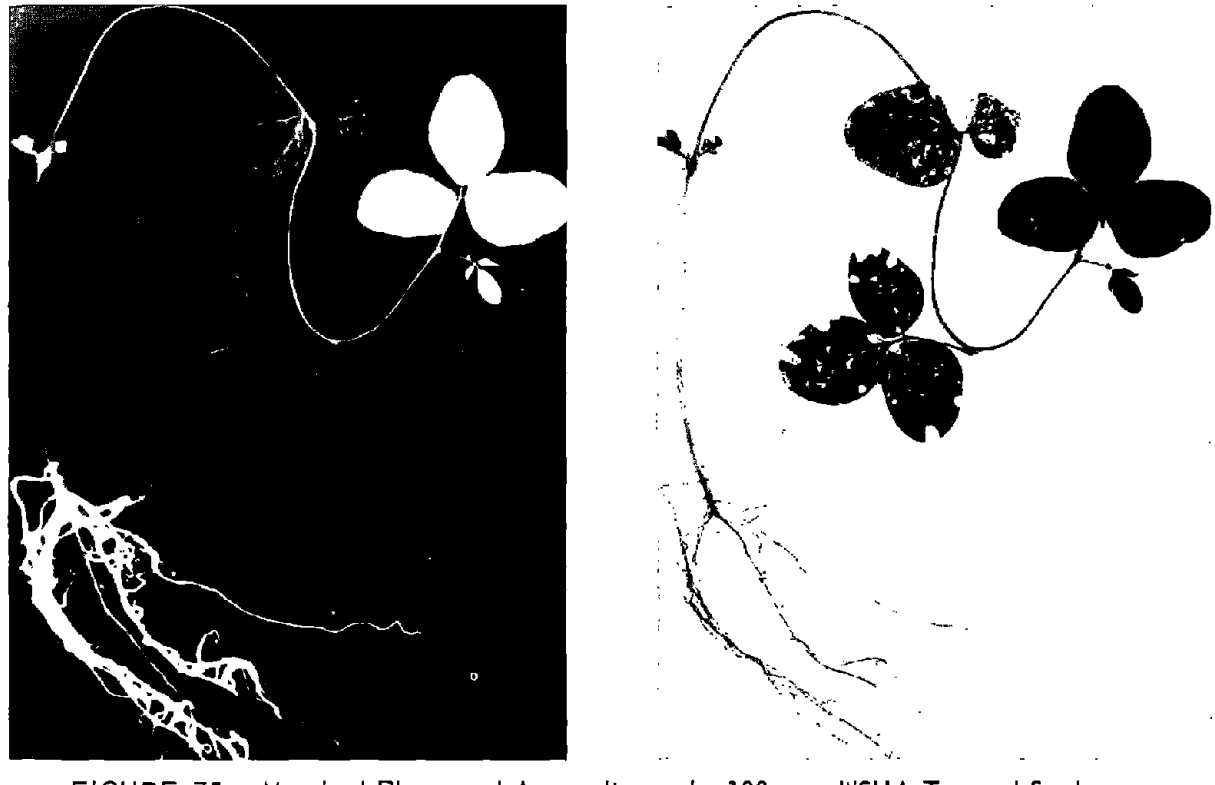

FIGURE 75. - Matched Photo and Autoradiograph, 100-ppm WSHA-Treated Soybean.

Conclusions and Discussion

It is clearly demonstrated in laboratory experiments that coal-derived humic acids are effective in promoting the uptake and transport of iron both in single-celled algae and in soybeans.

Field experiments using leonardite as a soil additive demonstrate greater yields from potatoes and soybeans. While very limited in scope, these results are rendered more credible in view of the laboratory demonstrated effects.

A great many questions remain to be resolved before a clear understanding of these effects emerges. Broader field testing would be most valuable, since plant response will no doubt differ greatly in different soil types. Varietal and species differences are already evident and must be taken into account, not to mention variation between crops.

On the mechanistic approach, it is still unclear how humic acids affect the uptake and transport of iron. It is known that inhibitors of oxidative phosphorylation and electron transfer also inhibit iron translocation. It is possible humic acids provide the free radicals necessary to stimulate electron transfer. Or perhaps the humate-iron complex provides the bivalent iron necessary to catalyze transport enzymes or even the better known enzymes such as aconitase, which is implicated in the citrate-isocitrate conversion.

It is likely that the uptake and transport of minerals other than iron are also affected by coal humate. It would be of considerable interest to know if the addition of humate results in a general effect such as alteration of cell walls or the permeability of the cell membranes, or if the effect is restricted to certain elements, and if so, to which elements.

In spite of many unresolved questions and a lack of long-term field results, there is good reason to be optimistic about the place of leonardite and oxidized coals in agricultural applications. Results to date indicate that at least in the calcareous soils common to areas adjacent to lignite deposits, the possibility exists for large-scale application of these byproducts. The immediate potential for an outlet of several million tons of oxidized coal makes this possibly one of the largest nonfuel applications for coal today.

Acknowledgments

The cooperation of Professor Donald E. Severson and the University of North Dakota Chemical Engineering Department in permitting the use of the isotope laboratory is greatly appreciated.

The assistance of Mr. Charles Brown and Mr. Gary W. Bryan of the University of North Dakota Biology Department with algal cultures is acknowledged. Mr. Roy Shaw of the Red River Valley Potato Processing Laboratory, East Grand Forks, Minn., Mr. Don Uhlir, and the Red River Valley Potato Growers Association provided facilities, advice, and other help in the cultivation and evaluation of the potato test plot which made the testing possible.

LEONARDITE IN FERTILIZER

By A. M. Cooley,[1] Gary Douglas,[2] W. H. Rasmussen,[3]
J. J. Rasmussen,[4] and J. Theis[5]

Introduction

Organic matter in soils may exert a beneficial effect in crop growth by controlling aggregation of soil particles, adding to the moisture holding capacity of the soil, and acting as a carrier of nutrients. The mechanisms by which organic matter and particularly humus control aggregation are still a matter of speculation, but the beneficial effects have been observed since the beginnings of agricultural science.

Oxidized organic residues of lignitic origin occur in large tonnages in almost all locations in which lignite is found. Compared with lignite, these deposits are rather soft and earthy in nature and have a lower heating content, limiting their use as fuel. In most instances this material is discarded during mining. The largest commercial use is as a viscosity control agent in oil drilling muds, and even this is of limited tonnage.

