



**A CURRENT APPRAISAL OF UNDERGROUND COAL GASIFICATION**

Report to

**U.S. BUREAU OF MINES**

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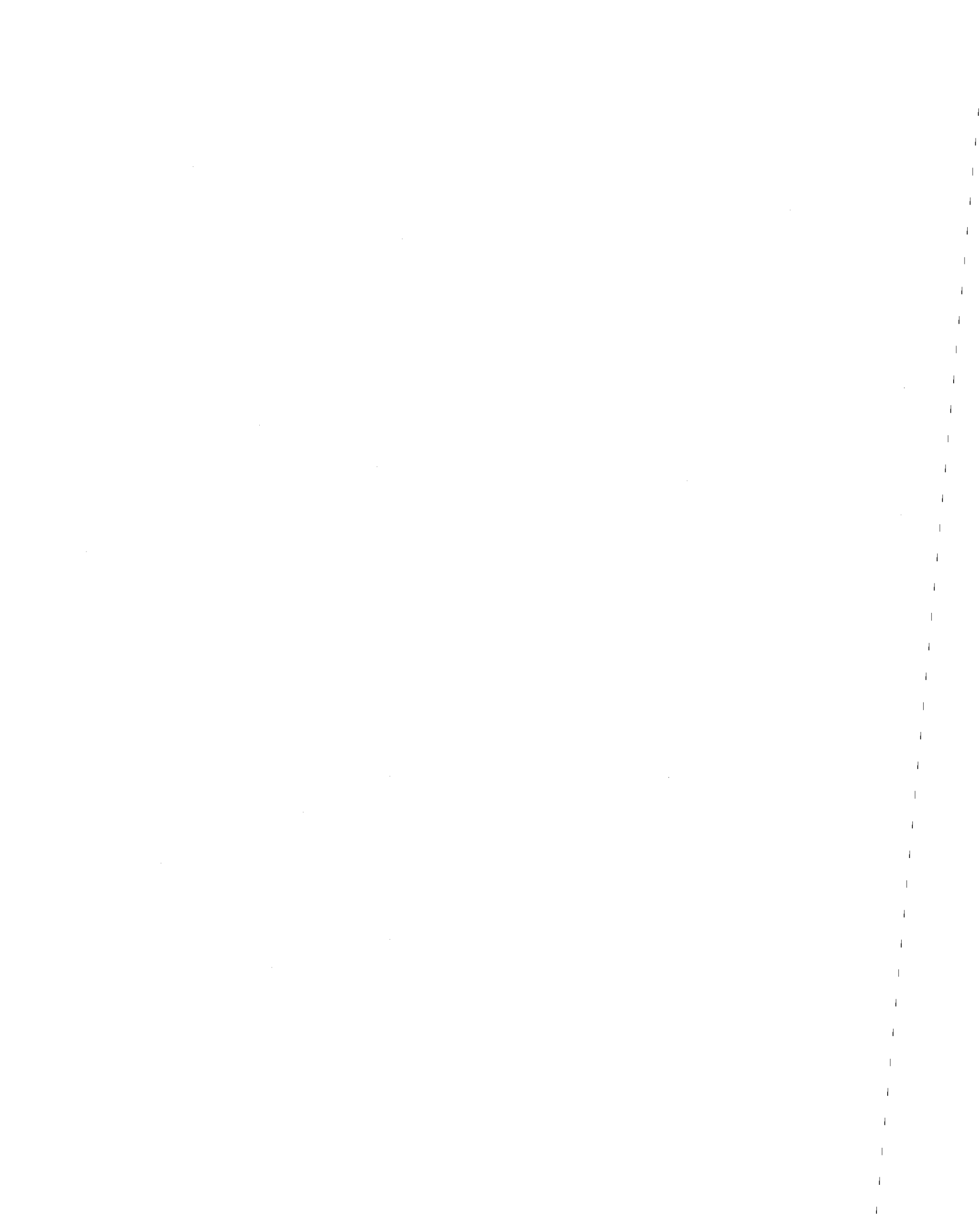
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## I. SUMMARY

### A. PURPOSE AND SCOPE

The Bureau of Mines in the Department of the Interior is increasingly concerned with the safety and health of personnel engaged in coal-mining operations, particularly below ground. The Bureau is also concerned with improving the utilization of domestic mineral resources, and reducing the environmental impact of mineral operations. One obvious way to improve safety and minimize health hazards would be to eliminate coal mining entirely by bringing the energy value of the coal to the surface in some other way, such as by partially burning it underground to form combustible gases and bringing these gases to the surface, where their energy content can be put to use. This technique might also improve the utilization of the coal resource.

Accordingly, the Bureau of Mines, interested in re-evaluating underground coal gasification technology in terms of current and expected conditions in the United States, requested Arthur D. Little, Inc., (ADL) to appraise the technology to determine:

- Whether the current (1971) state of the technology offers a technically feasible method for gasifying coal underground that is applicable to the reserves of bituminous and lower rank coals in the United States.
- Whether a program of research and further development of the technology could ultimately make it a technically feasible alternative to current open-pit and underground coal mining operations.
- What the nature and cost of further research and development work in the technology should be.

We based our appraisal on a review of past work in the United States and in other countries, during which we compiled a bibliography to supplement that compiled by the Bureau for the period 1945-60, and published in 1963 as Information Circular 8193. In addition, we reviewed progress in a number of technological fields that appear to have relevance to a further development of underground coal gasification technology. We also discussed various aspects of the technology with knowledgeable people in the field.

## B. METHODOLOGY

We first defined the criteria by which methods of underground gasification could be judged to be applicable to the coal deposits of the United States; that is:

- An underground coal gasification method must lend itself to operation on a large scale.
- The processing features must be controllable so that significant bodies of coal in the deposit are not bypassed, either ungasified or partially gasified.
- The processing features must be controllable such that the desired levels of heating value in the product gases are consistently obtained.
- The mechanical features must permit, to the extent necessary, control of undesirable factors, such as groundwater inflows and leakages of reactants and products.
- The process design and operation must be flexible enough to permit injection of bulk materials into voided spaces in the coal deposit to avoid ground subsidence at the surface, and possible deleterious underground effects, which would tend to reduce the quality and constancy of the product gases and the level of coal recovery.
- The process should not require any underground labor, either during operation or preferably even during the installation of the facilities.

We decided that new research and development work would be justifiable only if we could establish a reasonable chance that costs for the energy supply from a total system could be competitive with alternatives.

Finally, in review of related technology we were always alert to novel concepts and to finding new ideas that might be useful in determining the nature of new research and development work for the technology.

## C. FINDINGS AND CONCLUSIONS

### 1. The Applicability of Current Technology to U.S. Coal Deposits

Underground coal gasification is technically feasible, but economic feasibility is yet to be determined. Coal seams can be prepared for underground gasification without a need for labor to work underground during any stage of the operations. Gaseous oxidizing agents can be delivered to the prepared coal seam, and the gasification reactions carried on to produce combustible gases from the carbon content of the coal. These gases can be collected underground and brought to the surface for combustion in industrial equipment without the need to add fuels from other sources.

The technology upon which underground gasification can be based is the result of world activity in underground coal gasification which peaked during the period 1945-1960. Active experimental work (and reported commercial operations in the U.S.S.R.) was then under way simultaneously in Great Britain, Morocco, Belgium, Italy, the United States, the U.S.S.R., Poland, and in Czechoslovakia. Furthermore, experimentation in the U.S.S.R. began in 1933 and ceased (apparently) in 1965. Today, as far as is known, no significant activity seems to be under way anywhere in the world, nor have any plans for new work been reported. Thus, the currently available technology has been relatively dormant for about five to ten years.

The current technology would be limited in its application to U.S. coal deposits, since past experience indicates that:

- It is not yet certain that positive control can be achieved in new U.S. operations to the extent that high recovery of the coal values will be consistently obtained.
- It is not yet certain that methods to control or eliminate leakage of unwanted substances, mainly water, into the gasification areas, and leakage of gasification agents and products out of the gasification areas are reliable.
- It is not yet certain that positive control can be achieved in new U.S. operations to the extent that a uniform composition gas of constant heating value will be consistently obtained.

The current technology is also limited in that a single gasification installation does not yet have unit capacity high enough to suit U.S. commercial energy supply practices. Thus, multiple parallel operations would be required. The indications

are, however, that solutions to the problems posed by the limitations ultimately should also act toward increasing the capacity of single installations.

Many coal seams probably exist in many states that could be underground gasification candidates. The selection of attractive projects would most likely be made on the basis of technical and economic considerations rather than on the geographical location of the coal deposits alone.

## 2. Justification for New Activity

New activity in underground coal gasification is justified but with a limited scope. The technology may be competitive with alternatives that may be considered in the United States to balance future energy sources with energy demand. In addition, it offers quantifiable benefits by alleviating environmental hazards arising from the conventional mining and utilization of coal. Gases produced from coal underground can be treated by methanation and compression to behave in industrial equipment about like natural gas. Land disruption effects of conventional coal mining can be reduced, if not eliminated. The incidence of uncontrolled underground fires, or aboveground coal waste fires, can be reduced. The volume of contaminated acidic water drained from work-out underground mines can be decreased. Moreover, the improvements to underground gasification technology resulting from new activity could eliminate the ground subsidence resulting from roof collapse in conventional underground mines.

Some of the presently known underground gasification methods – i.e., blind borehole, borehole producer, and streaming techniques – can be modified and adapted to U.S. coal deposits. The modifications require advancement in the state of the technology.

New activity should include both analytical and experimental work but with a limited objective, namely: to obtain reliable production-oriented cost estimates for the product gas when the candidate methods are applied in the United States on a large scale.

## 3. Nature of New Work

The results of new work should achieve the following technical objectives. Achievement of the first objective would justify work on the remainder.

- *Prevention of Roof Collapse.* Results must show that positive control of the prevention of roof collapse can be achieved. Control levels would be acceptable when desired heating-value levels in the product gases are consistently achieved.

- *Knowledge of Burning Face Position and Temperature.* Results must show that the position and temperature of the burning-face can be reliably estimated for comparison with predictions of the desired burning-face positions and temperatures. Desired conditions are based on maintaining acceptable product-gas quality, product-gas quantity, and recovery of coal values.
- *Control of Operations.* Results must show how to incorporate and adjust control devices in the installations to eliminate differences between measured and predicted burning-face conditions.

Work should be undertaken in two steps, the first to lead to the second when the results justify. The major topics for work in the first step are:

- Extension of the capability of available curved-hole drilling technology to permit larger-diameter boreholes and longer travel distances in coal seams;
- Analytical study of underground cavity size in terms of roof stability and performance of the gasification process;
- Analytical and experimental development of stowing methods and techniques of operation, and the identification of suitable stowing materials;
- Analytical study of fire-face temperature measurement techniques and methods for estimating fire-front position.

The second step is the installation of a pilot underground gasification system and its operation to produce technical data on which reliable production-oriented costs can be estimated. The results should then be used to justify a second phase of work which would be oriented to establish prices for the product gas, and estimates of profitability for large-scale installations in the United States.

#### 4. Level of Effort

We believe a first phase involving the two-stage program of work is justified at an estimated total cost of about \$2.5 to \$3.5 million. The first stage might cost from about \$500,000 to \$1,500,000, depending largely on the amount of special equipment needed, and should be accomplished in about one year. The second stage should be accomplished in about two years; its cost of \$2-million is about equally divided between personnel and materials.



## II. INTRODUCTION

The basic difference between conventional mining and underground gasification of coal deposits is the location at which the coal's energy is extracted. Conventionally, coal is mined underground and brought to the surface before its heating value is recovered (e.g., by combustion with air). In underground gasification, the heating value is extracted in situ from the coal deposit and brought to the surface in the form of combustible gases. In neither case, however, is the total heat value of the coal deposit recoverable.

The technology of underground gasification of coal is about a century old. Although the first reference to the technique occurred in 1868, most of the activity occurred in the post World War II period from about 1945 to about 1960. At one time during this period, simultaneous large-scale experimental work was under way in England, France (Morocco), Belgium, the United States, Italy, and the Union of Soviet Socialist Republics; and probably also in Poland, Czechoslovakia, and Japan. The Russian work was of the longest duration, beginning about 1933 and extending to about 1965. The Russian work reached the stage where the extracted gas was used for large-scale generation of electricity to supply local industries. Thus one may consider such Russian installations as commercial. (An historical background is presented in some detail in Appendix A.)

Sponsorship for experimental work has come almost entirely from governmental sources. This has obviously been so in the U.S.S.R., and was so in the other countries reporting activity. In the United States, the work at Gorgas (Alabama) was co-sponsored by a private organization, the Alabama Power Company. The first U.S. work on electro-linking was sponsored by the Sinclair Coal Company at the University of Missouri.

About the same time that the Bureau of Mines initiated work at Gorgas, Alabama, a subsidiary of Union Carbide Corporation began field testing of an underground gasification installation near Institute, West Virginia. The testing work was conducted at this site for perhaps three years. To the best of our knowledge, results have not been published in the United States but a paper was presented by Union Carbide Corporation sometime between 1953 and 1956 in Europe, either the Netherlands or Germany. Also during the work on hydrafrac performed at Gorgas, the Pan American Petroleum Corporation and the Halliburton Oil Well Cementing Company cooperated with the Bureau of Mines and the Alabama Power Company.

No significant work is known to be in progress now. The situation in the U.S.S.R. can only be gleaned from an analysis of the literature pattern, and from the fact that, despite our efforts to make the necessary arrangements, it was not possible for us to arrange a special visit to the installations that had been widely

reported in the Russian literature. The last planned trial period for the technology of the U.S.S.R. seems to have been 1959-1965, and relatively little has been reported since 1965. In fact, nothing appeared in 1970 and early 1971 literature. It would seem that abandonment, if it has in fact occurred, has been for economic rather than technical reasons.

About ten years have now elapsed since the experimental work at Gorgas was terminated. In this period, work in other countries appears to have ceased entirely for lack of economic incentive. For this period in the United States, the economic and competitive position of coal relative to other fossil fuels and to nuclear energy has shifted dramatically.

Since about 1967, even though absolute coal demand is increasing, potential coal markets in electricity production are being lost to the increasing nuclear power generating capacity, a trend that may be reinforced when breeder reactors become practical. One factor that has encouraged this trend is the restriction that has been placed on the use of high-sulfur coals because of their sulfur-dioxide chimney emissions. Also, the health and safety precautions required for coal miners by the Federal Mine Health and Safety Act of 1969 have acted to raise the price of coal. The stability of coal price levels that prevailed in the post World War II years up to about 1967 has disappeared. On the other hand, coal appears to be becoming a potential raw material for the large-scale production of pipeline gas, two large projects having just been announced for construction in New Mexico.

Within such a framework, the attractiveness of the underground gasification approach could be markedly different in the United States in 1971 than it was in 1946 when the first U.S. experimental work began or in 1959 when it terminated.

### III. THE CONTEXT FOR AN APPRAISAL

#### A. UNDERGROUND ENERGY-RECOVERY TECHNIQUES

In addition to the conventional method of mining underground coal deposits – i.e., miners working underground to extract the coal and transport it to the surface – there are several possible techniques for extracting the coal, or its energy, that do not require men to actually work underground. These techniques may be categorized according to the form in which the energy in the coal is brought to the surface: i.e., solid, liquid, gas, or other (Table 1).

TABLE 1

TECHNICAL ALTERNATIVES TO EMPLOYING PEOPLE  
TO MINE COAL UNDERGROUND  
FORM OF PRODUCT

1. Solid	2. Liquid	3. Gaseous	4. Other Energy Form
Completely automated underground	Distillation of coal underground	Hydrogenate carbon to methane	Complete gasification to produce high-pressure steam
Thorough fracture of coal seam and flushing broken coal to surface	Dissolution of coal in solvent and bringing solution to surface	Partial oxidation of coal to combustible gases (CO + H <sub>2</sub> )	
Production of fine, ashless carbon			

Source: Arthur D. Little, Inc.

#### 1. Solid

One way to bring coal energy to the surface in the form of a solid would be to automate conventional underground coal mining practices so that the coal could be mined and extracted by remotely controlled mining equipment. Industry and government have developed technologies for coal mining and for other industries that would seem to be adaptable to a completely automated underground mining system. Another way would be to hydraulically fracture the coal seams very thoroughly and flush the solid coal to the surface. With both of these techniques, the coal would be brought to the surface in its natural form, that is, with its ash and sulfur content intact.

A theoretically possible alternative is the production of a fine ash-free and sulfur-free carbon powder that could easily be transported to markets and would burn without emitting any pollutants. This technique involves underground gasification, using a mixture of oxygen and carbon dioxide as the gasifying agent. At the surface, after particulate and sulfur removal the high CO content of the product gases would be reverted to CO<sub>2</sub> and carbon. Part of the CO<sub>2</sub> would be recycled to the gasifying agent, and the remainder vented to compensate for the oxygen input to the system.