The oxidized lignites are known in North Dakota as leonardite and are composed mainly of humic acids. The moisture content is comparable to that of lignite, but the oxygen content on a moisture- and ash-free basis is approximately 30 to 35 percent of the total substance, while that of lignite is approximately 25 percent. The humic acids may be extracted from the leonardite by using dilute sodium hydroxide solutions; these extracts usually are from 80 to 85 percent of the moisture- and ash-free material.

The humic acids, which range from relatively low to high molecular weight compounds, are responsible for the effects of leonardite in the soil and as an additive to fertilizers.

Leonardite, as it is mined, has very low initial solubility in water. Some material does go into what is thought to be colloidal suspension and is probably similar to the soluble and colloidal products described by Howard.[6]

> The ultimate oxidation products of the regenerated humic acids are carbonic acid, water, and so forth. Between the humic acids and these simple products, there appears, however, a whole series of acids distinguished broadly from the regenerated humic acids by

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[2] Plant agronomist, Northland Chemical Co., East Grand Forks, Minn.
[3] President, Northland Chemical Co., East Grand Forks, Minn.
[4] Vice president, Northland Chemical Co., East Grand Forks, Minn.
[5] Plant manager, Northland Chemical Co., East Grand Forks, Minn.
[6] Howard, H. C. Chemical Constitution of Coal: As Determined by Oxidation Reactions. Ch. in Chemistry of Coal Utilization, v. 1, ed. by H. H. Lowry. John Wiley & Sons, Inc., New York, 1945, p. 357.

> solubility in aqueous solution, neutral and acid as well as alkaline. Earlier workers gave these acids names largely on the basis of color or solubility. The reddish brown soluble acids formed in the early stage of oxidation of humic acids were called hymatomelonic acids, the golden ones formed in the next step, fulvo acids.

The functional group of humic acids consist mainly of OH (hydroxyl) groupings and COOH (carboxyl) groupings. Some of the hydrogens in the carboxyl groups are quite often replaced in leonardite by iron and calcium. Ammonia may also be added on the carboxyl grouping, but if the iron and calcium have not been removed or made insoluble, the ammonia is slowly lost. Leonardite ammoniated at room temperature gains from 4 to 5 percent by weight of nitrogen, but on storage half of the nitrogen is lost within 30 days if the iron and calcium are still present. Leonardite is quite acidic, having a pH of 4 to 5. The calcium content of a sample from southwestern North Dakota on a dry basis was 3.36. Calcium content is extremely variable even in the same mine, but this is not of great importance in making fertilizer.

If leonardites are washed with acid, the washings, though yellow in color, are clear. If the acid-washed material is then washed with water, the leonardite begins to go into colloidal suspension when the pH increases to about 1.8. Since the pH is from 4 to 5 in the "as mined" leonardite, it would appear that it is insoluble in water because of the iron and calcium. When these are stripped out by acid washing, the humic acids are more easily taken into colloidal suspension in water.

Humic acids from leonardite may be brought into colloidal suspension by alkalies such as sodium or ammonium hydroxide, but not by calcium or barium hydroxide.

Most of the literature on the use of humic acids from brown coals and other coals discusses the use of material made by chemical oxidation of coal substance. A large body of literature exists upon European practice and especially work done by soil scientists in Russia and the Balkan countries.

A number of articles published in Russia state that humic acids have some fertilizer value. This, however, was disputed by French scientists who stated that no fertilizer action was noted from the use of humic acids except from the action of the mineral constituents, such as ammonia, used in its preparation.

Askinazi[7] stated that ammonium humates increased the solubility and availability for plants of P_2O_5 from RPO_4 (where R represents a humate group) in

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[7]Askinazi, D. L. (The Effect of Ammonium Humates on the Availability of Phosphates of the Sesquioxides (iron and aluminum) to Plants.) Trans. Sci. Inst. Fertilizers Insecto-Fungicides (pub. in U.S.S.R.), No. 141, 1938, pp. 230-238.

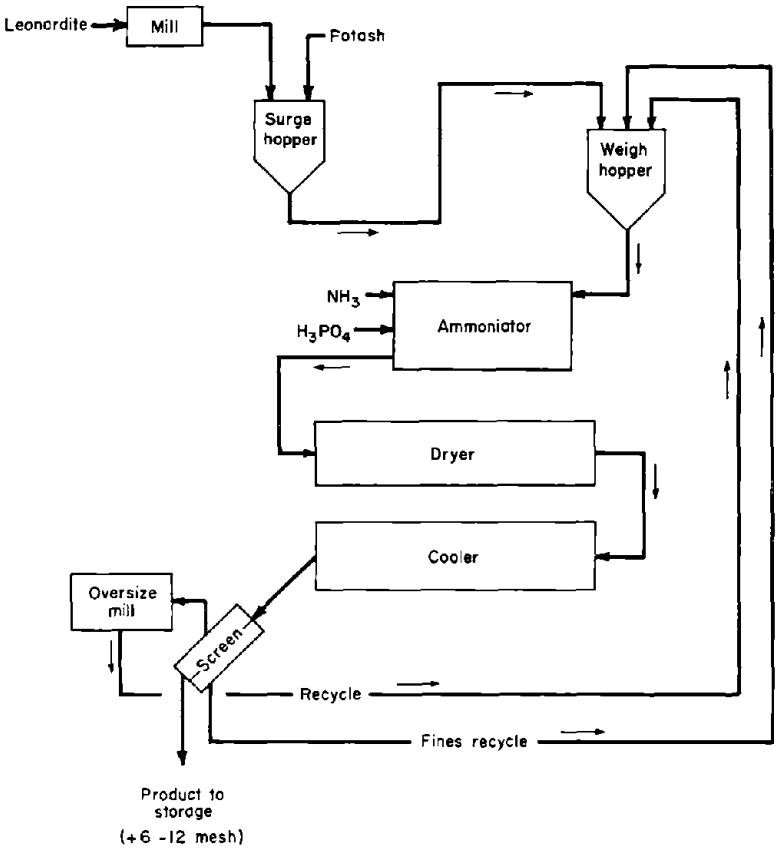

FIGURE 76. - Flow Sheet for Preparation of Pelletized Fertilizer.

the presence of $CaHPO_4$. Ismailovich[8] stated that humates increased the buffering action of soils. Humic acids inhibited the reversion of phosphates to the insoluble form.

Beran[9] stated that the persistence of organic insecticides in soils were studied and was found to be lessened by the presence of humic acids in these soils. Lindane, DDT, Aldrin, and parathion showed lessened persistence in soils high in humus.

Leonardite may or may not act in itself as a significant fertilizer material, but its effects as a carrier with fertilizing minerals are quite significant.

Production of Pelletized Fertilizer

The objective in producing pelletized fertilizer containing leonardite was to produce a fertilizer containing available nitrogen, phosphorus, and potassium in a direct combination with leonardite which would provide soluble or colloidal humic acids. The pellets in contact with water allow the soluble constituents to dissolve and the humic acid containing nitrogen to become colloidal for dispersal in the soil. The dispersed humic acids would then be where they could act as cementing agents in forming soil aggregates or soil "crumb" structure. The product discussed in this paper has been marketed under the trade name of Natro-gro.

The manufacturing process (fig. 76) consists first of pulverizing the leonardite. It was not necessary to pulverize to a fine size because subsequent action of phosphoric acid had a disintegrating effect. An impact mill was used and the output was minus 1/4-in with a range of sizes dependent upon

[8] Ismailovich, O. J. (The Influence of Ammonium Humate on the Physicochemical Properties of Soil.) Trans. Sci. Inst. Fertilizers Insecto-Fungicides (pub. in U.S.S.R.), No. 127, 1936, pp. 132-142.

[9] Beran, Ferdinand, and Johan A. Guth. (Organic Insecticides in Various Soils, With Particular Reference to Possible Ground Water Pollution.) Pflanzen schutz. Ber. 33 5/8, 1965, pp. 65-117.

the moisture content of the feed material. Dryer material usually pulverizes to a finer product.

The pulverized leonardite was mixed with potash and trace materials in a weigh hopper and conveyed to a surge hopper and then to the pelletizing drum, which was 8 ft in diameter and 12 ft long (fig. 77). Spargers within the bed of tumbling material were used to add 75 percent phosphoric acid and anhydrous ammonia. The phosphoric acid acted as a stripping agent to remove iron and calcium from the humic acid and to form relatively insoluble salts. It also disintegrated the coarse leonardite to a size amenable to pelletizing. An excess of acid was used and this was ammoniated by the anhydrous ammonia from the second sparger. The excess phosphoric acid and ammonia were controlled to provide the desired analysis. The heat that evolved assisted in the pelletizing and subsequent drying.

The retention time in the pelletizing drum was approximately 10 min. The pellets were dried in a direct-heat drier 6 ft in diameter and 40 ft long. The drier was heated by an oil burner. The dried pellets then entered a cooling drum, also 6 ft in diameter and 40 ft long. The discharge was screened through a minus 6- plus 12-mesh screen. The coarse material was reground and recycled through the surge hopper. The undersize was also recycled and served as seed nuclei for the pellets of the size desired for fertilizer.

Additions were controlled to give an analysis of 10-10-5, which is a rather low analysis fertilizer but a common analysis for garden and lawn use. Hobby gardeners are very apt to misapply high analysis fertilizers and damage foilage and roots.

A second reason for the low mineral analysis was to maintain high amounts of leonardite in the fertilizer. The analysis used was low compared with that of common field fertilizers, but was used in the first tests on field plots because only one formulation was made. Analysis is easily controllable, and subsequent testing will be done with analysis similar to that common in agricultural use.

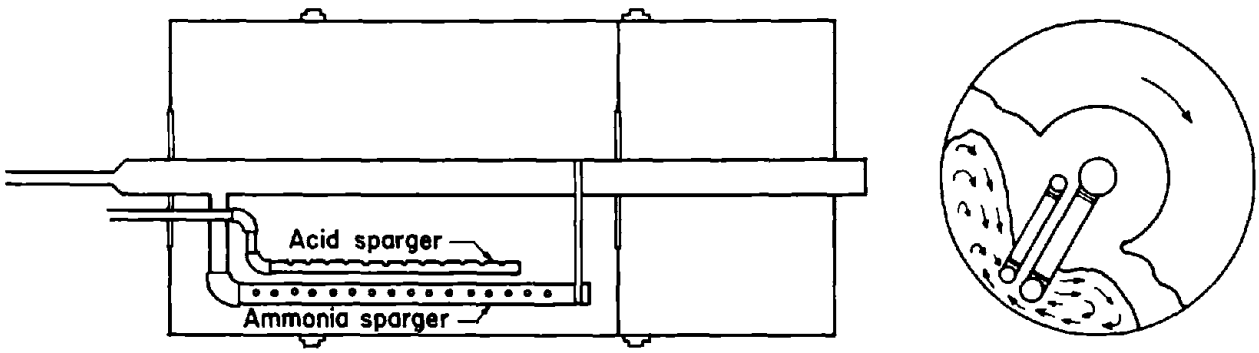

FIGURE 77. - Schematic Arrangement of Pelletizing Drum.

Field Testing

Test plots of barley, potatoes, and sugar beets were planted in the Red River Valley during the summer of 1967. The barley was planted near Beltrami, Minn., the beets at Fisher, Minn., and the potatoes near Merrifield in Grand Forks County, N. Dak.

Barley

Three drill widths through a 1/2-mi-long field were planted for each of the following: (a) 16-20-6, (b) 15-22-5, and (c) 10-10-5 Natro-gro at equal amounts of total substance per acre. This, of course, reduced significantly the amounts of nitrogen and phosphates in the Natro-gro application. Any advantages throughout the growing season could then be attributed to the leonardite. Table 30 lists the nitrogen uptake and utilization, plant counts after tillering, and yield.

TABLE 30. - Growth tests with barley at Beltrami, Minn., 1967 season[1]

Plot	Fertilizer	Plant analysis		Plants per[2] 3 ft of row	Yield, bu/acre
		Nitrate-nitrogen, ppm	Total nitrogen, percent		
A	16-20-6[3]	1,275	4.4	68	47.3
B	15-22-5[3]	945	4.8	84	47.6
C	10-10-5 (Natro-gro)	1,025	4.7	96	53.5

[1]Application rate 150 lb/acre.
[2]After tillering.
[3]Commercial fertilizer.

The nitrogen applied in Natro-gro was approximately one-third less, yet the barley uptake of nitrogen remained relatively constant in all three fertilizer compositions.