## 2. Liquid

One possible technique of recovering coal in liquid form would be to heat it underground in the absence of air to liberate its volatile combustible liquids and gases. The pyrolysis could be achieved by driving boreholes into the coal seam, linking them electrically, and passing an electric current through the seam. The passage of the current causes heat, which in turn causes distillation. Although patents have been issued (and operations proposed) for the in situ distillation of carbonaceous materials in general, the methods involve the construction below ground of processing facilities adjacent to the coal seam, and the distillation equipment can involve personnel working below ground.

Another technique would be to dissolve the coal in certain organic solvents, a technique that is well known and has been widely investigated. Using organic solvents, essentially anthracene-rich coal-tar fractions, one could recover the coal in a liquid form by using a process analogous to the Frasch process for the recovery of sulfur. The solvents could be injected into the coal seam through boreholes, which then could be used as passages through which the liquified coal could be brought to the surface. The temperatures of operation would be high, in the order of 800°F, and a hydrogen atmosphere would be required. Some means would therefore have to be provided to maintain the high temperatures without degrading the reducing atmosphere required for the solution process.

## 3. Gaseous

One technique to extract in situ the coal's energy in the form of a gas would be to force hydrogen into the coal seam under conditions suitable for transforming the carbon content of the coal directly (by hydrogenation) into methane, the basic component of pipeline gas. The reaction is highly exothermic. To achieve reasonable yields it must be carried out at high pressure, while to achieve reasonable reaction rates it must be carried out at temperature levels about 1700°F.

The alternative route to the production of a gaseous fuel from coal is through oxidation of the carbon content to carbon monoxide associated with elemental hydrogen. This partial oxidation approach, being perhaps the simplest way to achieve gasification, has been the basis of essentially the entire world experience in the technology.

#### 4. Other Energy Forms

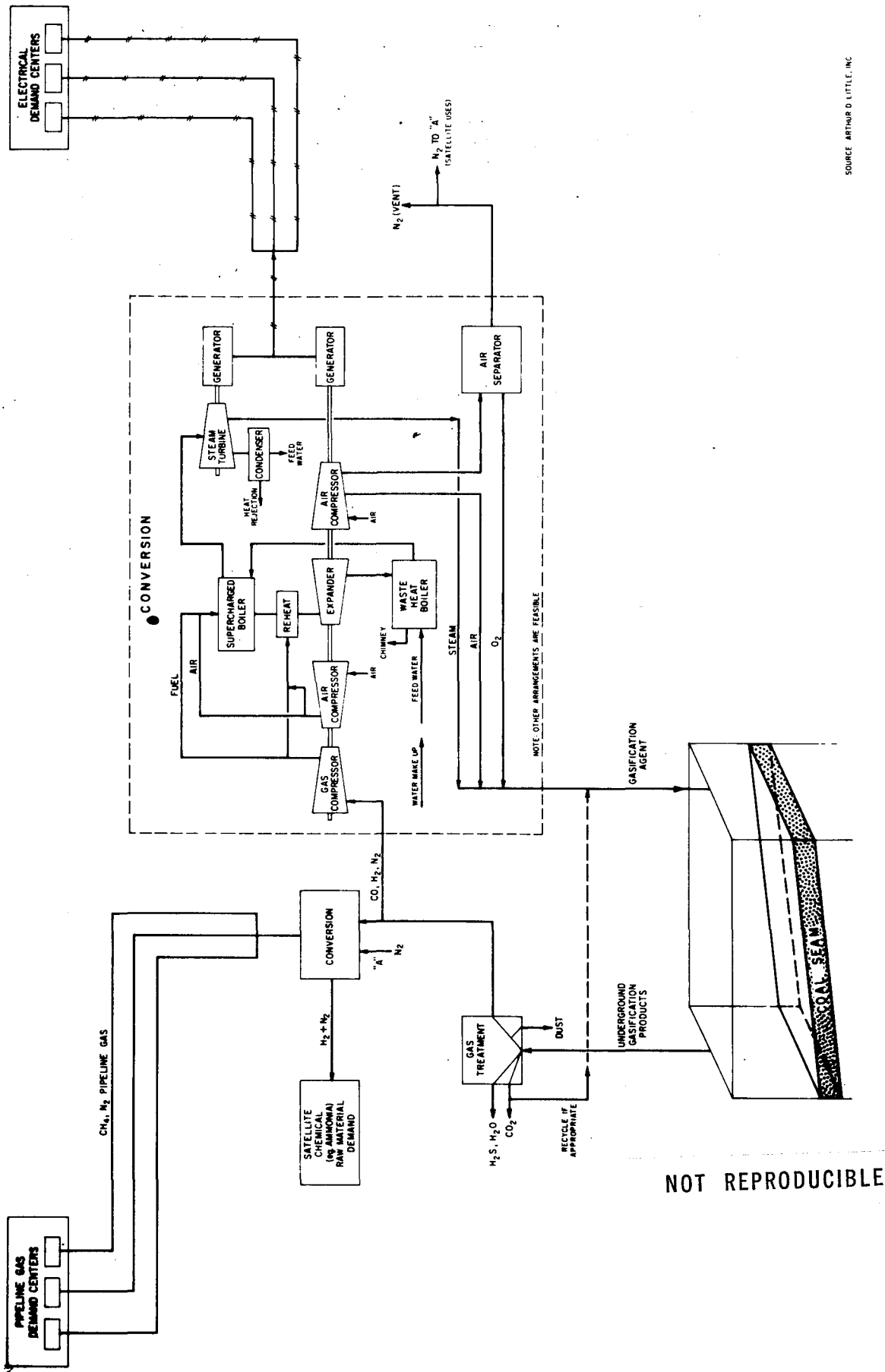
The coal could be completely oxidized by a synthetic geothermal steam approach to produce combustion gases and steam at high pressures. These high pressure gases could be utilized at the surface to run the turbines of electric power plants.

### B. COUPLING OF PRODUCT FORM TO U.S. ENERGY DEMAND

The process of recovering the energy in coal ends not with the solid, liquid, gaseous, or other products, but when these products are either converted to electricity for transmission to the point of use, to a high-heating-value (over 900 Btu/std. cu. ft.) gas for transmission to the point of use, and/or to a feedstock suitable as a raw material for chemical manufacture (e.g., as hydrogen/nitrogen mixtures suitable for conversion to ammonia). Thus the energy form in which the coal deposit is recovered must be coupled to the demand centers. The coupling involves successive joining of energy recovery, energy conversion, and energy transport to constitute a supply/demand system, all components of which would interrelate technically and economically. Underground gasification to recover the energy in coal would be only one of the components in the supply/demand system.

Figure 1 illustrates a coupling procedure that could be used to connect underground coal gasification product gases to U.S. energy demand market centers. The first aboveground operation on the product gas would be to purify it to remove its sulfur, dust, surplus carbon dioxide, and moisture. This purification system would include surge chambers designed to equalize, through storage, variations in the composition of the gases brought to the surface. The purified gas could then be treated to produce a pipeline gas, a feedstock for ammonia production in a satellite industry, and/or high-voltage electricity. The system would also provide for the utilization of otherwise waste energy to produce the gasification agents (i.e., appropriate mixtures of oxygen, nitrogen, and steam).

One approach to producing electricity for transmission would be a conventional power plant, mine-mouth type, using the product gas as a fuel to run the turbines. The gas would be scrubbed of its sulfur content beforehand, thereby removing the sulfur-dioxide stack emission problem. Another approach would be to take advantage of the fact that the power-generation plant would be located



SOURCE: ARTHUR D. LITTLE, INC.

ILLUSTRATIVE COUPLING  
 UNDERGROUND GASIFICATION PRODUCTS TO ENERGY MARKET SUPPLY  
 Figure 1

NOT REPRODUCIBLE

near the underground gasification site and hence would be dedicated to a fuel of a single character, a clean combustible gas, so that there would be no need to provide for the use of alternative solid and liquid fuels. Then, one could consider the use of energy-conversion cycles that have already been tried but which are not in general use because of the desire of most electric utilities to interchange solid, liquid, and gaseous fuels at will to benefit from competitive supply conditions. For example, a supercharged-boiler/gas-turbine cycle (Figure 1) could be adapted to provide the air, steam, and oxygen components of the gasifying agent.\*

The coupling of the components constituting an energy supply/demand system can be analyzed quantitatively and optimized to suit a given set of external constraints, namely: the size and the geographical distribution of the electrical-energy and pipeline-gas demand centers, the potential to site a satellite chemical manufacturing industry, and the character of the coal deposit. In determining the optimum for a particular system configuration, two criteria appear to be important:

- *Recovery of enough of the coal resource so that it is not wasted or made unavailable to future generations.* Current coal recovery practice is probably a good minimum goal.
- *Costs for the energy supply from the total system that are competitive with alternatives.* The economic problem becomes of major interest when methods of carrying out underground coal gasification have been shown to be technically feasible. The level of nitrogen content in the gasifying agent could be significant.

### C. PRODUCT-GAS QUALITY

Product-gas quality is significant mostly because gas that contains a minimum of carbon dioxide helps to conserve the coal resource. The carbon dioxide produced underground represents carbon brought to the surface in an unusable form and wasted by venting to the atmosphere. Thus, that portion of the carbon in the coal deposit is lost in the same way as if it had been left underground and unrecoverable. Even if all or part of the carbon dioxide could be recovered and recycled as a component of the gasification agent, in effect some of the coal energy would be expended in the process.

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\*There are many alternatives to the details illustrated in this system. For example, see article on Converting Coal Gas to Electricity in July/August 1971 issue of the MIT Technology Review.

Other components in the product gas determine the economic competitiveness of the system. It would be preferable if sulfur were present in the gas as hydrogen sulfide rather than as sulfur dioxide because  $H_2S$  would be more readily removed in a purification system. Under the conditions needed in underground gasification, however,  $SO_2$  would be formed instead of  $H_2S$ . Any oxygen in the inlet gases that is not consumed underground for gasification and is mixed with the product gases will constitute a potential explosion hazard.

Ideally, the product gas would contain all of the carbon in the coal deposit as carbon monoxide and all of the hydrogen as elemental hydrogen, but such a goal appears to be unattainable. The gases will contain  $CO_2$  and  $H_2O$  and sometimes even  $O_2$ .

It should be emphasized that any method of gasifying coal in place must bring the energy in the coal out of the ground in a usable form and probably the most usable form is as carbon monoxide. The production of carbon monoxide is basic to the evaluation of any process. However, we can shift carbon monoxide to hydrogen and by the use of water or steam we can produce large quantities of hydrogen covering up initial carbon monoxide formation. Carbon monoxide produced is a measure of coal reacted.

#### D. UNDERGROUND COAL GASIFICATION: TECHNICAL APPRAISAL CRITERIA

The technical factors which are important in assuring that a particular method or operation of the technology is practical in the context of U.S. energy needs and U.S. coal deposits, and which are probably significant in assuring that a system coupling underground coal gasification to the energy demand centers in the United States will be competitive with present practices, are as follows:

- *An underground coal gasification method must lend itself to operation on a large-scale.* For example, unit electricity-generation sizes in the immediate future may be in the 1000 to 1500 MW range. In terms of annual coal supply, this range represents a range of 3- to 5-million tons. It appears then, that either a single or a cluster of underground coal gasification operations should be capable of such coal consumption rates in deposits containing adequate reserves, i.e., in the range of 100- to 150-million tons.

- *The processing features must be controllable so that significant bodies of coal in the deposit are not bypassed, either ungasified or partially gasified.* This is important not only in terms of avoiding an irreversible loss of coal reserves for future generations, but also in terms of the adverse economic effect of unrecovered coal. It appears that a reasonable goal is having the assurance of coal recovery by underground gasification at a level equivalent to that achievable in normal underground mining operations. Useful recovery in underground mining ranges from a low of about 29% to a high of about 91%, and averages statistically for the United States at about 57%. Any substantial improvement would, of course, enhance the attractiveness of the method.
- *The processing features must be controllable such that the desired levels of heating value in the product gases are consistently obtained.* Although outputs from aboveground installations based on underground gases could vary at each production level, the aboveground operations are facilitated and maintenance problems are decreased by constant, predictable quality in the product gases from underground operations.
- *The mechanical features must permit, to the extent necessary, control of the influence of external factors, such as groundwater inflows and leakages of reactants and products.* These factors would act to reduce coal recovery and to produce gases of irregular quality.
- *The process design and operation must be flexible to permit injection of bulk materials into voided spaces in the coal deposit, where this is necessary.* Such a flexibility would avoid ground subsidence at the surface, and possible deleterious underground effects, such as blocking of the fireface and roof collapse. Such occurrences would tend to reduce the quality and constancy of the product gases and the level of coal recovery.
- *The process should not require any underground labor either during operation or even during the installation of the facilities.* If underground labor is required, the work areas should be non-hazardous.



## IV. CURRENT STATE OF THE TECHNOLOGY

### A. THE TECHNOLOGY

Underground gasification of a coal deposit (or seam) involves two basically distinct sets of operations: pregasification and gasification.

The pregasification operations are those used to provide access to the coal deposit and to prepare it for gasification. The gasification operations are those used to supply the gasification agents, establish the contact between these agents and the coal, collect the gasification products, and control the overall process.

#### 1. Pregasification

Since the gasification agents have to be delivered from the surface to the coal and the products removed from the coal to the surface, access to the coal seam is necessary. Access can be achieved by shaft and/or shaftless methods. Shaft methods involve the use of conventional underground mine-openings; shaftless methods involve the use of boreholes.

##### a. Shaft Access

Shaft access may be achieved by using conventional vertical and inclined shafts, entries, galleries, slopes, and similar underground work. Such openings are commonly developed using the conventional underground drilling, blasting, rock removal, and ground support techniques. Since shaft access necessitates that men work underground, the openings must be safe and well ventilated. Hence reports of past underground installations generally describe conventional lined shafts (timbered or concreted) and conventional roof bolted and timbered entries, galleries, and other underground openings. Many reports also describe the use of bulkheads – often conventional brick or concrete designs – to control the flow of gasifying agents and to limit the coal burning to specific areas of the mine.

The most positive method of creating a linkage path between shafts in order to initiate the gasification reactions has been directional drilling. Horizontal or inclined holes have been drilled from underground openings, usually into the coal seam, to link adjacent galleries with a definite path for gas flow.

More recent techniques for access to an underground coal seam involve the construction of shafts by large-hole drilling methods, and, as required, the use of steel and/or concrete casings. Shafts of 6-8 feet in diameter, which allow access of men and materials to underground locations, are routinely drilled to depths of several thousand feet, and large-hole shafts up to 20 feet in diameter are possible.

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## b. Shaftless Access

Shaftless access to coal seams can be achieved by drilling small-diameter holes from the surface. The method has already been used to perform various gasification functions, such as igniting the coal seam, supplying combustion air or other gases, and withdrawing product gas.

Over recent years, techniques for drilling vertical or inclined holes from the surface, and for drilling horizontal or inclined holes underground, have progressed considerably. Thus, one can now drill long holes that stay within a coal seam, or that even follow undulations and irregularities along the seam. Holes that curve around a 90° angle are now possible, as are holes drilled over a long distance to intersect another hole at some known point deep below the surface. Techniques for keeping the drill in the coal seam by redirecting its path, without stopping the drilling, have also been developed. (The techniques are based on the natural tendency for the bit to remain within the coal when the floor and roof are harder than the coal.) Some of these advanced techniques have been used in underground gasification experimental work requiring special types of holes.

In 1953, experimental work in Great Britain (USBM-259)\* showed that locating a fulcrum immediately behind a drill bit enabled one to alter the direction of the advance of a slightly inclined borehole by varying the thrust on the drill rod. An increase in thrust was found to induce a rise; while a decrease of thrust induced a fall. The precise quantitative relationships between rise or fall and change of thrust depended on the design of the drill bit used. The control scheme used in this drilling work involved an instrument devised in the U.S.S.R. (160) comprising two geiger radiation-counters separated by a lead shield, which was mounted near the drilling bit. An electric cable passing through the drill stem transmitted amplified signals from the counters to the surface. Because the natural radioactivity of the surrounding strata exceeded that of the coal, counter signals were at a minimum when the device was in the center of the seam. If the device deviated toward the top or bottom of the seam, the top or bottom counter gave an increased signal. If the instrument left the coal seam and entered the surrounding strata, both counters gave increased signals.

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\*Numbers in parentheses in this chapter refer to entries in Appendix B. If the number is preceded by the prefix "USBM," then the reference appears in the Bureau of Mines bibliography (122).