The plant count showed increased numbers of tillers with the leonardite fertilizer. Tillering is the ability of grains to produce several stems from one initial seedling. An increase in tillering increases the plant population and the potential yield. There was a significant yield advantage for the leonardite fertilizer that could be attributed to the increased plant population.

Potatoes

On each plot, two fertilizer treatments were applied at identical rates. Each treatment was applied to four 1/2-mi-long potato rows. The fertilizers were (a) 16-16-8 and (b) 10-10-5 Natro-gro. As a result, the total amounts of nitrogen, phosphate, and potash applied with Natro-gro was significantly less. Any advantages through the growing season could be attributed to the leonardite.

The nitrogen applied at Natro-gro was over 30 percent less; however, table 31 indicates that there was a substantial increase in the uptake and utilization of nitrogen when Natro-gro was used.

TABLE 31. - Growth tests with potatoes near Merrifield, Grand Forks County, N. Dak., 1967 season[1]

Plot	Fertilizer	Plant analysis			Yield	
		Nitrate-nitrogen, ppm	Total nitrogen, percent	Specific gravity	Hundredweight	Bu/acre
A	16-16-8 (Commercial)	820	4.7	1.095	162	270
B	10-10-5 (Natro-gro)	1,600	5.2	1.096	134	224

[1]Application rate 300 lb/acre.

The total yield was substantially less with Natro-gro, which could be attributed to the high nitrogen demand of potatoes. The Natro-gro did not supply a level of nitrogen that could support the early season potential yield to harvest. Future testing will include higher analysis so that identical rates of minerals will be used.

Specific gravity of potatoes is a measure of the dry solids content. The two fertilizer applications showed no significant difference in the two fertilizer treatments.

Sugar Beets

Two drill widths (12 rows each), 1/2-mi in length, were fertilized with identical weights of total fertilizer. The following materials were used: (a) 5-45-5 and (b) 10-10-5 Natro-gro. This, of course, doubled the amount of nitrogen applied and reduced significantly the level of phosphate applied. Any advantages throughout the growing season could be attributed to the increased nitrogen or leonardite. Of these two, the leonardite would appear to be the most important since the nitrogen applied in either fertilizer plot was very low compared to the requirement of sugar beets.

Table 32 shows the differences in emergence and yield. The Natro-gro appeared to delay plant emergence by about 3 days. However, the final yield did not show the effect of emergence because the final yield of both tons/acre of beet and lb/acre of sugar were significantly higher.

The decrease in percentage in sugar content with the Natro-gro could be attributed to the substantially lower level of phosphate fertilizer applied. Future testing will include identical analysis of nitrogen, phosphorus, and potassium.

TABLE 32. - Growth tests with sugar beets at Fisher, Minn., 1967 season[1]

Plot	Fertilizer	Seedling emergence, plants/100 ft		Yields		
		6/8/67	6/11/67	Ton/acre	Sucrose, percent	Sucrose, lb/acre
A	5-45-5 (Commercial)	145	175	8.873	17.0	3,010
B	10-10-5 (Natro-gro)	81	140	10.925	15.9	3,474

[1]Application rate 100 lb/acre.

The test results show that there are beneficial effects from the humic acids. Even if not directly caused by the humic acids, there appears to be an advantage in incorporating them in mineral fertilizers.

The tests, however, have not been observed over a long enough period of time to determine the effect on soil structure or the stability of humus in the soil.

THE USE OF CHAR TO IMPROVE THE PHYSICAL QUALITY OF COKE

By Charles C. Boley[1] and M. Merle Fegley[2]

Introduction

The coking industry exists mainly to serve the steel industry by providing coke for blast furnaces. Blast furnace coke must be strong, else it will crush under its burden of iron ore and limestone, and thus impede the upward blast of air. Further, it is generally considered that coke should be porous and 4- by 2-in. in size for best results. Most coke in this country is produced from a blend of two or more coking coals found by experience to produce better coke than any individual coal. The present paper discusses another way of improving the physical characteristics of coke, that of blending of char with coking coal, prior to coking the blend. Char, in the context of this paper, is a partially devolatilized, nonagglomerated coal product that is prepared from coal by a preliminary low-temperature carbonization, generally at less than 1,200° F. There are many variations in the effects that chars may have when added in a coking blend. The addition of char does not improve the cokes from all coals, and the mechanism by which coke is sometimes improved is not well understood. Entrained-bed carbonization produces finely sized char from coking coal suitable for blending purposes.[3]

Blending of char with coal from which the char was made may improve the physical qualities of the resultant cokes. The general objective of the present study is to determine to what extent such improvement is possible with Western coking coals. This report describes the improvements in coke quality obtained by blending selected percentages of four entrainment-carbonization chars produced from a Western coking coal.

Coal and Char

The coal used was high-volatile A bituminous, obtained from the Kaiser Steel Corp.'s Sunnyside mines located in Carbon County, Utah. The coal had been washed in Kaiser's preparation plant near Dragerton, Utah, where modern cleaning units removed most of the rock and high-ash material to produce a relatively uniform, low-ash product identified as "washed 6 × 3 inch." A 60-ton carload of this coal was used for most of the work. At a late stage of the study an additional quantity of about 6 tons was obtained. Analytical information on Sunnyside coal is given in table 33.

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[1] Project coordinator.

[2] Chemical engineer.

Both authors are from the Grand Forks Coal Research Laboratory, Bureau of Mines, Grand Forks, N. Dak.

[3] Gomez, Manuel, W. S. Landers, and E. O. Wagner. Entrained-Bed Carbonization of Highly Fluid Bituminous Coals. BuMines Rept. of Inv. 7141, 1968, 34 pp.

Landers, W. S., E. O. Wagner, Manuel Gomez, Charles C. Boley, and J. B. Goodman. Entrained-Bed Carbonization of Bituminous Coal: Tests on an Australian Coal. BuMines Rept. of Inv. 6608, 1965, 51 pp.