In vertical straight-line drilling, the conventional method of preventing the borehole from wandering away from the straight-line path is to use a close-fitting guide rod which follows immediately behind the bit. The guide rods, typically 9" long, are spaced 2' 6" apart throughout the length of the hole, the leading unit being immediately above the drill bit. Flutes in the rods enable the drilling fluid to return; the flow can be further facilitated by shortening the guide members. With this equipment straight holes have been drilled consistently with deviations of less than 3" in a 200-ft length.

Drilling from the surface directionally into an inclined coal seam to pair holes for gasification of the seam has been achieved successfully in the U.S.S.R. (160) (236). According to the literature, before the drilling of the second hole is started a detailed geological section of the strata to be penetrated by the new hole is plotted, accurately showing the location of the hole to be paired. The new borehole is drilled from the surface into the strata at an incline up to a predetermined point. Its path through the strata is determined by analyzing the sectional drawing and choosing the path most suited to the capability of the drilling equipment. Then the drill is directed along a curved path until its bit intersects the coal seam. Drilling is continued along the coal seam until the hole runs parallel to the borehole to which it is to be paired. The direction and inclination of the drilling are controlled through a twin-geiger-counter device such as that previously described. The Russians report that boreholes over 400 feet long have been drilled in a coal bed from the surface 600 feet above the bed. The cost of this kind of inclined drilling is reported to be about 2-1/2 times greater per unit length than for vertical drilling. The drilling time for a 5"-diameter hole averaged 95 minutes per foot of path through overburden, and 80 minutes for coal.

To control the direction of the path being drilled, various special instrumentation techniques have been developed; for example:

- *Remote-Reading Compass.* A remote-reading device was developed in the United Kingdom in conjunction with the Admiralty Compass Observatory. The device measures the angle between the center line of the borehole and the horizontal component of the earth's magnetic field.
- *Coal-Sensing Device.* Another development is an instrument which can reliably detect when the drill bit is approaching the boundaries of the coal seam and which in addition can distinguish whether it is nearing the roof or the floor. Its principle is based on the different degree of scatter of gamma rays in coal and in shale, the usual adjacent stratum.

- *Hole-Intersection Detector.* The intersection between a vertical and horizontal borehole can be located by measuring the intensity of radiation emanating from a source in the horizontal borehole with a scintillating counter lowered down the vertical borehole. The intensity measurement gives indication of the distance between the vertical borehole and the approaching horizontal borehole.
- *Remote-Reading Inclinometer.* Deflection of boreholes from horizontal can be measured by a remote-reading inclinometer, which works on the principle of electrical resistance of a circuit, and utilizes a pellet of mercury to produce a variation in resistance of the circuit depending on the angle of inclination from the horizontal.

Further improvements in the shaftless access technique are possible without recourse to new technology. For example, inclined boreholes could be drilled instead of vertical holes. Or a drill string could be guided into a curved path through the coal seam until it connects with the bottom of a vertical borehole. Specific techniques could be developed to drill 9-inch or 12-inch diameter holes from the surface, starting at say a 30° angle, down into the coal seam, at which point the hole would then be curved to continue a horizontal (or some desired angular) path for say 1000 feet or more. An electrically powered “down-the-hole” turbine-type drill could probably be used. Although casing a curved hole may present some problems, drill holes along the arc of a 200-foot radius circle should be practical.

#### c. Linking

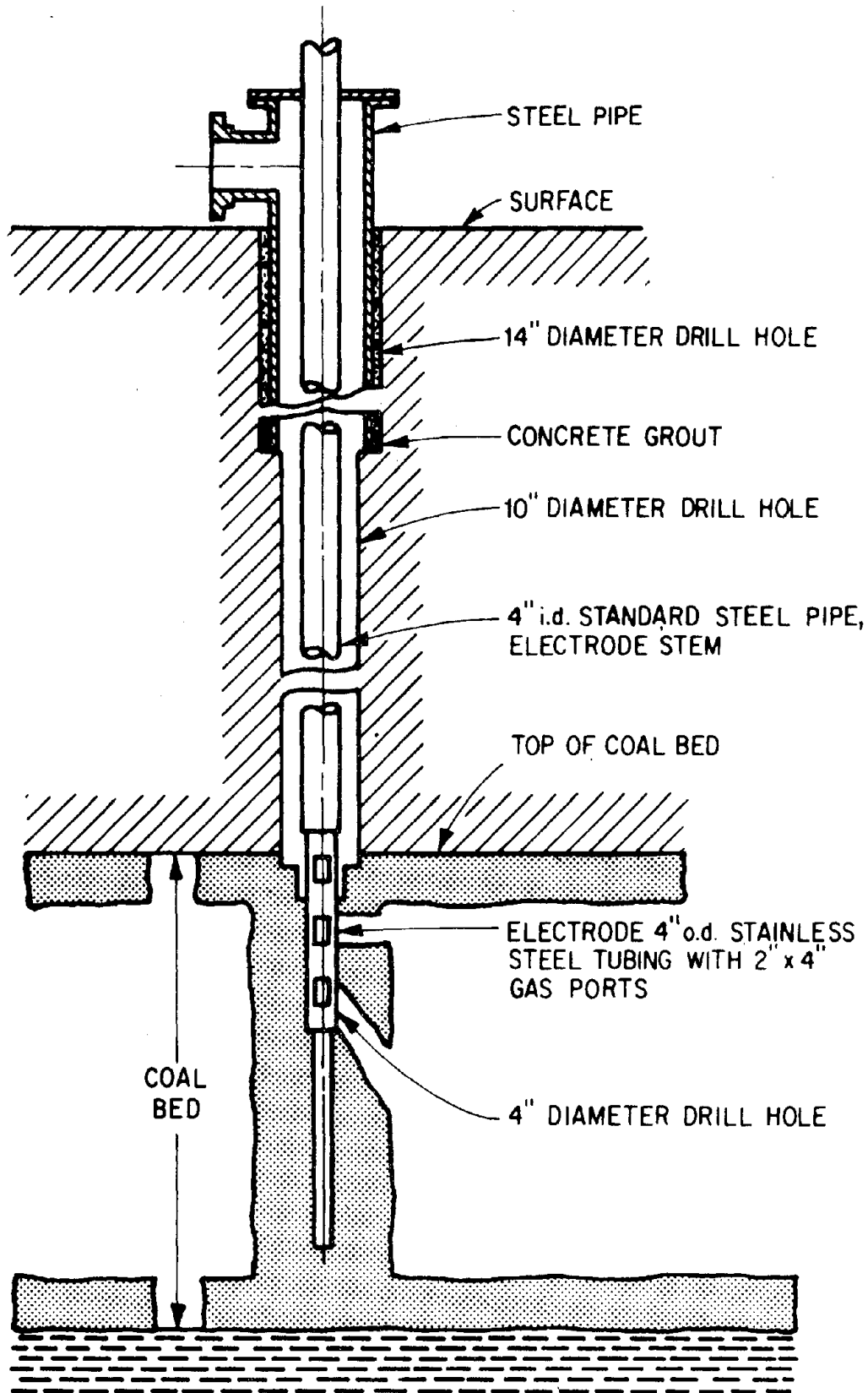
The process of joining two boreholes, or other definable points within a coal seam is called “linking.” Some coal seams in their natural state – e.g., some lignites – may be permeable enough so that gasification between definable points can be initiated and progress without any man-made link. However, most coals require a better link than the natural permeability provides to speed up the gasification process. As already noted, one method is to drill a hole between boreholes, shafts, or tunnels.

Three other linking techniques that have been well investigated and applied in various underground gasification tests and installations are electrolinking, hydraulic linking, and pneumatic linking. These procedures result in the formation of low-resistance paths for air flow, paths which are less definable than a drilled hole. Hydraulic and pneumatic linking, which often involve actual breakage of the coal seam, are sometimes referred to as fracturing. The use of explosives underground is basically a fracturing method.

(1) *Electrolinking.* The process of electrolinking, the electrocarbonization of coal, was first tried in the United States in 1947 in the laboratory of the University of Missouri, field tests were undertaken subsequently under a cooperative contract between the University of Missouri; and the Sinclair Coal Company of Kansas City. More recently, in 1951 at Gorgas, the Bureau of Mines, in cooperation with the Alabama Power Company, further investigated the electrolinking and electrocarbonization of coal underground. In England, about 1952, study and investigation were also directed to the application of the technique to underground gasification processes. In the Russian work, which began prior to World War II, electrolinking-carbonization was successfully applied in large installations (USBM-583, USBM-590).

In the process of electrolinking, electrodes are installed within the coal bed at a given spacing. Passing an electric current between the electrodes carbonizes the coal to form a path of increased permeability through which gases may be pumped. Figure 2 illustrates the construction of a borehole and the seating of an electrode within the coal bed, employed in the Gorgas, Alabama experiments. An unlined hole was used and the electrode and electrode stem, which together were approximately 150 feet long, were kept under tension by counterweights to prevent buckling and striking the side of the hole. The counterweight was about 80% of the gross weight of the electrode. In this installation, electrode spacings of approximately 150 feet were operated successfully.

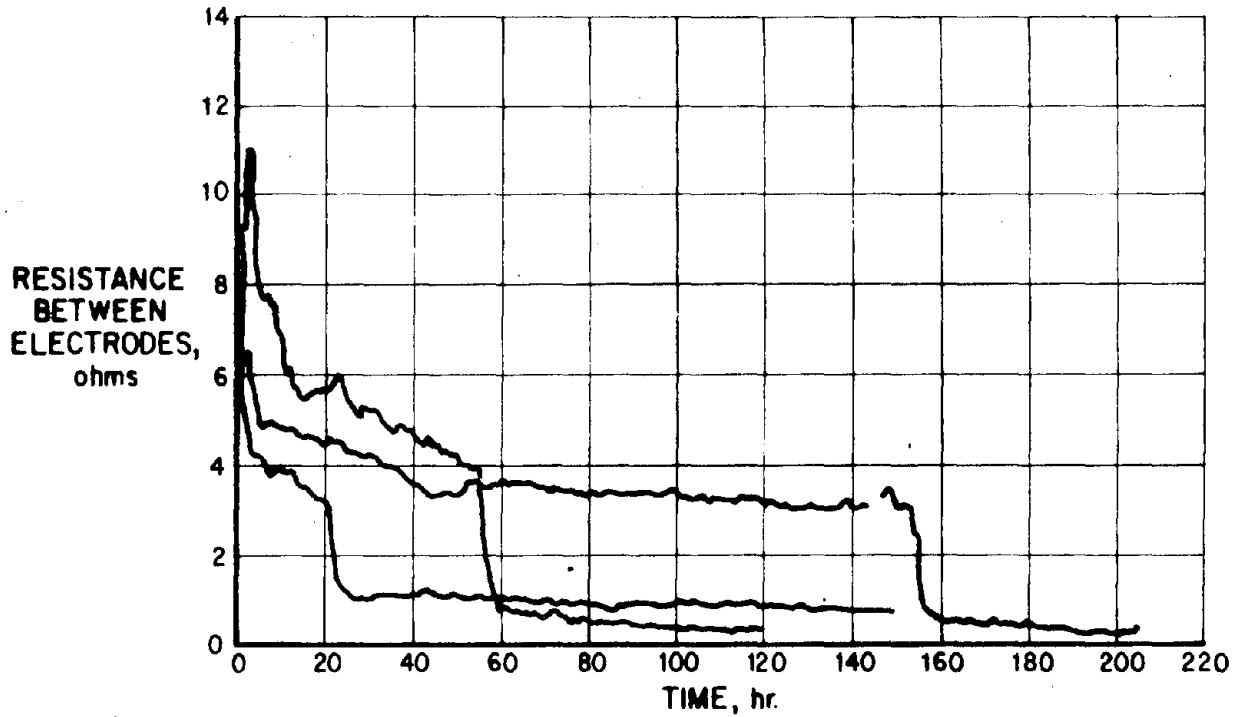
Figure 3 plots path resistance between boreholes being linked versus elapsed time during three tests. The general shapes of the three plots are similar. The initial resistance in each test was approximately 14 ohms, or approximately 0.1 ohm per linear foot between the electrodes. The resistance decreased gradually to 3.5 to 4.0 ohms, and then decreased suddenly to approximately one ohm, after which a relatively steady state was achieved. The initial rapid decrease from the 14-ohm level resulted primarily from a rapid decrease in contact resistance between the electrodes and the coal bed, while the period of slower decrease to the 3.5-4 ohm level should be considered to be the electrolinking period: i.e., the period when a low-resistance electrical path is being established between the two electrodes. The very sharp decrease in resistance from 3-4 ohm level value to an approximately 1 ohm level is attributable to electrical breakthrough: i.e., the establishment of path continuity between electrodes. The final very slow decrease in resistance with time is considered to be the electrocarbonization period: i.e., the period during which heat generated by current flow continues to carbonize the coal in the seam and to increase the cross-sectional area of the path. The gases evolved during this period are typical of the usual products of coal carbonization, and their analyses change as temperatures within the path increase. Simultaneously with gas evolution, porosity is introduced and the permeability of the path is increased. The periods of time required to attain electrical breakthrough in the three tests were quite different because the current paths were erratic and depended on the character of the coal between the particular pair of boreholes used for each test.



SOURCE: (129)

**INSTALLATION OF ELECTRODES AND THE WELL FOR ELECTROLINKING BOREHOLES AT GORGAS, ALABAMA**

Figure 2



SOURCE: (129)

**RESISTANCE-TIME CURVES FOR ELECTROLINKING-CARBONIZATION TESTS AT GORGAS**

Figure 3

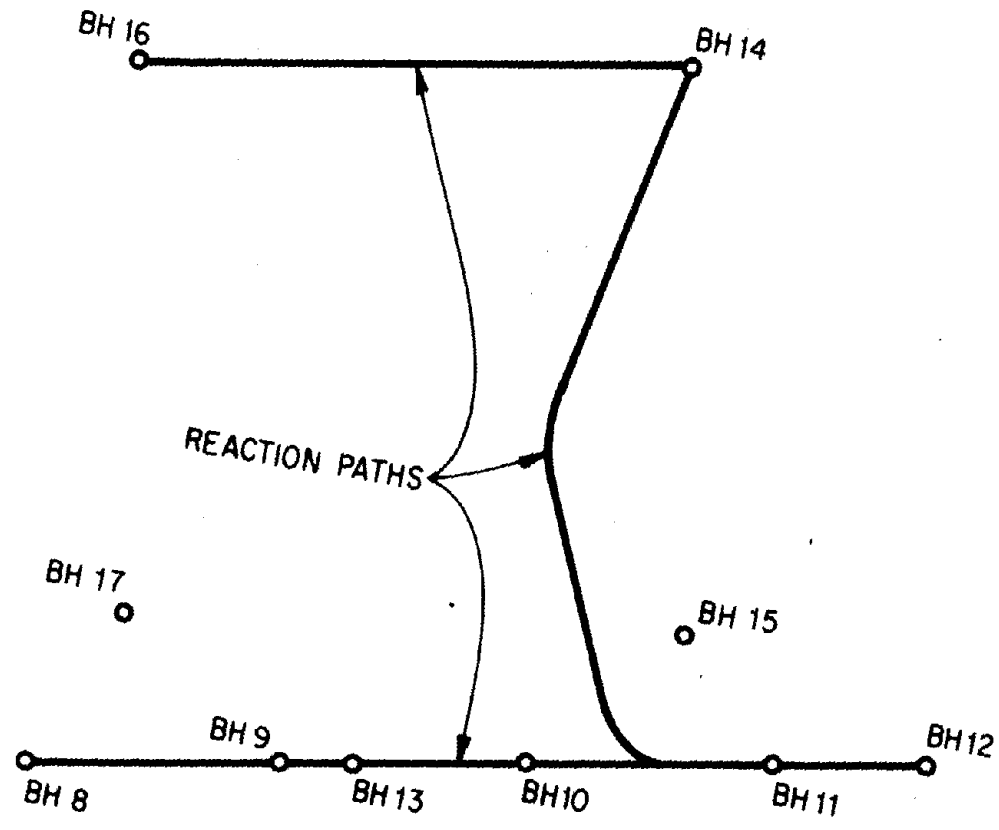
Figure 4 shows a pattern of electrolinked carbonization paths among a number of boreholes, and illustrates one difficulty – i.e., the lack of control – when employing this technique. The paths shown in Figure 4 were determined by test-drilling the site after gasification operations in the electrolinked paths had been completed. The path from BH-8 to BH-12 was electrolinked and gasified first. The path from BH-14 to BH-15 was electrolinked and gasified second. The actual reaction path was deflected to the left and BH-15 never actively entered the reaction zone. A path from BH-16 to BH-17 was tried next. Here the actual path formed was from BH-16 to BH-14 at right angles to the path expected.

Thus, the path of the current between two electrodes may be markedly affected by coal bed changes resulting from prior experimental work on the undisturbed coal seam, and the resultant unpredictability of electrolinking in the establishment of single gasification paths appears to offer a major difficulty. But, if multiple paths are to be established simultaneously, as could well be the case in a commercial application of area gasification, the precise path between two individual electrodes may be inconsequential. Estimates made during the three tests indicated that about 80% of the electrical energy had passed through the coal bed during the electrolinking phase, and this proportion rose to about 97% toward the end of the electrocarbonization phase.

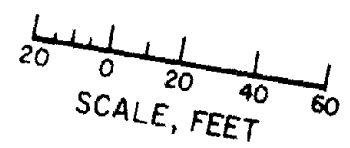
Whether or not electrocarbonization should have proceeded further in order to prepare a bed of greater permeability for the gasification operations is not yet well established. As far as can be discerned from the literature, the results of British and Russian work were similar to those reported above.

(2) *Hydraulic Linking.* The process of hydraulic linking involves injecting fluids under high pressure into a previously undisturbed coal seam to cause fracturing and consequently an increase in permeability. Hydraulic fracturing techniques have been used in oil-field work for many years and the method has been tried in the United States and in Russia in connection with underground coal gasification.

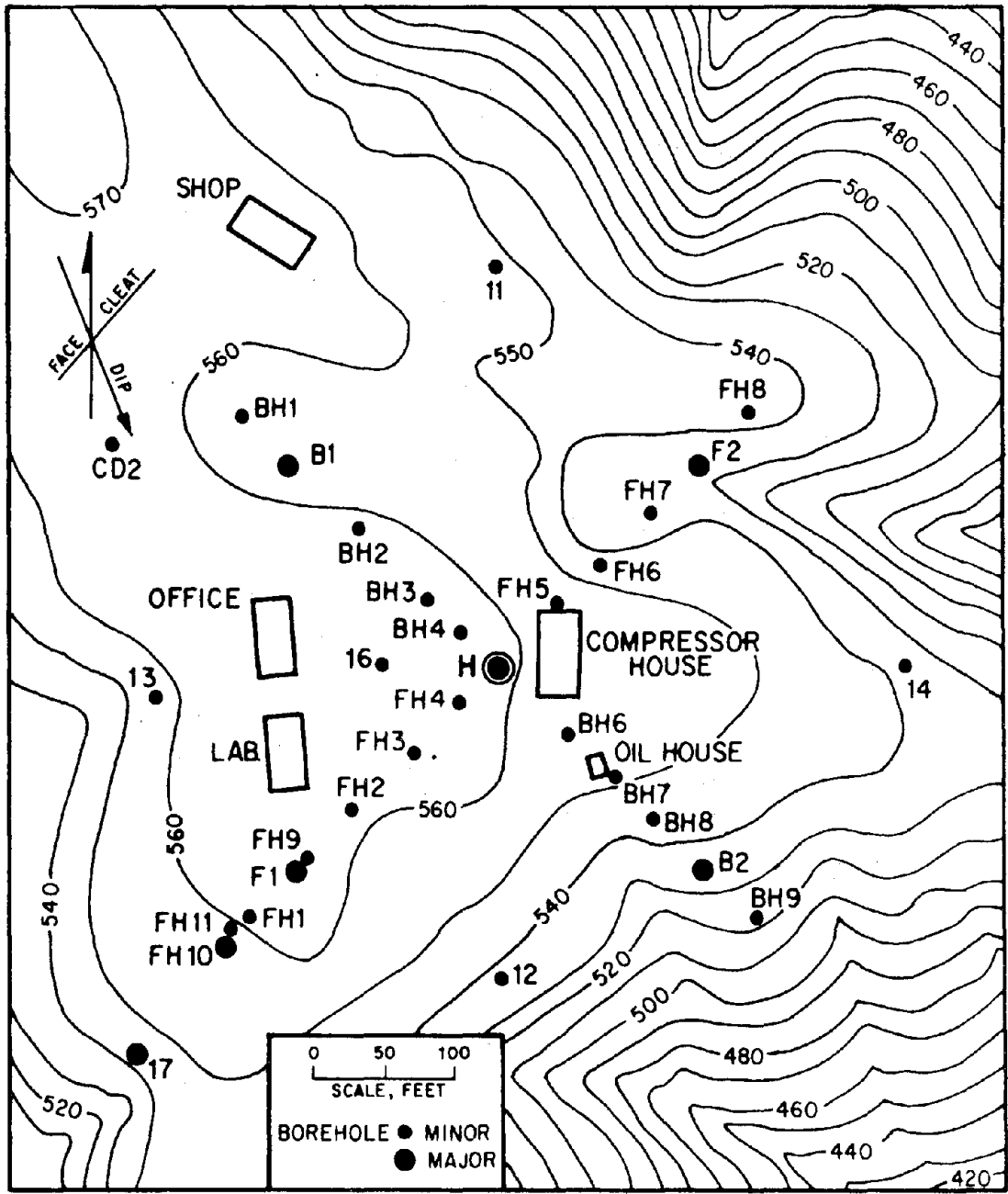
In the United States, several tests were carried out at Gorgas, Alabama, by the Bureau of Mines (USBM-722). In the second and final test in 1957 (40), the coal bed was fractured by injecting at a rate of 200-600 gpm at 900-1000 psi pressure, 11,000 pounds of sand suspended in 33,580 gallons of water containing a gelling agent for stabilization. The fluid fractured the coal, and the sand served as a propping agent to hold the cracks and crevices open after release of the pressure. Fracturing continued for about three hours. The injection took place in a centrally located drill hole (Hole H, Figure 5), specially constructed as shown in Figure 6.



SOURCE: (129)



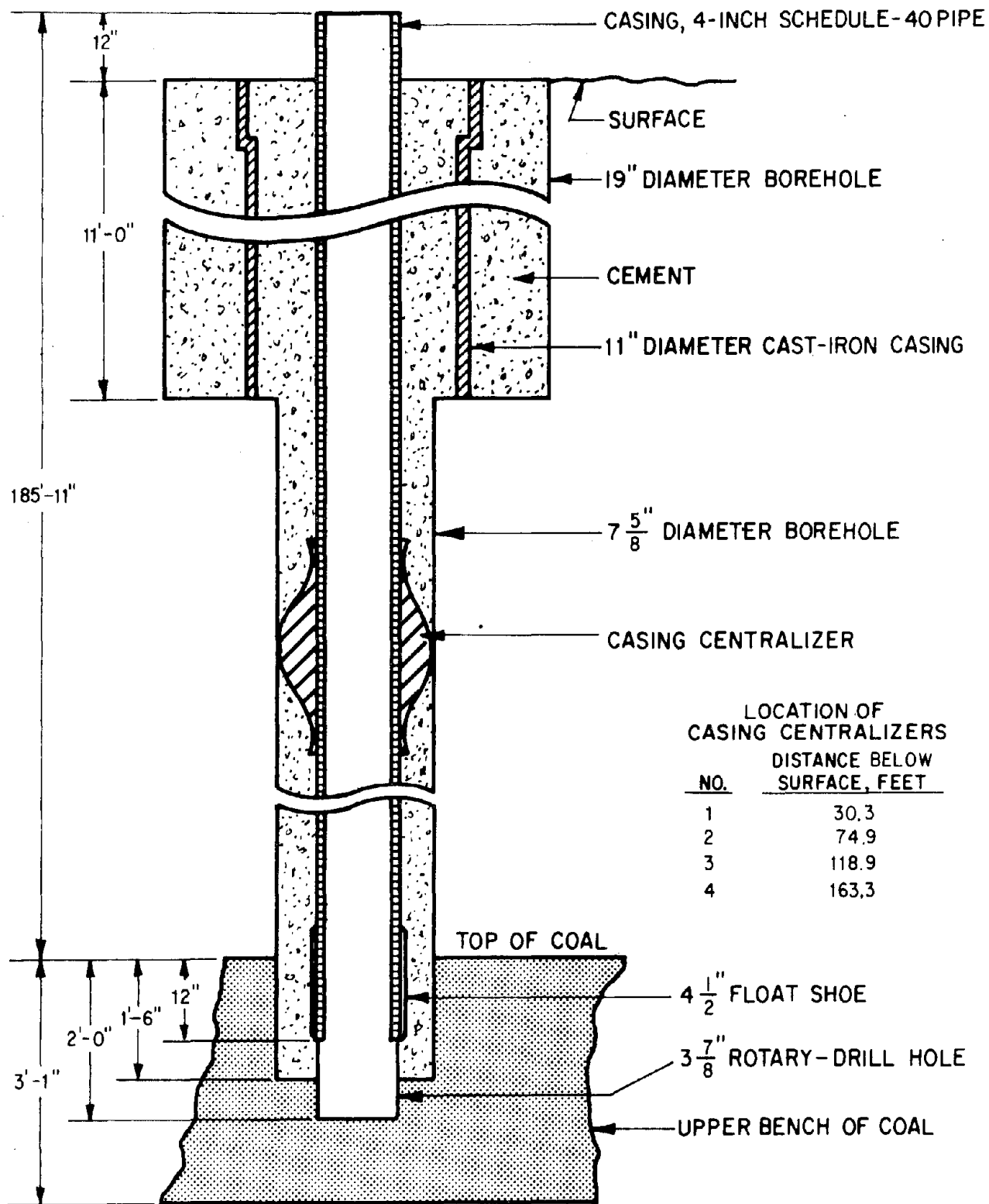
PLAN VIEW OF REACTION PATHS INITIATED BY  
ELECTROLINKING AT GORGAS  
Figure 4



SOURCE: (40)

LAYOUT AND TOPOGRAPHY OF TEST AREA FOR  
HYDRAULIC FRACTURING AT GORGAS

Figure 5



LOCATION OF CASING CENTRALIZERS	
NO.	DISTANCE BELOW SURFACE, FEET
1	30.3
2	74.9
3	118.9
4	163.3

SOURCE: (40)

CROSS-SECTION OF INJECTION BOREHOLE H IN TEST AREA

Figure 6

Pressures measured during the fracturing operation at other boreholes some distance from the injection hole indicated that the fracturing fluid penetrated only to about 150 feet around the point of injection. However, increased air acceptance was noted at test boreholes up to 280 feet from borehole H. Measurements at existing boreholes 400 feet away indicated that fracture effects may have extended considerably farther than was evident from observations at the test boreholes.

Since air acceptance is a measure of the permeability of the formation, tests were carried out at an inlet pressure of 65 psig. Air was pumped in and the air that flowed out of all other holes was measured while maintaining the inlet pressure. Air acceptance tests were also carried out in another area, 800 feet west of Borehole H, before and after fracturing. The air acceptance before fracturing was 6-13 std. c.f.m., and after a first hydraulic fracturing, which used a fracturing fluid of oil and fine sand, the air acceptance was 650 std. c.f.m. After a second fracturing attempt, with a fluid and a coarser sand, the acceptance at the same location rose to 1172 std. c.f.m. However, the large increase after the second test was attributed to the large number of open boreholes in the vicinity. The conclusion was drawn that in both cases, there was a 50- to 100-fold increase in permeability at the injection borehole. Air acceptance to other boreholes was increased about five-fold. (These effects should last at least several years.) Subsequently the hydraulically fractured areas were successfully gasified.

While the past work demonstrated the feasibility of employing hydraulic fracturing as a linking technique for underground coal gasification, there has been no recent work in the United States on hydraulic fracturing of coal seams for gasification. The Bureau of Mines, however, has been working on hydraulic fracturing of U.S. oil-shale deposits at its Laramie Energy Research Center preliminary to in situ retorting. While oil-shale deposits in the western United States are quite different than coal, being hard, compact and impermeable, some of the work at Laramie may have application in coal seam fracturing. For example, the researchers have been able to fracture thick oil-shale zones (20 feet) in three separate places within the zones by using "packers" to direct the hydraulic forces at specific areas. They have also shown that gels in hydraulic fracturing fluids greatly reduce fluid friction. They have also done considerable work with incorporating liquid explosives in the fluids, and this technique shows some promise for further increasing the permeability in coal seams. For example, it may be possible to electrolink or to fracture hydraulically, fill the fractures with liquid explosives, and explode them to produce larger volumes of fractured structures.

Since 1960, a number of discussions of hydraulic fracturing have appeared in the Russian literature. For example, experiments in brown coal seams of the Podmoskovnyi Basin (55) established that hydraulic fracturing in many cases has advantages over electrolinking and pneumatic linking. Other reports (65, 157, 167, 182) discuss hydraulic fracturing and its application with some conflicting statements. Klimentov (167), discussing the use of hydraulic fracturing fluids containing sand to create permanent highly permeable fractures, concludes that the best results are obtained when water without sand is used for fracturing. On the other hand, Belova (182) concludes that the permeability can be improved by hydraulic fracturing and injection of sand.

(3) *Pneumatic Linking.* A coal bed has a natural permeability. If an inlet and an outlet are provided and air is pumped into the inlet under pressure, some of the air will be recovered at the outlet. The pressure drop and the flow rate are a measure of the permeability.

The natural permeability of coals varies with their ranks. Brown coals (or lignites) have permeabilities that average about 1000 times more than the permeabilities of bituminous coals. The use of natural permeability of the coal, particularly if it is naturally high, permits linking to occur pneumatically without initial preparation.

In the United States, Russia, and England, attempts have been made to take advantage of the natural permeability of coal seams to develop gasification paths without linking; that is, one simply by applying the air under pressure, igniting the coal seam, and then gasifying the coal. One of the most successful and widely reported operations of this type was in Russia, in the Moscow Basin (129, USBM-9).

Work has also been done on the use of high-pressure air to fracture coal formations pneumatically as a separate step (160). Generally, it is possible to achieve initial success this way, but upon release of the pressure, the new fractures tend to close, eliminating the temporarily increased permeability. This closing tendency also occurs in hydraulic fracturing if there is no sand to prop the fractures open after the pressure is released.

The air acceptance of a borehole rises rapidly after unit air pressure equals unit weight of overburden so that the bed can be disrupted and can accept air in a volume sufficient to support rapid travel of the combustion zone during gasification. The air pressure required can be determined by the following formula:

$$P = \frac{DH}{144} + 75$$

where P is the required pressure in psig, D is the average weight (or density) of overburden in pounds per cubic foot, and H is the depth (in feet) of the bed to be linked pneumatically. The additional 5 atmospheres (75 psi) is added to insure breakup of the seam.

Bituminous coal beds, such as those at Lisichansk, are only slightly permeable (0.0015 darcy)\*, and their permeability decreases at increasing depths.

At Lisichansk, with 300 to 500 feet of overburden, pneumatic linking, even after increasing pressures as high as 600 psig, was not capable of supplying enough air through the coal beds for adequately rapid linking.

At 300-500 feet, bituminous coal beds may have a permeability some 40 to 60 times greater than surrounding strata. Since the application of air under pressure is most effective in the strata already more permeable, the permeability of the coal bed is preferentially increased and the permeability of overburden is not significantly affected. Thus, permeability can be increased in coal seams irrespective of depth if high enough pressures are used.

But this may not be necessarily so. For example, from 1947 through 1952, generators were being prepared in the U.S.S.R. at about 250-foot depths, where permeabilities of the bed and the surrounding strata were both relatively high and similar, in the range of 0.2 to 1.8 darcys (160). Hence, linking was not sufficiently selective and consumption of air was high, even at relatively low inlet pressures of

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\*A "darcy" is a measurement of permeability derived as follows:  
Viscous flow through a porous medium is described by Darcy's equation

$$\frac{\Delta p}{L} = \frac{a\mu V}{gc}$$

where

- $\Delta p$  is the pressure drop in  $l^i$  force/ft<sup>2</sup>
- L is the thickness of the medium in ft
- V is the superficial velocity of the fluid (based on total cross-section) in ft/sec
- $\mu$  is the fluid viscosity, 1/ft sec
- a is the viscous resistance coefficient in ft<sup>2</sup>
- gc is a dimensional constant, 32.17 ft/sec<sup>2</sup>

The quantity 1/a is the permeability coefficient the unit of which is a darcy. A darcy is the permeability of a porous medium to viscous flow for the flow of 1 ml/sec/cm<sup>2</sup> of surface of a liquid of 1 centipoise viscosity under a pressure gradient of 1 atm/m.

150 to 225 psig. Undoubtedly, losses of air of significant magnitude occurred to the surrounding strata.

Some basic data for the Lisichansk high-pressure pneumatic linkage experiences are as follows:

- Average pressure of air blast – 430 to 515 lb/sq in.
- Average linking distance – 39 ft.
- Average air consumption – 295 to 355 c.f.m.
- Rate of linkage – 10 to 115 ft/day
- Air consumption per foot of linkage channel – 43,060 cu ft.
- Electricity consumption per foot of linkage channel – 244 kwhr.