TABLE 33. - Analyses of coal and chars used for blending in 500-pound oven tests

	Sunnyside[1] base coking coal		Sunnyside chars (dry basis)			Lignite[2] char
	As-received	Dry basis	High-volatile	Medium-volatile	Low-volatile	
Proximate analysis, percent:						
Moisture	5.2	-	-	-	-	-
Volatile matter	37.8	39.9	16.0	9.8	5.8	16.6
Fixed carbon	51.5	54.3	75.0	80.0	84.2	69.1
Ash	5.5	5.8	9.0	10.2	10.0	14.3
Ultimate analysis, percent:						
Hydrogen	5.7	5.4	3.0	2.3	1.7	2.4
Carbon	73.8	77.8	77.3	81.2	84.0	74.9
Nitrogen	1.5	1.6	1.9	1.8	1.8	1.4
Oxygen	12.8	8.7	8.0	3.8	1.8	6.4
Sulfur	.7	.7	.8	.7	.7	.6
Ash	5.5	5.8	9.0	10.2	10.0	14.3
Heating value Btu/lb.	13,210	13,930	12,890	13,100	13,240	12,130

[1] Carbon County, Utah.
[2] Baukol-Noonan mine, Burke County, N. Dak.

Four chars were used in the study. Three were prepared at distinctly different volatile-matter levels from the Sunnyside coal, and one was produced from a North Dakota lignite (Baukol-Noonan mine, Burke County). All chars were made using the entrainment-carbonization process in which crushed coal is blown vertically upward through a hot, refractory-line tubular reactor. The reactor used for producing the four chars was 10 in ID by 31 ft long. Further details on entrainment carbonization are given in the appendix.

Analytical data on the four chars also appear in table 33. It will be noted that the lignite char was similar in composition to the high-volatile char produced from bituminous coal, except for a somewhat higher ash content.

Experimental Equipment and Procedures

The experimental coke oven is a "slot" type charged with about 500 pounds of coal through a 6-in pipe at the top (fig. 78). Inside dimensions of the oven are 13-1/2 in between the heated walls and 36 in between the two narrow doors. The bottom and walls of the oven are 2-in-thick silicon carbide tiles, made especially for the purpose and backed by suitable high-temperature refractory shapes. The roof is constructed of a castable refractory; the two doors each have approximately a 14-in thickness of refractory. The oven is charged with a fixed volume of coal (slightly over 10 cu ft), to a depth of 36 in. The oven is heated electrically by six pairs of silicon-carbide,

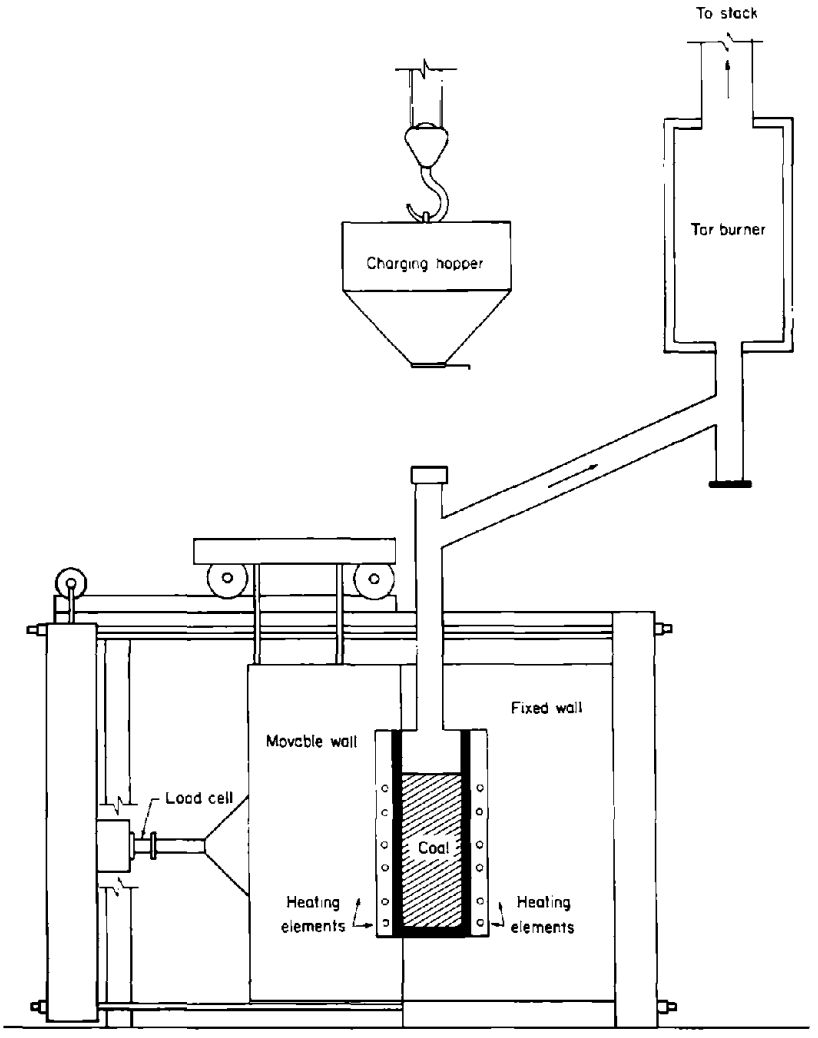

FIGURE 78. - Movable-Wall Coke Oven, 500-Pound Capacity.

high-resistance, electrical heating elements.

Since experimental interest is focused entirely on coke, no byproducts are recovered. Gases and tar vapors produced during coking are discharged from the oven through a gas offtake and pass into a tar burner where a pilot flame ignites them. The products of combustion are exhausted into the atmosphere.

There are no standard procedures in the operation of experimental coke ovens. For this study, the following procedures were used: The coking coal was crushed to about 80 percent through 1/4-in screen, and the chars were crushed to 100 percent through 20 mesh. The blends were adjusted to 3 percent moisture, and about 0.2 percent of fuel oil was added to stabilize bulk density. Oven temperature was 1,700° F at the time of charging, with a programed increase of 30° per hr until 1,965° F was reached. This final temperature was held constant until the coke was pushed from the oven and water-quenched.

Standard coke-testing procedures, as published by the American Society for Testing and Materials (ASTM),[4] were used, except that testing was not done

[4]American Society for Testing and Materials. Standard Method of Drop Shatter Test for Coke. D141-66 in 1969 Book of ASTM Standards: Part 19, Gaseous Fuels: Coal and Coke. Philadelphia, Pa., March 1969, pp. 3-7.

_____. Standard Method of Test for Volume of Cell Space of Lump Coke. D167-24 (reapproved 1967) in 1969 Book of ASTM Standards: Part 19, Gaseous Fuels: Coal and Coke. Philadelphia, Pa., March 1969, pp. 8-11.