Early experiments with pneumatic linkage in Russia used oxygen-enriched air, but the danger of spontaneous combustion and explosion developed in the inlet hole, and linking had to be carried out finally only with an air blast. Spontaneous combustion slows down the linking process, and is dangerous. Research has shown that spontaneous combustion is less likely to develop with high-velocity blasts than with low velocity because the heat of combustion is dissipated in the blast, and temperature rises are restricted. Dirty boreholes and leakage around casings create conditions leading to spontaneous combustion. Clean, well-cased, and cemented holes and air blasts in excess of 90 to 115 c.f.m. have been suggested to insure against its occurrence.

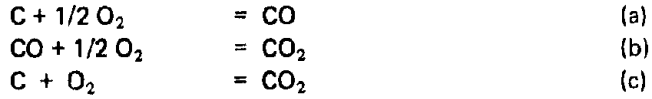
## 2. Gasification

The procedures employed in the underground gasification of coal have been based on the production of a low-heating-value but combustible mixture of carbon monoxide and hydrogen. The coal is reacted in situ with suitable oxygen-containing gasification agents. The gasification reactions that occur are shown in Table 2.

TABLE 2

REACTIONS INVOLVED IN THE GASIFICATION OF COAL

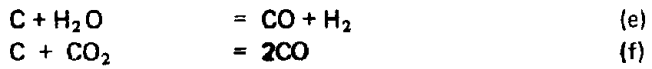
The oxidation of carbon



The oxidation of hydrogen in the volatile matter in the coal

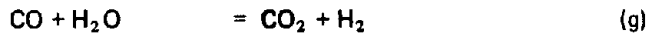


The gasification of carbon with water vapor or carbon dioxide



Carbon monoxide

Hydrogen Shift



Hydrogasification of the carbon in the coal



Also, the complex decomposition of complex higher hydrocarbons in the coal.

Source: Arthur D. Little, Inc.

For aboveground gasification carried out say about 2000°F, where conditions are readily observable and controllable, thermodynamic equilibrium is generally closely approached and the product gases are high in CO and H<sub>2</sub>, and low in CO<sub>2</sub>, H<sub>2</sub>O and CH<sub>4</sub>. However, thermodynamic equilibrium is less approachable in underground gasification and kinetic factors predominate. The primary focus of underground gasification has therefore been to produce at least a combustible gas of constant quality, in contrast with the focus of aboveground gasification work on producing a high heating-value gas preferably containing some methane.

a. Gasification Agents

The gasification agents employed underground have been the same as those used aboveground. The reactions in Table 2 indicate that these can be O<sub>2</sub>, CO<sub>2</sub>, and/or H<sub>2</sub>O (steam). Accordingly, air, oxygen-enriched air, alternating steam –

air cycles, and steam-enriched air mixtures have been used in underground gasification. The use of preheated CO<sub>2</sub> to gasify coal by reaction (f) has been proposed in the patent literature (317), but this may not be practical because it would be necessary to preheat CO<sub>2</sub> to ultra-high temperatures. Thus, oxygen is essential in the gasification agent so that the reactions (a), (b), (c), and (d) can be employed to provide the heat necessary to support the endothermic reactions, (e) and (f). Control of combustion-zone temperature is obtained by providing a diluent in the gasification agent such as nitrogen, or a species such as CO<sub>2</sub> or H<sub>2</sub>O, which acts to decrease the reaction-zone temperature by promoting the endothermic reactions (e) and (f).

Increased use of oxygen in the gas stream can increase the rate of gasification. A laboratory study (20) showed that when the oxygen content is increased from 21-34% to 100% the rate of movement of the gasification zone increases by a factor of 12-30 for brown coal.

#### b. Contacting Methods

There are three basic ways in which the gasification agents can be contacted with coal during underground gasification. The contacting can be such that the "flame front" – the hottest area where the gasification reactions occur rapidly – advances in the same direction as the gas flow, e.g., forward burning. The contacting can be such that the flame front advances in a direction opposite to the direction of the gas flow, e.g., backward burning. Finally, the contacting can be such that the flame front advances perpendicular to the direction of the gas flow, as in the stream method of contacting or the borehole producer method.

In certain instances, one method has been used for linking or initiating gasification and a second method for continuing the gasification. In England, a flat seam of coal was gasified by a multiple path system using the borehole producer method (160). Initially, the gas flow was of the perpendicular type. Later, after some of the coal had been burned, the method was changed to forward burning. Similar multiple-contacting-method approaches have been used for Moscow Basin coal using pneumatic linking. In general, the more successful applications of the forward and backward burning methods have been in connection with flat seams of lower-grade coal, and for the streaming method in connection with steeply pitching seams.

#### c. Gasification Products

Gasification products depend of course on the type of gasification agent. Thermodynamically, one would expect the gasification products to have a low CO<sub>2</sub> content. Most underground coal gasification work shows CO<sub>2</sub> levels in the product gases above 5-10% when using air, and levels as high as 50% when using

oxygen. Several mechanisms have been proposed to explain these high CO<sub>2</sub> levels (113). For example, it has been proposed that both CO and CO<sub>2</sub> are formed simultaneously during the initial combustion of coal, but rates for reaction (f) in Table 2, the conversion of CO<sub>2</sub> to CO by reacting with hot carbon, are slow. Thus, at the gas velocities normally used in underground gasification, insignificant quantities of CO<sub>2</sub> are converted to CO in this way. Other explanations offered are that the high CO<sub>2</sub> levels result from the combustion of CO in the product gases with free oxygen uncontacted with coal, i.e., with oxygen that has bypassed the coal.

The heating value of the product gas depends on the air rate and on the thickness of the coal seam. It has been indicated (113) that the highest heating value of product gas can be obtained over long periods of time when using air rates of up to 200,000 ft<sup>3</sup>/hr in a single borehole.

Table 3 shows the range of heating values of the product gases obtained from underground gasification operations for various types of gasification agents. If the product gases were to contain only CO or only H<sub>2</sub>, the heating values would be about 320 or 275 Btu/SCF, respectively. When perpendicular contact of gas and coal is involved, the contacting efficiency decreases rapidly as the size of the passageway increases unless the air rate is increased to maintain a high gas velocity. After a certain stage, such as when the passageway diameter reaches 10-20 feet, the product gas can contain unreacted oxygen and/or a higher CO<sub>2</sub> content, and has a lowered heating value.

**TABLE 3**  
**HEATING VALUE RANGE IN PRODUCT GASES FROM**  
**UNDERGROUND COAL GASIFICATION**

Gasification Agents	Heating Value of Product Gas Btu/SCF
Air	50-140
Oxygen	180-200
Steam cycle when using intermittent air-stream sequence	250-280
High hydrogen gas when operating stream method without air flow	200-235

Source: USBM-9, 129.

#### d. Control of Gasification Process

The temperature at which the gasification reactions are carried out has been controlled by draining the coal and strata of groundwater, by controlling the volume of inlet gases, by oxygen enrichment of the air blast, by using enriched air/stream injection or by using alternating air and steam cycles. The Russian experience indicates that gasification temperature should be controlled at levels below the fusion point of the ash to prevent the blocking of the reaction face by the slag layer. Also, unfused ash can provide some roof support when gasifying high-ash coals.

Loss of contacting efficiency occurs when a considerable amount of coal has been gasified. This can come about either by roof collapse or the generation of large open passageways. Roof collapse need not occur, however. For example, the high-ash coals of the Moscow Basin were gasified at temperatures below the fusion point of the ash, and this left a porous ash sufficiently strong to support the roof. Furthermore, in the United States at Gorgas the overlying strata fused and collapsed in such a way as to provide a passageway narrow enough to retain good contacting between the reacting gases and the coal seam.

When using air rates of about 25,000 ft<sup>3</sup>/hr in a single 4"-diameter borehole, the product gas quality drops off when the cavity has reached a width of 10-20 feet (113). Much higher air rates are necessary to produce good quality gas from larger passageways. It therefore appears that for successful gasification of coal accessible to a single borehole, without the incidence of roof collapse, the maximum cavity size depends on the strength of the roof strata and the size of ducting for reactant and product gases; and adequate air compressor capacity should be available for proper gasification until the limiting cavity size is reached.

In order to prevent roof collapse, wet and dry stowing techniques have been considered in the U.S.S.R. (USBM-526) to fill the cavities left by a burned-out coal seam.

#### e. Control of Groundwater

Seepage of groundwater into the coal to be gasified can quench the gasification reactions. Seeping is therefore undesirable and must be controllable. Groundwater can enter the coal seams through flow out of a porous overlying stratum, or more generally, via natural faults or fissures in the strata resulting from roof collapse. Seepage of groundwater has been controlled by providing sump areas for collecting it and pumping it to the surface. Coal seams have been dried by high-pressure air flow when using a pneumatic fracturing method for linking. Brown coals or lignites contain large amounts of combined moisture, and some degree of drying has been found necessary beforehand for proper gasification.

#### f. Recovery

There are various ways to calculate coal recovery in underground gasification. Because coal strata are usually of even thickness, it is possible to calculate coal recovery from geometric considerations, if the position of the burning face can be determined accurately. This is a "mining"-type recovery calculation in that the result is analogous to considering unrecovered coal as "pillars" left underground.

Coal recovery can also be calculated from a carbon balance which, when combined with the geometry of the seam isolated for gasification, indicates the fraction of underground coal brought to the surface. Any  $\text{CO}_2$  in the product gases is coal that has been gasified but also coal that represents a loss, since  $\text{CO}_2$  has zero heating value. Coal recovery can, therefore, also be computed on the basis of the heating value of the total gas production as a fraction of the total heating value in the coal underground that is considered affected by the gasification operations.

Reports of coal recoveries calculated in such a manner vary widely. Large-scale work in the U.S.S.R. indicates coal recoveries ranging from about 15% (devolatilization of coal only) to about 40% by the stream method (perpendicular contact) at Gorlovka in the Donets Basin (USBM-9), and also to about 40% for the borehole producer method at Chelyabinsk (USBM-9). In England, using a combination of borehole producer and forward burning in the experiment P-5 (160), recoveries as high as 84% were obtained.

A summary of coal losses and recoveries in the U.S.S.R. (49) during underground gasification has shown that the magnitude of the losses depends on the distance between boreholes. At the Podmoskovnaya station the losses amounted to 21% with the network of boreholes 25 x 28 meters while the losses were 52% with a borehole network of 25 x 40 meters. At the same station losses varied between 8% and 50% from 1951 to 1958. At the Lisichansk and South Abinsk stations the losses varied from 2% to 50%.

### 3. Methods

The methods reported in the literature for carrying out underground coal gasification can be conveniently classified as shaft methods, as shaftless methods, and as combinations of these two. Shaft methods require some kind of underground development such as shafts, entries, galleries, slopes, or inclines where men have to work underground at some stage in order to prepare the coal seams for subsequent gasification. Shaftless methods do not require such underground work, since preparation is done from the surface invariably involving the use of

drill holes to reach the coal seams. Combination methods involve some underground work, but use surface drill holes for the air inlets and gas outlets. Combination methods have been involved in much of the experimental and test work reported in the literature.

Table 4 is a summary of some of the experimental and commercial gasification installations reported in the literature. It is evident from the entries that an underground gasification system employing shaftless methods can be completely developed and operated with the current state of the technology without having men exposed to the hazards of underground work. However, if for some reason the results of underground gasification become much more attractive by having some limited access to the installations through shafts or inclines, facilities such as drilled shafts can be provided such that only a small risk of exposure of men to dangerous or hazardous conditions would be involved.

#### a. Shaft Methods

The literature contains extensive reports of experimental work on three shaft methods: chamber, borehole producer, and stream.

*(1) Chamber Method.* The chamber, or warehouse, method requires the preparation of underground galleries and the isolation of coal panels (Figure 7). The blast of air for gasification is applied from the gallery at the previously ignited face of one side of the panel and the product gas is removed by the gallery at the opposite side of the panel.

In one of the first tests in the Moscow area of the chamber method (129), an attempt was made to gasify the virgin coal bed, using its natural porosity and the presence of natural fissures. The rates of gasification were low, and the product gas was of variable composition, sometimes containing unconsumed oxygen.

In another attempt in the U.S.S.R. at Kuznetsk (129) a 60 x 22-foot panel containing 1000 tons of coal was isolated in a 15-foot-thick seam, and ignited. Gasification with air proceeded smoothly for 30 days, during which time 200 tons of coal were burned. The product gas had a calorific value of 250-490 Btu per cubic foot, but it appeared that much of the coal was left underground as coke.

A variation of the chamber method in which the coal panel was prefractured by dynamite blasting in holes drilled into the panel was also tried in the U.S.S.R. (129). Subsequent gasification produced only poor gas of irregular quality flowing intermittently, presumably because the coal fractured irregularly, permitting the gasifying air to bypass the reaction zone.

Another attempt in the Moscow region (129) involved actually breaking the coal in a panel by hand, followed by gasification. Although this test produced gas of 121-193 Btu/ft<sup>3</sup> in heating value, it eliminated only the loading and hauling of

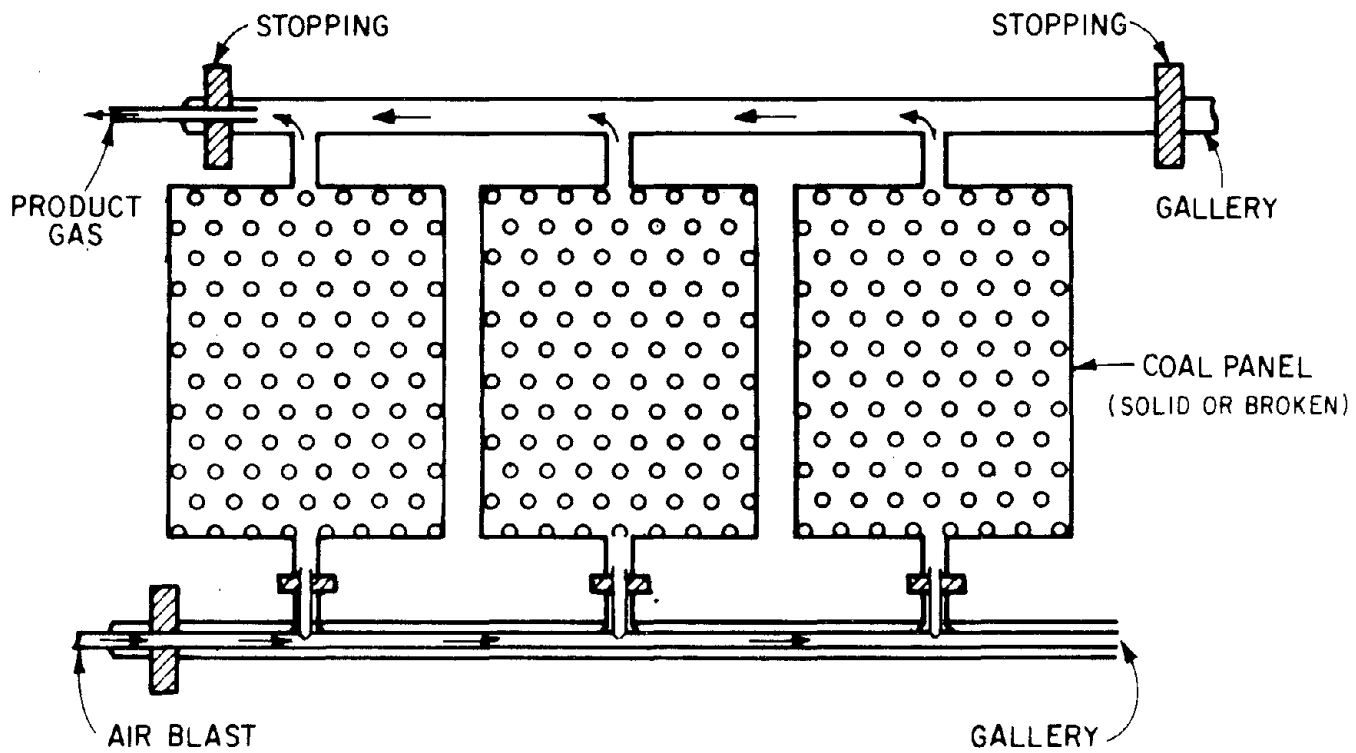
TABLE 4

UNDERGROUND GASIFICATION METHODS

		Coal Seam				Type		Operation		Linkage		Pattern		Blast		C.V. Product Gas		Remarks
Ref.	Country	Location	Type	Thickness Inches	Depth Ft.	Dip °	C.V. Btu/lb	Technique	Operation	Linkage	Pattern	Blast	Btu/SCF	Gas	Efficiency	Remarks		
A.																		
	160	Russia	Lisichansk	30	100	40	11,600	Streaming	Commercial	Gallery	Panels	30% O <sub>2</sub>	86					
	160	Russia	Gorlovka	72	200	75	10,000	Streaming	Commercial	Gallery	Panels	30% O <sub>2</sub>	130					
	7	Poland	-	39	-	-	-	Producer	Experimental	Drill Holes	Parallel	Air	80				6% Heat Loss	
	45	U.S.	Gorgas	35	25	2	14,000	Streaming	Experimental	Gallery	U-Shape	Air	47				High Gas Loss	
	129	Belgium	Bois-la-Dame	36	525	87	14,000	Streaming	Experimental	Gallery	37° Panel	Air	56				35-45% Thermal Efficiency	
B.																		
	422	U.S.	Gorgas	37	180	2	15,000	Percolation	Experimental	Electro	Square	Air	93					30-50% Gas Loss
	40	U.S.	Gorgas	37	180	2	15,000	Percolation	Experimental	Hydraulic	X-Pattern	Oxygen	195					
	76	U.S.	Gorgas	37	180	2	15,000	Percolation	Experimental	Hydraulic	St. Line	Air	84					44% Thermal Eff
	41	U.S.	Gorgas	37	180	2	12,000	Percolation	Experimental	Hydraulic	50' Circle	Oxygen	124					
	160	U.K.	Newman-Spinney	36	75	8	12,800	Streaming	Experimental	Boreholes	St. Line	Air	90					40% Gas Loss
	160	U.K.	Newman-Spinney	36	100	8	12,800	Percolation	Experimental	Pneumatic	Rectangular	Oxygen	85					
	160	Russia	Yushno Abinsk	276	100	75	12,000	Percolation	Commercial	Pneumatic	Inclined	Oxygen	100					65% Heat Recovery
	160	Russia	Lisichansk	30	100	40	11,600	Percolation	Commercial	Pneumatic	Inclined	Air	100					High Pressure Used
	9	Russia	Moscow Field	72	65	0	4,900	Percolation	Commercial	Pneumatic	75' Square	Air	85					
	677	Russia	Shatsky	120	150	0	4,900	Percolation	Commercial	Pneumatic	25 Meter Grid	Air	-					
	160	Russia	Stalinsk*	98	1500	80	14,000	Streaming	Commercial	Pneumatic	Inclined	Air	-					
	160	Russia	Tula	390	180	0	4,900	Percolation	Commercial	Pneumatic	25-Meter Grid	Air	105					
C.																		
	182	U.S.	Gorgas	42	125	2	14,000	Streaming	Experimental	Gallery	St. Line	Air	70-90					4-40% Gas Loss
	160	U.K.	Newman-Spinney	36	240	8	12,800	Streaming	Commercial	Boreholes	Parallel Unit	Air	57					84% Coal Recovery
	129	Morocco	Djerada	-	160	90	-	Streaming	Experimental	Gallery	Panels	Air	-					Combustible Gas Produced
	160	Russia	Lisichansk	30	100	40	11,600	Streaming	Commercial	Boreholes	Panels	43% O <sub>2</sub>	100					47% Efficiency

\*Proposed

Source: Compilation by Arthur D. Little, Inc., from references noted.



SOURCE: (129)

### THE CHAMBER METHOD

Figure 7

coal to outside the mine. It required all other conventional underground development and coal breaking operations to be done.

The main result of the work with the chamber method was that it could produce a combustible gas if there were proper coal-gas contact.

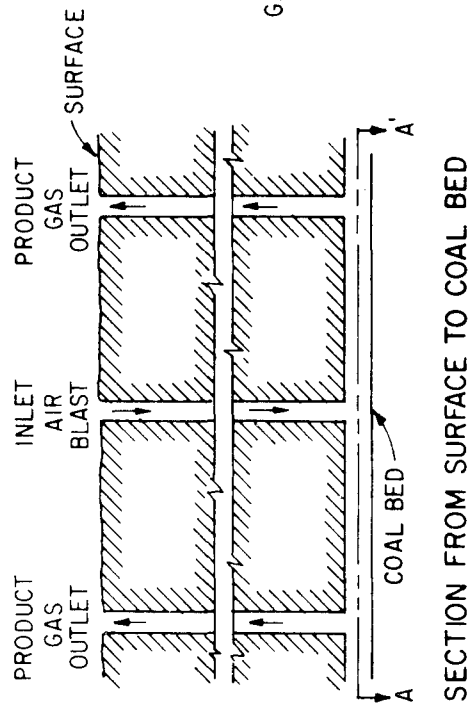
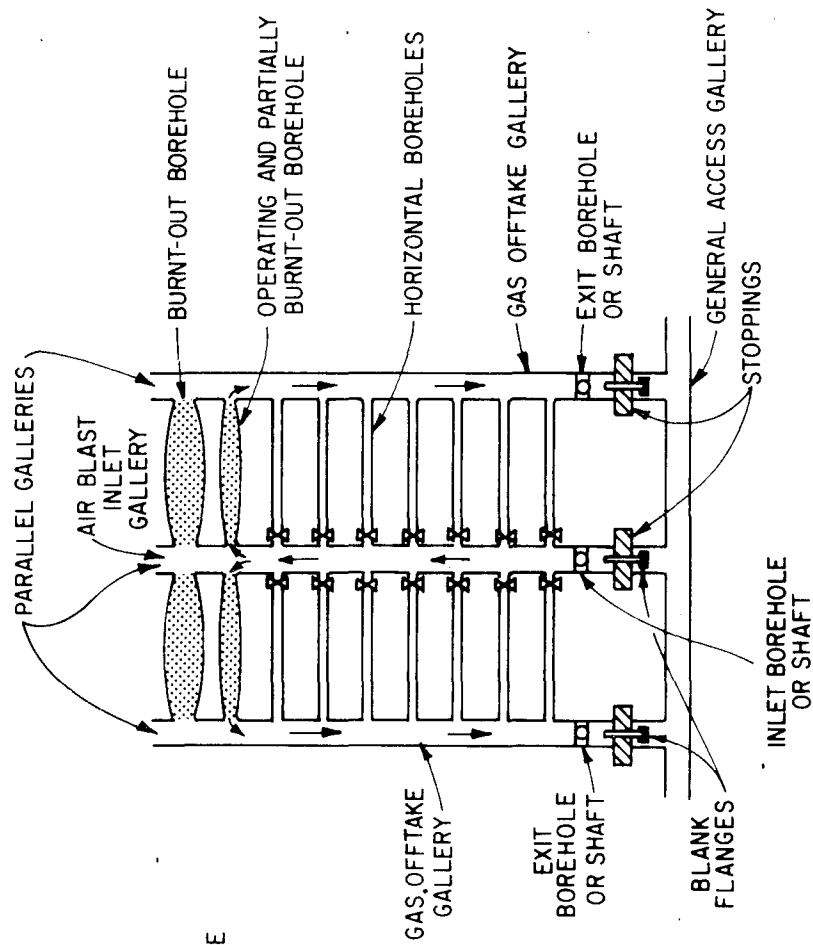
(2) *Borehole Producer Method.* The borehole producer method also requires underground work, namely, the development of parallel underground galleries. These galleries can be located about 500 feet apart within the coal bed. From such galleries, 4-inch-diameter boreholes are drilled about 15 feet apart, from one gallery to the opposite. Boreholes are fitted with valves, and provision is made for electric ignition and for operation by remote control. (See Figure 8.)

The gasification is started by igniting the horizontal boreholes farthest from the general access gallery with the control valves closed on all the other boreholes. Gasification air comes down the central inlet shaft or vertical borehole, through the boreholes being gasified, and out the off-take galleries and shafts or vertical boreholes. As one set of horizontal boreholes is gasified the valves on the next set are opened and the gasification proceeds, in this way retreating toward the general access gallery.

Careful control of the operations makes possible better utilization of coal and the production of a higher-heating-value gas of a somewhat constant quality. Calorific values of gases produced in a number of experiments (129) using this technique ranged from 160 to 246 Btu per cubic foot.

Work reported by the Bureau of Mines at Gorgas (40) indicates the maximum width of channel that seems practical to produce from a set of boreholes. The maximum attainable width would determine the number of drill holes needed. The borehole producer method was employed except that linking was by hydraulic fracture rather than by drill holes. Figure 9 shows a sketch of the probable finished configuration of the cavity (i.e., the situation after gasification of a 3-foot seam). The gasification procedure employed was the following:

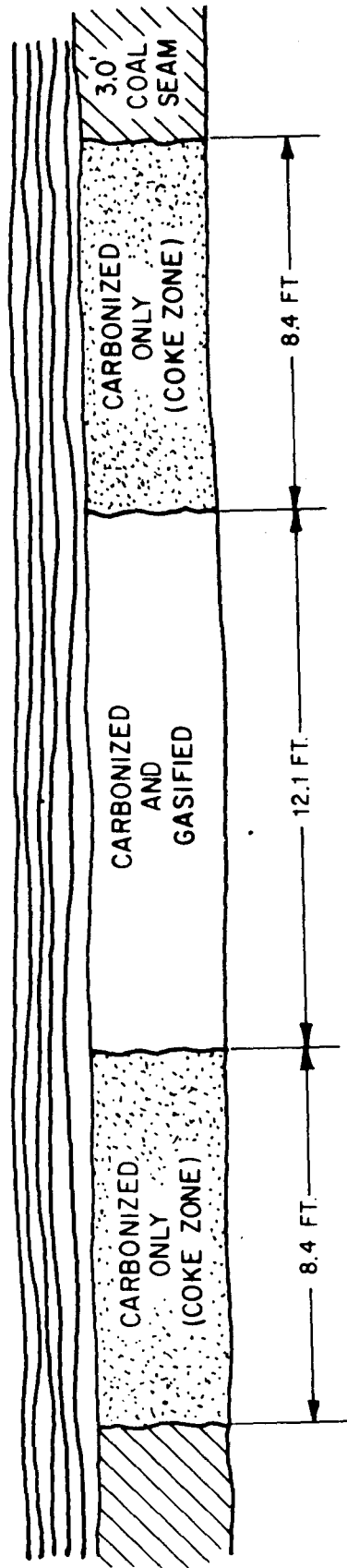
- Two 4-inch-diameter steel-cased boreholes about 200 feet apart and 185 feet and 163 feet deep were prepared.
- The coal seam between them was hydraulically fractured with a water gel-sand mixture at 900-1100 psi and 200-600 gpm for 79 minutes.
- The boreholes were linked by backward burning for 50 days (intermediate boreholes were used) with about 150 cfm of air. Ignition was with hot charcoal.



SOURCE: A. D. L. & (129)

## THE BOREHOLE PRODUCER METHOD

Figure 8



BETWEEN TWO 4-INCH BOREHOLES ±200 FEET APART

SOURCE: (40)

PROBABLE CROSS-SECTION OF FINISHED CHANNEL AFTER LINKING AND GASIFICATION

Figure 9

- Gasification was carried out for 94 days with about 500 cfm of air.

The probable cross-section size calculation, shown in Figure 9, was based on the assumption that the full 3-foot depth of the coal bed was gasified and carbonized along the 200-foot path. The variation in the compositions and heating values of the product gases during the test is shown in Figure 10. Calculations indicated that 266 tons of coal were gasified and 370 tons were carbonized, resulting in a 44% thermal efficiency or coal recovery. The drop-off in heating value as the cavity enlarges is quite evident.

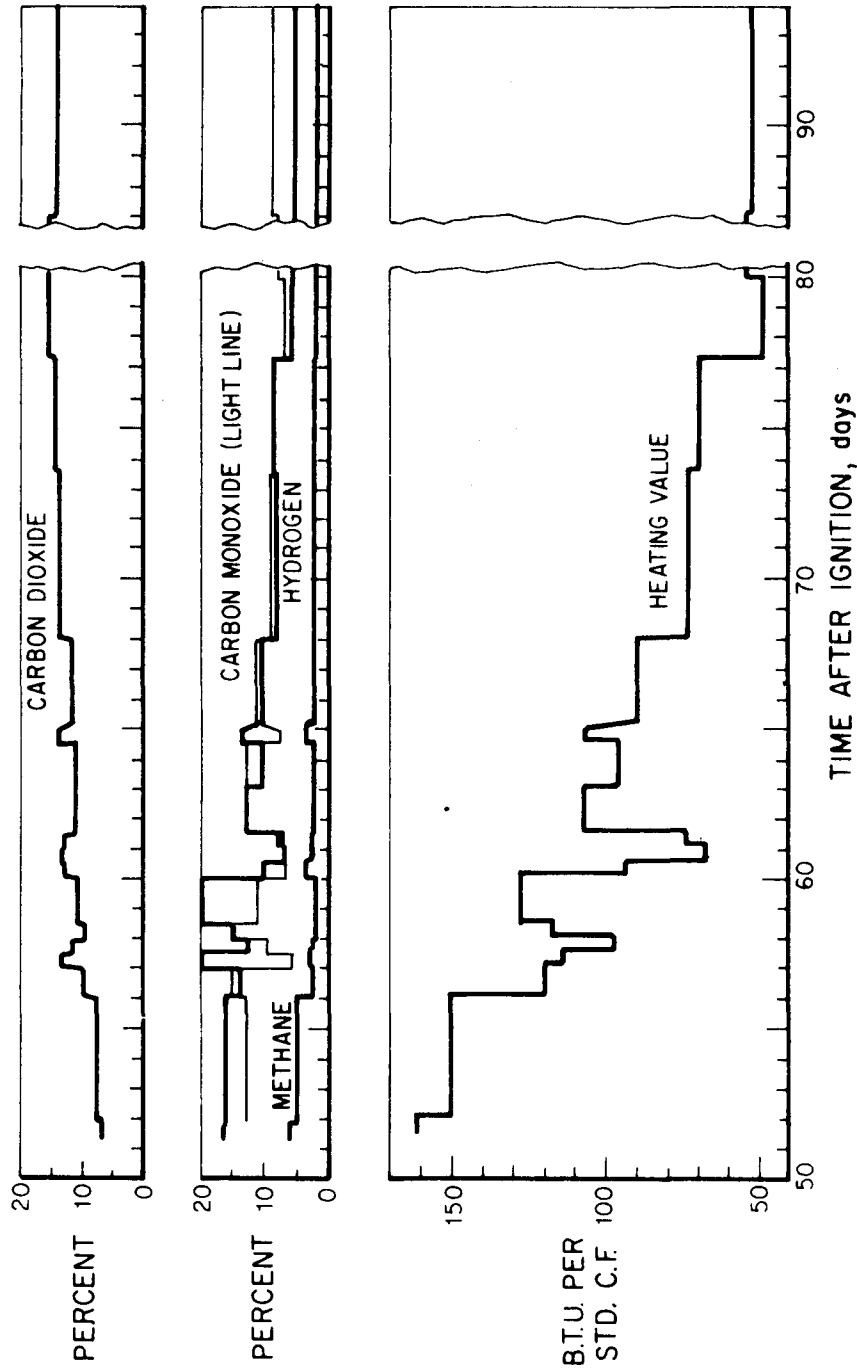
Another experiment in Great Britain (160), carried out in a 2.5-foot-thick coal bed, produced a reaction channel about 26 feet wide and 400 feet long during one portion of a test in which the coal seam was prepared by the borehole producer technique. The inlet and outlet gas boreholes were 12"-diameter cased holes and the 400-foot-long initial linking hole was 14" in diameter. The initial air velocity was about 700 cfm, which was increased over the 17-week test period to a maximum of about 3000 cfm.

(3) *Stream Method.* In the stream method the gas/coal contact is perpendicular. A substantial amount of underground development work is required. A general arrangement of a typical installation is shown in Figure 11. The method is particularly applicable to steeply dipping coal seams. Inclined galleries are constructed parallel to the coal seam, which are connected at the bottom by a horizontal fire drift. At Gorlovka, in the U.S.S.R., where this method was used with some success, the inclined galleries in the coal bed were 60 yards long and 100 yards apart, so that the panel contained about 12,000 tons of coal. Gasification is started with a fire in the horizontal drift and proceeds up the slope of the coal seam, with air coming down one inclined gallery and the gas going up the other inclined gallery.

One obvious advantage of the stream method is that ash and roof collapse material drops down, fills voided space, and at the same time does not tend to choke off the combustion zone at the burning coal face.

At the Gorlovka site, the stream method was applied to a 6-foot seam, dipping at 70-75°, and the effect of using oxygen enrichment of the blast was investigated (USBM-9). The researchers reported that the most satisfactory operation was with 27-30% oxygen in the blast. With this amount of oxygen, a gas of 112-146 Btu per cubic foot was produced.