_____. Standard Method of Tumbler Test for Coke. D294-50 in ASTM Standards on Coal and Coke, 14th Edition. Philadelphia, Pa., December 1962, pp. 165-166.

_____. Standard Method of Test for Sieve Analysis of Coke. D293-50 in 1965 Book of ASTM Standards: Part 19, Gaseous Fuels: Coal and Coke. Philadelphia, Pa., March 1965, pp. 56-57.

in duplicate owing to lack of sufficient coke. Tumbler and drop-shatter data were obtained, as well as size analyses and porosity data. Several special nonstandard tests were also conducted.

Although the specific laboratory procedures for conducting physical tests of coke quality are standardized, the basic meaning of each test is less precise. In general, the ASTM tests have been designed to reflect good performance of coke in a blast furnace. For example, coke must have good impact and compression resistance because it is handled roughly and must support a heavy burden of iron ore and limestone. This impact and compression resistance is partially indicated by the percentage of tumbled coke larger than 1 in, as determined in the tumbler test. Coke must also have abrasion resistance because pieces are ground against each other during their descent in a blast furnace. This abrasion-resistance quality is partially indicated by the percentage of tumbled coke larger than 1/4 in. Further, size and porosity data are helpful because the blast can reach more coke surface in a coarse, porous coke than in a small-sized, relatively nonporous coke.

No one test tells everything, and even blast furnace operators do not completely agree about the relative importance of the tests. However, the tumbler test seems to be commonly regarded as of first importance, followed by the drop-shatter, size-analysis, and porosity tests, in that order. In the present study, it was felt that a single measure of overall coke quality was desirable, combining the principal results of all tests with appropriate regard to their importance. Such a measure was developed by Schulze and Soth[5] while working with Sunnyside coal several years ago and was termed "coke physical index."[6] It permits a relatively clear summation of the physical data. The coke physical index also has the advantage of smoothing out minor data deviations that are inherent in the testing procedures.

Tests and Results

Twenty-two test runs were conducted: Three with unblended Sunnyside base coal, and 19 with two-component blends composed of selected percentages of Sunnyside and of one of the four chars, as shown in table 34.

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[5] Schulze, W. G., and Glenn C. Soth. Use of Coal Plasticity in Coke Plant Coal Blending. Proc. Blast Furnace, Coke Oven, and Raw Materials Committee. American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, v. 19, 1960, pp. 58-76.

[6] The coke physical index is a modification of Campbell's earlier "physical fuel value." Certain factors in Campbell's work were adjusted; and, also, recognition of tumbler hardness and small sizes of coke (before and after tumbling) were included. It is the sum of the following four factors:

Tumbler data:	(Stability) plus (hardness) minus 70.
Drop-shatter data:	[(Percentage on 2-in) minus (percentage through 1/2-in)] multiplied by 0.4.
Size-analysis data:	[(Percentage of 4 × 2-in) minus (percentage through 5/8-in)] multiplied by 0.2.
Porosity data:	[2.75 minus (apparent specific gravity) minus (true specific gravity)] multiplied by 10.

TABLE 34. - Blend composition and number of coke-oven tests

Char concentration in blend,[1] percent	Sunnyside char			Lignite char
	High-volatile	Medium-volatile	Low-volatile	
5	-	-	1	-
10	3	1	2	1
12.5	1	1	1	-
15	2	1	1	1
17.5	1	-	1	-
20	-	-	1	-

[1] In addition, 3 runs were made with unblended Sunnyside base coal.

Selections of blend compositions for the 22 runs were made as the series progressed using information gained from preceding runs to determine most efficient compositions for succeeding runs. A limited supply of medium-volatile char was a factor in selecting compositions.

Results of physical tests conducted on 21 of the 22 product cokes are given in table 35. One test was omitted because results were clearly erroneous. The error probably occurred in the coke-testing procedure.

Table 35 shows detailed tumbler, drop-shatter, size analysis, porosity, and yield data for each coke. Also included are coke physical index values, which, as previously indicated, are useful in evaluating overall coke quality. In the present discussion, quality of coke and the extent to which it is affected by char additions are measured by this index.

In several cases, duplicate and triplicate coke runs were conducted. This was done to indicate repeatability of the coke quality tests when the entire 500-pound coke oven test is replicated. Since present interest is focused on the coke physical index, the following values of this measure of coke quality are abstracted from table 35 to show reproducibility:

Char blended with Sunnyside	Coke physical index	
	Individual runs	Average
None	17.8	17.2
	18.4	
	15.4	
10 percent of low-volatile char	51.3	51.8
	52.2	
10 percent of high-volatile char	47.5	48.4
	47.8	
	49.9	
15 percent of high-volatile char	49.9	52.3
	54.7	

TABLE 35. - Results of physical tests on coke produced from unblended and blended Sunnyside coal