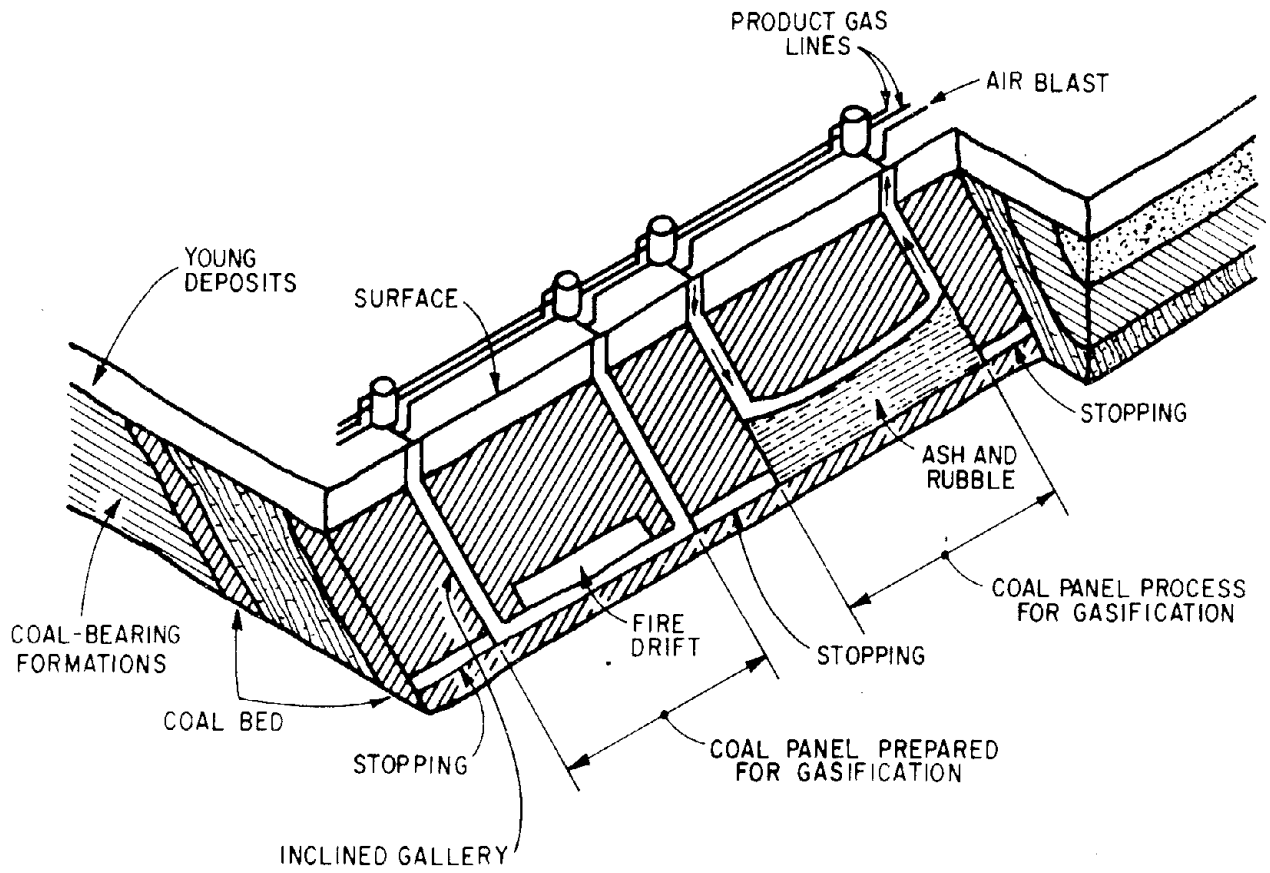
Another result of the work at Gorlovka (USBM-9) was the production of a hydrogen-rich gas, when the air blast was interrupted. By running alternately with and without air blasts for periods of 4 to 6 hours, a gas containing about 45%



SOURCE: (40)

VARIATION IN COMPOSITION AND HEATING VALUE OF  
PRODUCT GASES-BOREHOLE PRODUCER METHOD

Figure 10



SOURCE: (129)

## THE STREAM METHOD

Figure 11

hydrogen with a heating value of 180 Btu/ft<sup>3</sup> was produced during the no-blast period. When the air blast was enriched to a 35% oxygen content, the heating value of the product gas rose to 235 Btu/ft<sup>3</sup> during the no-blast period, while during the blast period the gas produced had a heating value of 137 Btu/ft<sup>3</sup>. The use of steam in the blast gas was also reported and a mixture of enriched air and steam gave uninterrupted production of a gas of 295 Btu/cubic foot heating value (USBM-9).

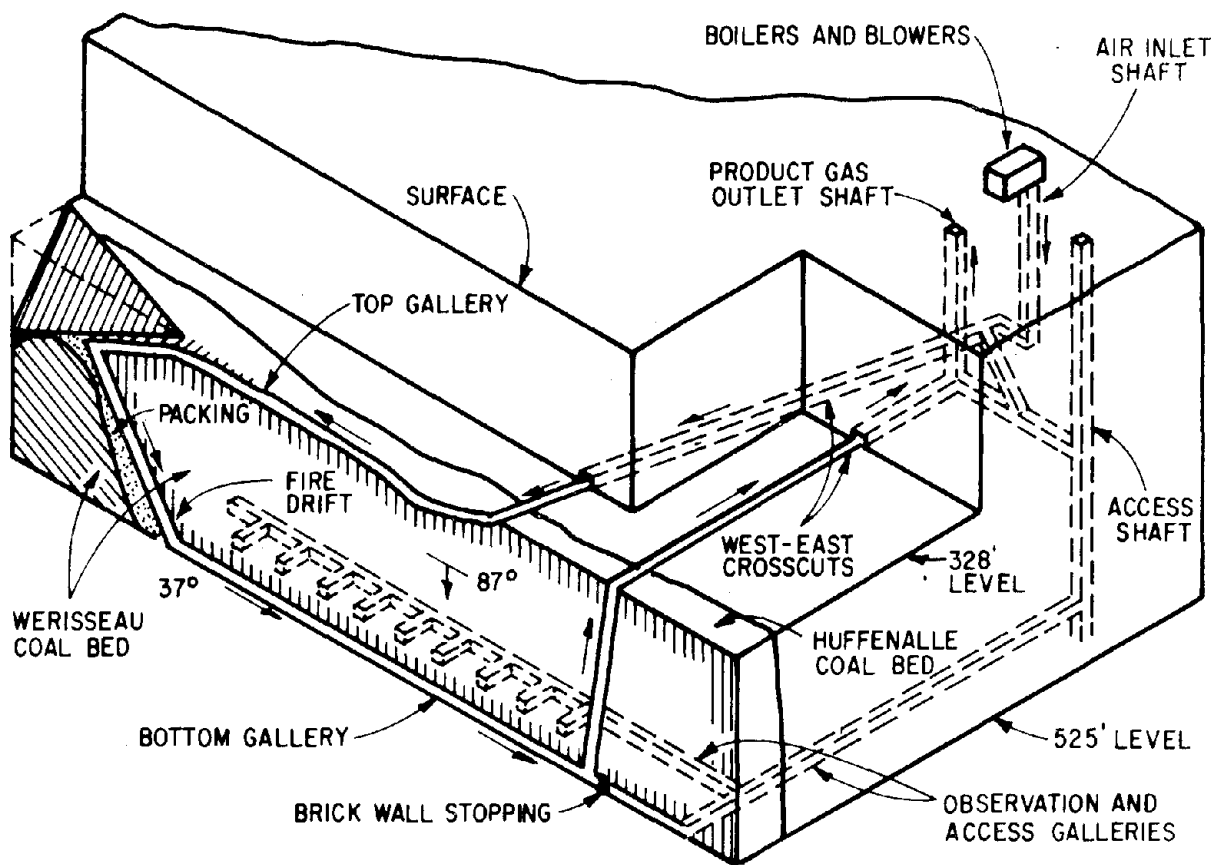
A variation of the stream method was used in the experimental test carried out by the Socogaz group at Bois-la-Dame, Belgium (129). Figure 12 illustrates this installation. The coal was a semi-anthracite containing about 13% volatile matter. The coal bed was approximately 3-feet thick, dipping at an angle of 87°, containing approximately 20% ash. In the experimental installation, the fire drift was constructed at an angle of 37°. The objective was to burn the coal panel in a generally sidewise direction instead of upward as in the Russian work at Gorlovka. A combustible gas was produced at Bois-la-Dame on several occasions. But gasification results were poor, and the attempt to burn the coal panel sidewise has been considered to be unsuccessful.

#### b. Shaftless Methods

In shaftless methods, all development and gasification is carried out through boreholes drilled from the surface into the coal seam. No underground labor is required. A great variety of borehole spacings and locational patterns have been used, as have been numerous different pregasification and gasification procedures.

The general approach used in the development of shaftless methods has been to make the coal bed more permeable to gas flow between inlet and outlet boreholes. First a linking technique has been employed, then the coal seam has been ignited by passing air, or other gasifying agents, through the inlet borehole to the outlet borehole.

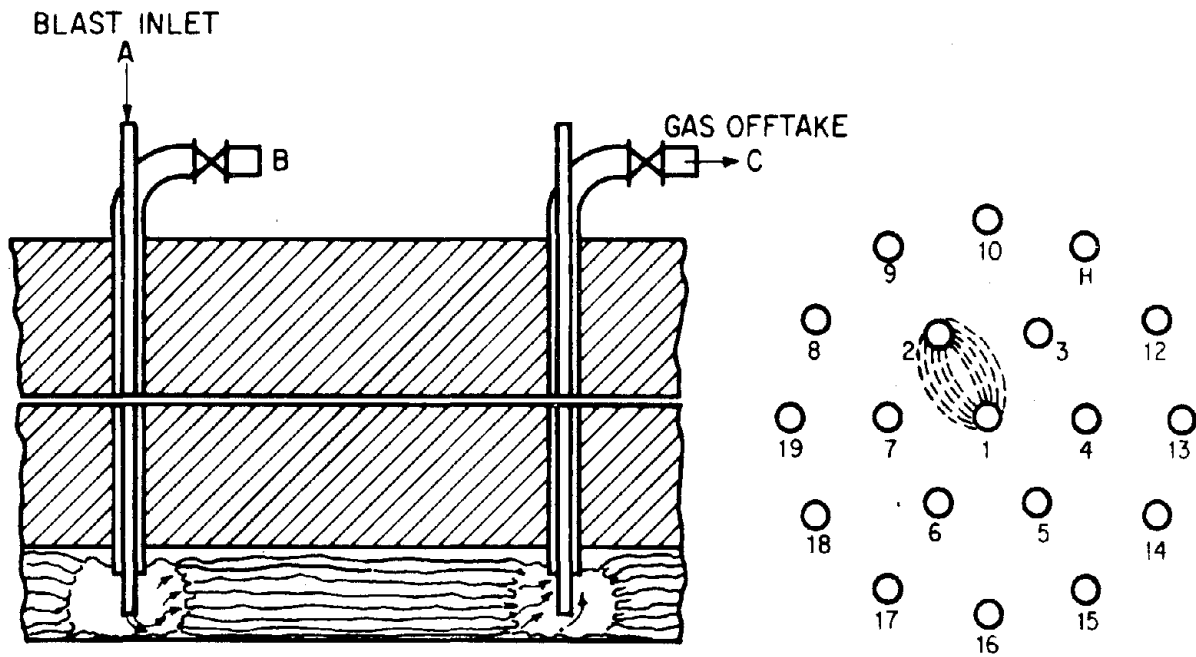
The simplest and the most direct approach to accomplish shaftless gasification of a coal seam is by the so-called percolation, or filtration, method. An installation using this approach is shown in Figure 13. The coal seam is penetrated by two or more boreholes some distance apart and gasification takes place between different pairs of holes to the extent required to produce a product gas continuously. For some coals, the method can be made to work using only the natural permeability of the coal bed and the presence of fissures. Some lignites, for example, have a naturally high permeability. This approach, however, has not often been possible with high-rank coals. Thus, in such cases, it becomes necessary to connect boreholes by some linking technique that will increase the permeability and/or fracture the coal seam so that an increased rate of acceptance of gas flow can be obtained.



SOURCE: A.D.L. & (129)

PANEL NO.1 AT BOIS-LA-DAME

Figure 12



(a) SECTION THROUGH BOREHOLES

(b) PLAN OF BOREHOLES

SOURCE: (USBM-9)

PERCOLATION METHOD

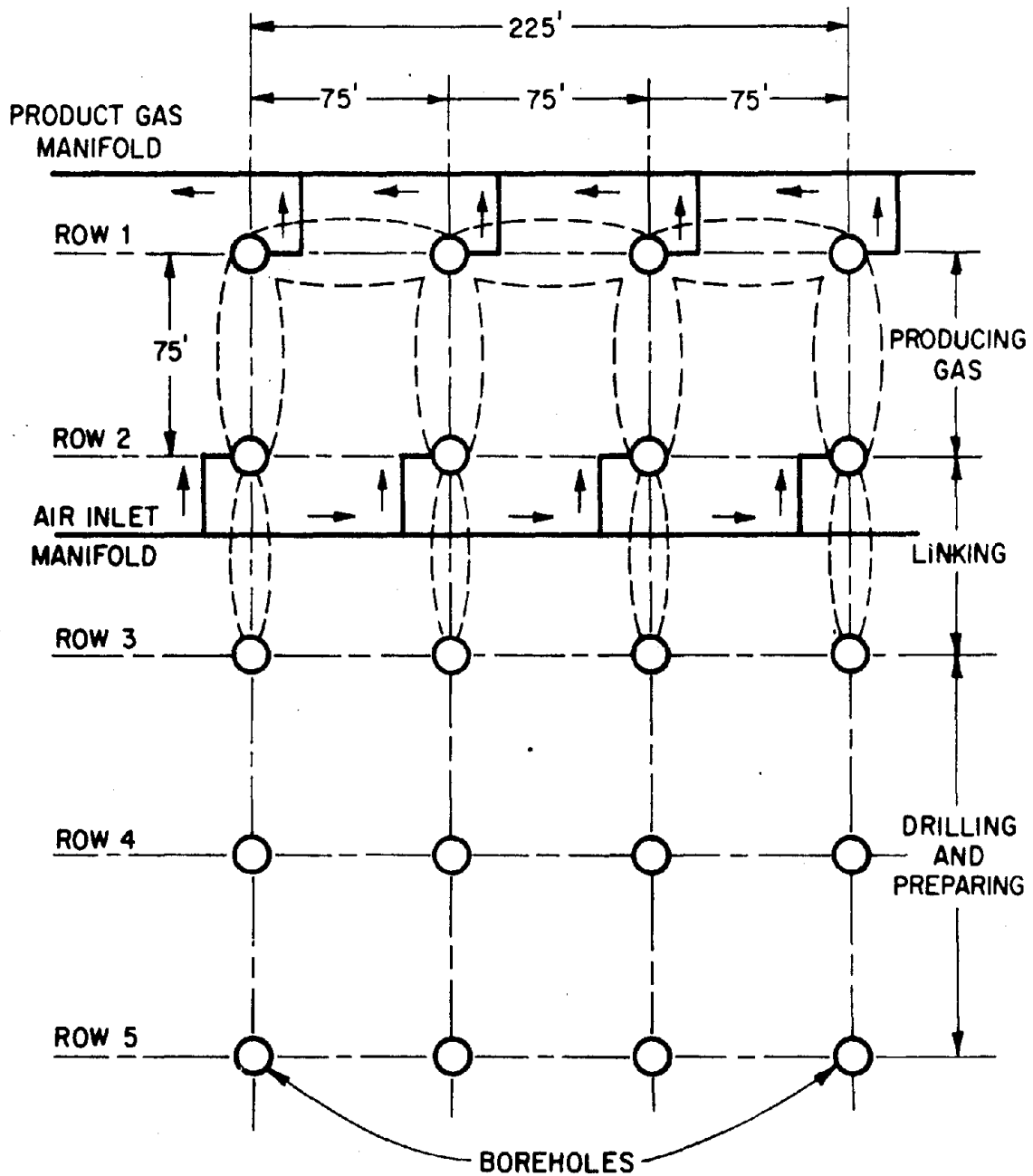
Figure 13

As shown in Figure 13, the original development and operation of the percolation method involved drilling a number of boreholes 20 to 40 yards apart in a pattern of concentric rings. The method of operation was to fire the coal at the bottom of a borehole, electrically or with glowing charcoal, and to maintain combustion in the area around the base of the hole by supplying air or oxygen through the central pipe of the borehole. Initially, the product gases passed up the annulus and were withdrawn at the surface. However, as the coal was heated, fissures formed and it became possible to pass the gases through the coal seam to an adjacent borehole. One percolation installation operated in Russia in the Moscow region — a good example of a shaftless gasification system — has been described in detail (129). The plant (Figure 14) operated on coal of the Novo-Basovsk bed, which is a brown coal, containing approximately 30% moisture, 37% ash, and having a heating value of 4900 Btu/lb. The bed ranged in thickness from 1-1/2 to 15 feet, but coal thicknesses less than 3 feet were not gasified.