Char addition, percent	Type of char: Produced from--	Type of char: Volatile matter, percent	Tumbler data: Cumulative percentage retained on-- 1 in	Tumbler data: Cumulative percentage retained on-- 1/4 in	Drop-shatter data: Cumulative percentage retained on-- 2 in	Drop-shatter data: Cumulative percentage retained on-- 1/2 in	Size analysis data: Cumulative percentage retained on-- 4 in	2 in	1 in	5/8 in	Avg. size, in	Porosity data: Specific gravity Apparent	True	Cell space, percent	Coke physical index	Coke yield, dry basis, percent
0	-	-	5.0	72.0	23.5	93.8	0.3	24.5	82.5	89.7	1.66	0.791	1.83	56.8	17.8	63.3
0	-	-	8.2	73.4	16.1	94.1	1.0	20.2	82.7	89.0	1.64	.807	1.84	56.1	18.4	62.4
0	-	-	5.9	70.9	15.0	92.1	.3	29.0	84.5	93.6	1.73	.772	1.85	58.3	15.4	64.4
5	Sunnyside	5.8	15.9	71.8	31.8	95.8	.8	40.6	87.8	91.6	1.94	.831	1.83	54.6	35.9	65.6
10	do.	16.0	24.9	71.1	37.6	95.0	.6	46.2	90.4	92.6	1.99	.815	1.85	55.9	47.5	59.8
10	do.	16.0	26.1	69.4	39.1	96.6	.0	44.4	89.8	92.3	1.95	.818	1.86	56.0	47.8	62.2
10	do.	16.0	26.8	69.6	41.0	97.0	.6	42.3	90.3	94.9	1.92	.824	1.83	55.0	49.9	63.9
10	do.	9.8	25.4	68.6	44.2	96.2	.6	58.7	90.9	93.4	2.17	.803	1.84	56.4	51.5	64.6
10	do.	5.8	25.0	66.4	50.4	95.8	3.5	64.7	90.2	92.6	2.30	.824	1.86	55.7	51.3	63.1
10	do.	5.8	26.5	67.1	51.3	95.4	8.1	64.2	90.0	91.1	2.44	.831	1.87	55.6	52.2	63.8
12.5	do.	9.8	30.9	63.6	58.3	96.8	2.8	63.9	91.3	94.2	2.27	.827	1.84	55.1	58.4	66.3
12.5	do.	5.8	32.3	57.3	60.4	96.2	5.0	71.5	91.8	94.3	2.44	.807	1.87	56.9	55.1	67.0
15	do.	16.0	35.5	59.1	47.1	94.6	.4	51.4	84.8	88.0	1.95	.836	1.83	54.3	49.9	66.2
15	do.	16.0	36.4	67.3	32.6	97.0	.0	47.5	90.1	94.0	1.96	.814	1.85	56.0	54.7	65.0
15	do.	9.8	30.0	52.7	56.0	94.8	1.3	60.7	86.2	88.5	2.15	.810	1.83	55.7	43.7	65.9
15	do.	5.8	34.1	52.3	71.7	96.2	5.9	71.2	89.0	92.1	2.51	.849	1.86	54.4	55.4	66.4
17.5	do.	16.0	31.4	49.6	48.1	92.6	.0	48.6	79.0	82.0	1.81	.845	1.83	53.8	34.0	65.9
17.5	do.	5.8	36.8	48.2	67.5	94.0	2.3	58.5	81.7	84.5	2.13	.801	1.82	56.0	49.0	66.4
20	do.	5.8	24.5	32.3	61.0	84.6	2.8	49.0	63.1	65.2	1.78	.806	1.86	55.4	8.2	67.9
10	Lignite	16.6	28.6	64.6	35.2	95.2	.2	46.9	87.3	91.0	1.90	.826	1.80	54.1	44.1	61.3
15	do.	16.6	32.3	54.6	56.0	94.6	1.9	55.7	83.4	86.4	2.04	.829	1.85	55.2	45.2	63.9
[1]15	-	-	34.5	70.5	40.5	96.5	1.4	49.4	[2]92.9	95.6	2.08	.80	1.86	57.1	59.4	67.8

[1] Blended with 2 low-volatile and 1 medium-volatile Oklahoma blending coals. See BuMines Inf. Circ. 8010, p. 3. Test data are averaged from runs made in Denver and Tuscaloosa slot-type ovens, as reported in table 3, p. 9, of the same reference.

[2] Interpolated.

Replicated values check each other moderately well in most cases. The standard deviation of all replicates is 1.84 index points. Most of this variability developed in the 15-percent pair; without it, the standard deviation would have been only 1.40 index points.

All coke physical-index data in table 35 are summarized and illustrated in figure 79, using averages where replicate runs were made. The following factors are evident:

1. The addition of any of the four chars to Sunnyside coal, in concentrations up to 17.5 percent, led to significantly improved coke as measured by the coke physical index.

2. Best coke was made from blends of 10- to 15-percent concentrations of char.

3. Quality of cokes prepared with lignite char is nearly as good as the quality of those prepared with Sunnyside char.

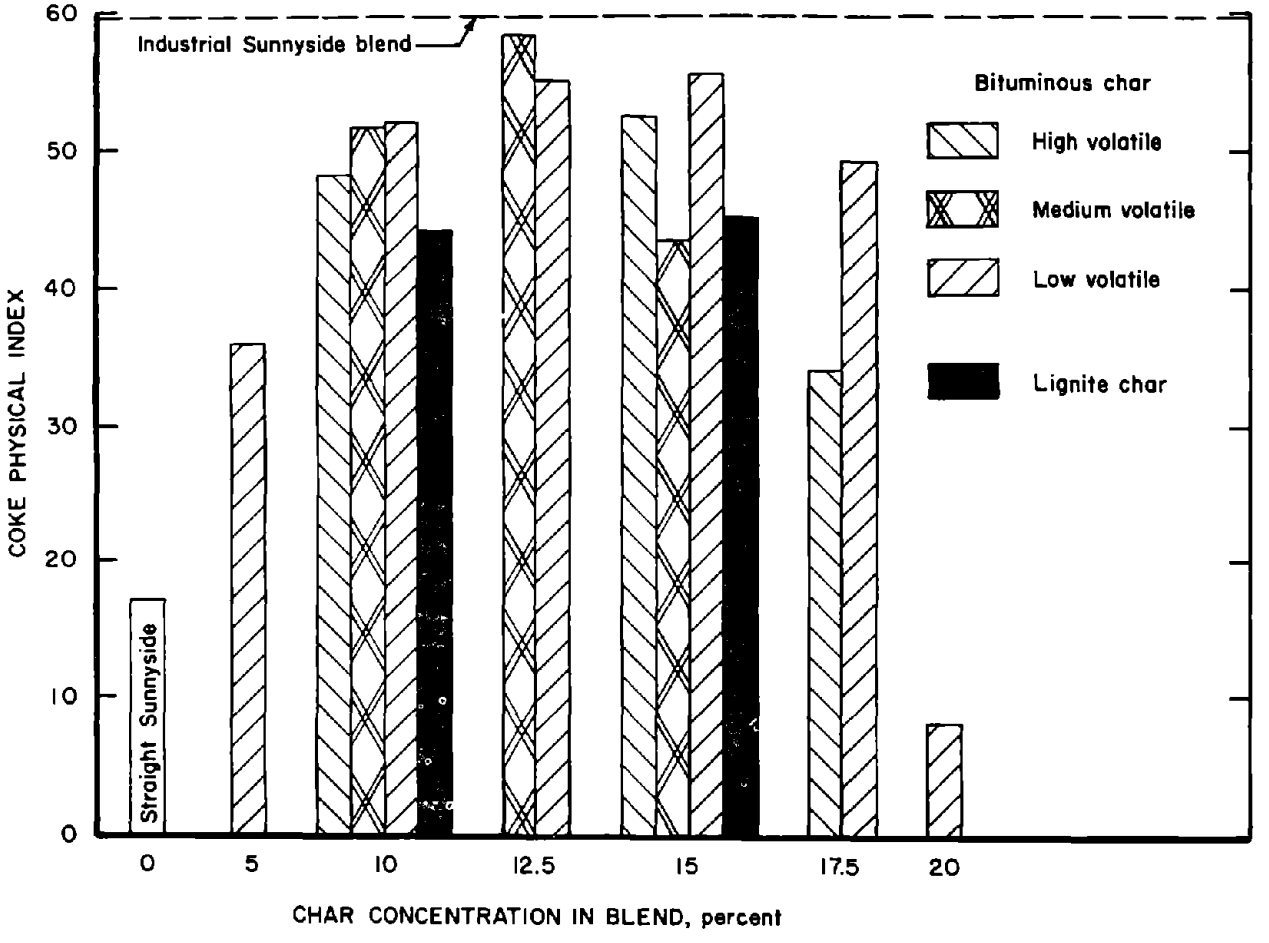

FIGURE 79. - Effect of Char Additions on Physical Quality of Coke Made With Sunnyside Coal.

Differential effects among the chars are not so evident. However, a statistical examination of the data indicates that there are no significant differences between the effects due to high-volatile char and those due to medium-volatile char, and no significant differences between medium-volatile-char and low-volatile-char effects. It appears that a significant difference does exist between high-volatile-char and low-volatile-char effects (with a probability exceeding 9 out of 10).

Any conclusion about lignite-char effects as compared with bituminous-char effects is tentative because only two runs were made with lignite char. Statistically, the present data indicate that there is a good probability (better than 9 out of 10) that bituminous char can be depended on for somewhat better results than lignite char. However, there are so many lignite chars that have not been tested that it seems best not to generalize on these results. It should be pointed out that quite notable improvements to straight Sunnyside coke are possible using blends containing lignite char.

A comparison of these experimental coke qualities with those of industrially acceptable coke is of interest. Several years ago the Bureau of Mines cooperated in a coking study[7] with Kaiser Steel Corp., which then used Sunnyside as its base coking coal, along with three lower volatile blending coals. At the time of the study, the Bureau operated two slot-type experimental coke ovens. Both were used with the Sunnyside-based coke blend that Kaiser was then using to produce acceptable coke for its blast furnaces. Average coke physical index for the Kaiser blend as listed in table 35 was 59.4. This value was approached closely by several of the char-blend cokes in the present study. Four of the char-blend cokes exceeded 54 in the coke physical index, and the best coke had an index of 58.4, only one point less than the 59.4 for Kaiser's industrially acceptable blend.

In this study, the reason for making the two runs with lignite char was technical interest rather than expectation that this use of lignite would be economically attractive. Certainly the long distances that separate the lignite deposits and the operating coke ovens of this country would be an economic hurdle, regardless of what the technical possibilities might be for blending lignite char with bituminous coal for making metallurgical coke.

The case is better, of course, for bituminous chars, since their use could conceivably permit local operation for both components of a coking blend. In any event, a detailed economic study of coal-mining, transportation coke-making, and blast-furnace costs would be necessary. The technical study presented here would need to be expanded to include three- and possibly four-way blends and full-scale oven tests. Furthermore, numerous coke-oven operating conditions would need to be examined in detail and optimized. Additional work is now underway using Allen coal, a second Western coking coal found in Las Animas County, Colo.

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[7] Staff, Division of Bituminous Coal. Comparative Evaluation of Coking Properties of Four Coals. BuMines Inf. Circ. 8010, 1961, 22 pp.

Conclusions

Results from this study support the following conclusions using the coke physical index as a measure of coke quality:

1. The use of any of the four char blends with Sunnyside (Utah) coking coal, in concentrations of 10 to 15 percent, resulted in markedly better coke than is obtainable from unblended Sunnyside coal.

2. The use of char produced from lignite in a blend with Sunnyside coal also resulted in markedly improved coke, nearly as good as those made with blends of Sunnyside char and Sunnsyide coal.

3. The best coke made with a blend of Sunnyside coal and char approached closely in coke physical index an industrially accepted coke produced from Sunnyside coal and three blending coals.

4. The use of the low-volatile (5.9 percent) char produced slightly better coke than the use of the high-volatile (16.0 percent) char. The difference was significant at the 90-percent level.

Appendix

Char was produced by entrainment carbonization, in which crushed coal is blown vertically upward through a hot refractory-lined tubular reactor. The reactor used for this purpose is 10 in ID and 31 ft long. During passage through the hot reactor, most of the coal is carbonized; the extent of carbonization is dependent upon temperature. Heat to maintain this carbonization reaction is generated by a simultaneous combustion reaction, in which all available oxygen in the injecting airstream is consumed by combining with the coal and coal products that are being conveyed upward. The process thus generates its own heat. The percentage of coal consumed in the combustion reaction, to maintain the heat-consuming carbonization reaction, is small. Carbonization temperature can be adjusted during operation by adjusting the rate of coal feed, the rate of air feed, or both.

All feed to the process (coal and air) enters at the bottom of the reactor, and all products of both carbonization and combustion reactions emerge at the top. Products consist primarily of partially carbonized coal (char), tar and water vapor, and fixed gases. Char is removed from the hot stream by a knockout vessel and a cyclone, both maintained hot to prevent tar condensation. Tar and water vapor may be recovered quantitatively by passing the vapors through a series of appropriate condensers; and tar "light ends" (mainly benzene, toluene, and xylene) may be removed by an oil scrubber, an activated-carbon column, or both. Where char is the only product of interest, a simpler method for disposing of tar and water vapor is to knock them down in the form of an emulsion by direct water sprays. The latter method was used while producing char for the present study.

The entrainment carbonization process was originally developed[8] for non-agglomerating coals (lignites and subbituminous coals) because bituminous coals tended to soften and adhere to the inside of the reactor. Later, techniques were found whereby bituminous coals could also be processed.[9]

[8] Parry, V. F., W. S. Landers, J. B. Goodman, and G. C. Lammers. Drying and Carbonizing Fine Coal in Entrained and Fluidized State. BuMines Rept. of Inv. 4954, 1953, 43 pp.

[9] Work cited in footnote 3.

U.S. GOVERNMENT PRINTING OFFICE: 1970 O -387-352