The natural permeability of the coal bed is used, although it may be increased pneumatically by use of high-pressure air, or by electro-linking carbonization. When the pneumatic method is used, backward burning is applied in order to develop the reaction zone. By 1955-56, gas production at the plant had reached approximately 90% of designed capacity. The annual gas production was reported to have been 15.6 billion cubic feet of gas, a quantity sufficient to operate a 15,000 kw electric generating station, if one assumes that 10,000 Btu is required to generate 1 kwh of electric energy.

The plant used a number of boreholes spaced approximately 75 feet apart, arranged on a square pattern. A production of 45 million cubic feet of gas per day, i.e., at the annual production rate noted above, required at least four generators, each composed of not less than eight boreholes operating simultaneously. Each generator is prepared for regular operation in two stages, i.e., first, four boreholes in a row are ignited and linked to each other, forming a 225-foot fire front; next, four boreholes are ignited in a second row, 75 feet distant, and linked to the corresponding borehole in the fire front of the first row (Figure 14). The result is a generator composed of four parallel gasification passages, each 75 feet long, terminating at right angles in a fire front 225 feet long. Gasification proceeds by blowing air at low pressure. The air enters the boreholes in the second row and the gas is removed from the boreholes in the first row.

While gasification is being conducted, linkages are being established between a third row of boreholes and the second row. When the gasification and establishment of this linkage are completed, gasification begins between the third and second rows. Additional rows or boreholes are thus successively linked and gasified over the life of the installation. Thus, for a 1000 MW power plant, the gasification area might be about 3 miles wide and the gasification direction would



SOURCE: (129)

**PLAN OF A SHAFTLESS GENERATOR  
MOSCOW REGION PLANT**

Figure 14

advance at right angles over a total distance representing coal adequate for a 20-30 year life of the generation equipment. The actual distance would depend on coal recovery and seam thickness. The capital requirements would be low.

There are really no other basic shaftless methods since the drilling of boreholes is the basis of shaftless access to seams. However, there are numerous variations of the percolation method which involve various borehole sizes, locational patterns, linking, and gasifying procedures.

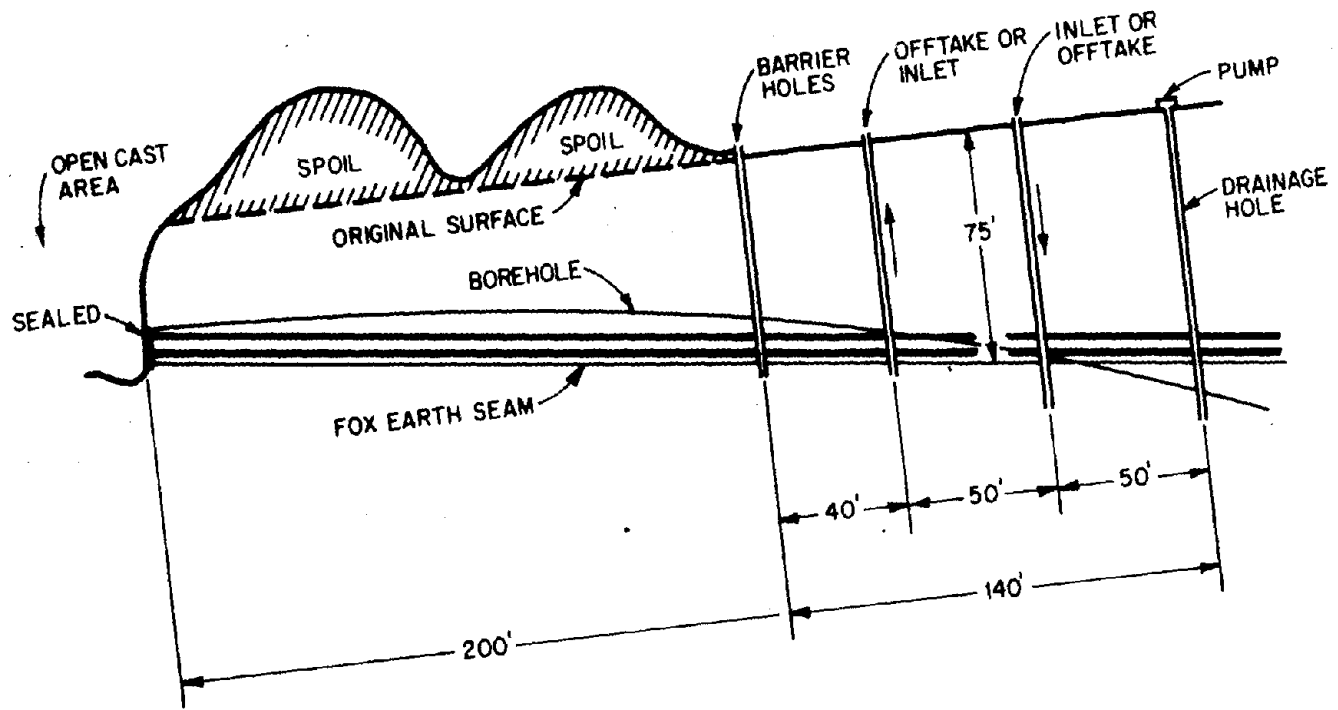
A good example arises from the work of the British Ministry of Fuel and Power beginning in 1949. The first installation (160) involved a shaftless technique somewhat different than the percolation method. Figure 15 shows a sketch of the work at Chesterfield in Derbyshire, where tests were conducted in flat-lying coal beds. A four-inch-diameter hole was drilled from an exposed coal face through the inclined coal bed to link the vertical boreholes drilled from the surface. The installation was operated using a reversing flow of air and gas through the vertical boreholes and during part of the trials a combustible gas having a heating value of 60-100 Btu/cubic foot was produced.

Another shaftless method, having possible future interest for selected seams, involves the use of nuclear explosions to fracture coal beds before gasification, the basis for a study by the U.S. Atomic Energy Commission and the Bureau of Mines under a project known as *Thunderbird*. The concept is to fracture a 200-foot-long series of coal beds in Wyoming at a depth of 1000 feet. After fracturing, the coal would be ignited and burned under controlled conditions, with oxygen or air-oxygen mixtures provided through one borehole and with gas extraction through the borehole originally drilled to place the explosive. Resources of deep coal amenable to this type of development are tremendous. One hundred square miles are said to contain 20 billion tons. This gasification approach is probably limited to very deep coal seams where there is a substantial thickness of coal. A trial has been proposed, but has not yet been carried out.

### c. Combination Methods

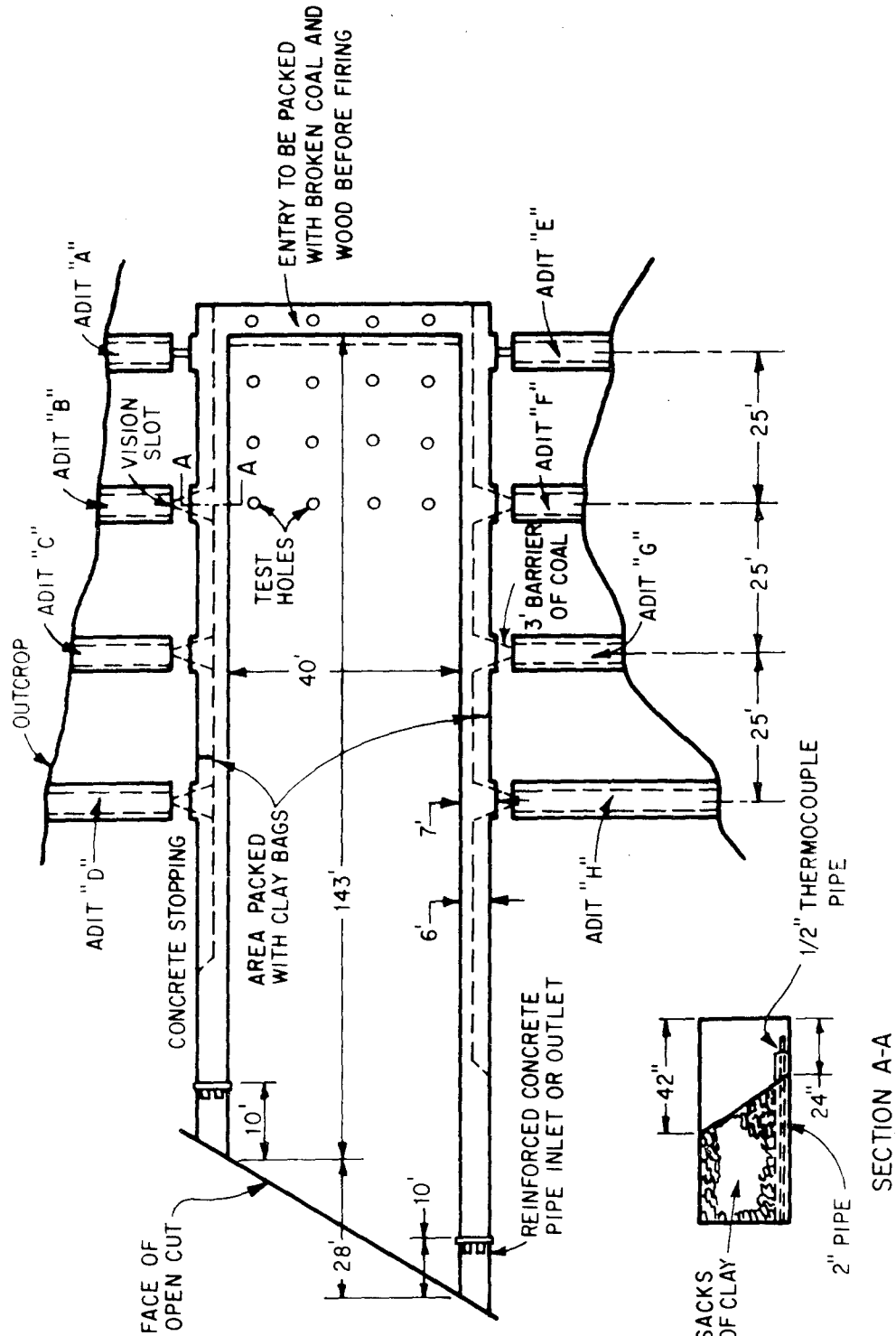
Methods involving the combination of shafts and boreholes have been studied and tried in a number of cases. One reason is the obvious advantage of easy direct inspection of the result of experimental work. For example, the first set of trials in the United States at Gorgas, Alabama, involved a U-shaped underground gallery and surface drill holes (Figure 16). The installation for the second set of trials was similar. It used straight-line underground galleries connected to the surface by a series of boreholes.

The Gorgas work was done in a 34- to 46-inch coal seam of high-volatile A bituminous rank. In the first test in the U-shaped channel, runs were made with



SOURCE: (160)

FIRST GASIFICATION SYSTEM AT CHESTERFIELD  
Figure 15



SOURCE: (USBM - 45)

PLAN VIEW OF A GASIFICATION MINE - FIRST GORGAS EXPERIMENT

Figure 16

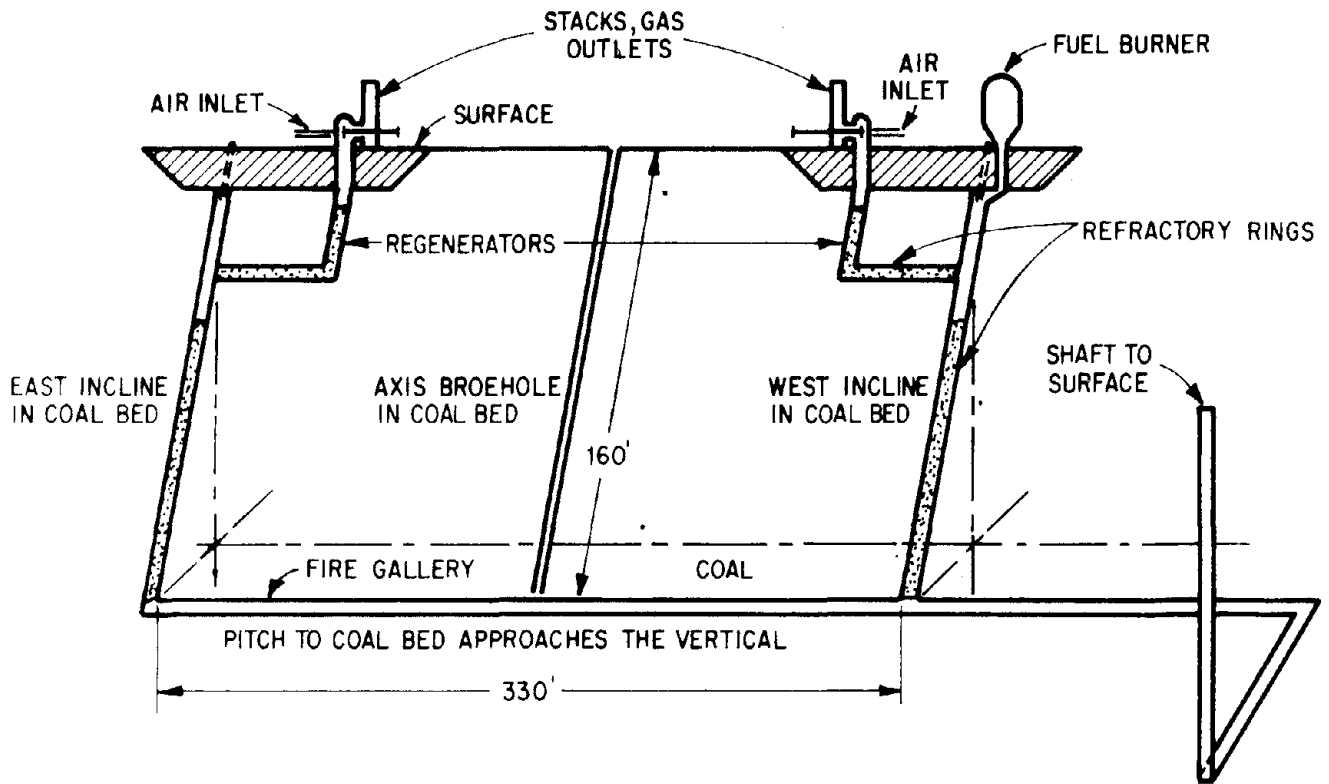
air which produced a product gas of 46.8 Btu/cubic foot average heating value. When using oxygen-enriched air a heating value as high as 134.5 Btu/cubic foot was obtained. The work at Gorgas employed the stream method for flat-lying coal seams. Combustible gases were produced at Gorgas at certain times, but in general, there was excessive bypassing of the reaction face by the air blast, subsequent mixing of unreacted air with combustible gases with combustion of this mixture prior to leaving the installation.

Another combination system that used underground openings and boreholes from the surface was the French work at Djerada in Morocco (129). The installation is shown in Figure 17. The intention was to ignite the coal panel at the bottom and, in much the same manner as in the Russian work at Gorlovka, to burn the panel from the bottom upward. As shown, the fire gallery is connected to the surface by inlet and outlet shafts, the shafts in turn are filled with refractory rings and the passages are fitted with regenerators so that in using reversing flow operation some of the sensible heat in the product can be saved and used for preheating and inlet air. The operation in this experiment was continuous for 5 months. A combustible gas was produced, the oxygen content was nil and remained so throughout the experiment, but the percentage of combustible components varied widely. Operational difficulties, such as leakage at the surface and high resistance to flow within the passages, were encountered.

An interesting combination method was also tried in the British experiments at Newman Spinney (near Chesterfield) in the final trial of the program, No. P.5. (74, 113, 160). The general layout of the underground development for this work, and the plan of the installation, is shown in Figure 18. It consisted of driving a gallery 225 feet long from a shaft; then drilling four parallel 14-inch-diameter boreholes, 75 feet apart and 400 feet long from the gallery rising with the seam. These boreholes were intersected at their dead ends with vertical holes drilled from the surface. The system was ignited in the gallery at the mouth of each borehole, where air entered through three vertical 12-inch-diameter holes.

The system operated for 118 days, gasifying about 900 tons of coal and producing gas with an average calorific value of 57 Btu/ft<sup>3</sup> from a 2.5-foot-thick coal bed of 12,500 Btu/lb heating value coal. Air rates of up to 13,000 cfm were used for the total air supply through the three vertical holes. The operating results are summarized in Figure 19 in terms of the variation with time of the main operating conditions during the trial, namely: thermal yield, heating value, maximum air pressure, and average air rate. Figure 20 shows the estimations of the areas of coal consumed after 32 hours, 58 hours, 89 hours, and after about 2800 hours when the test was finished.

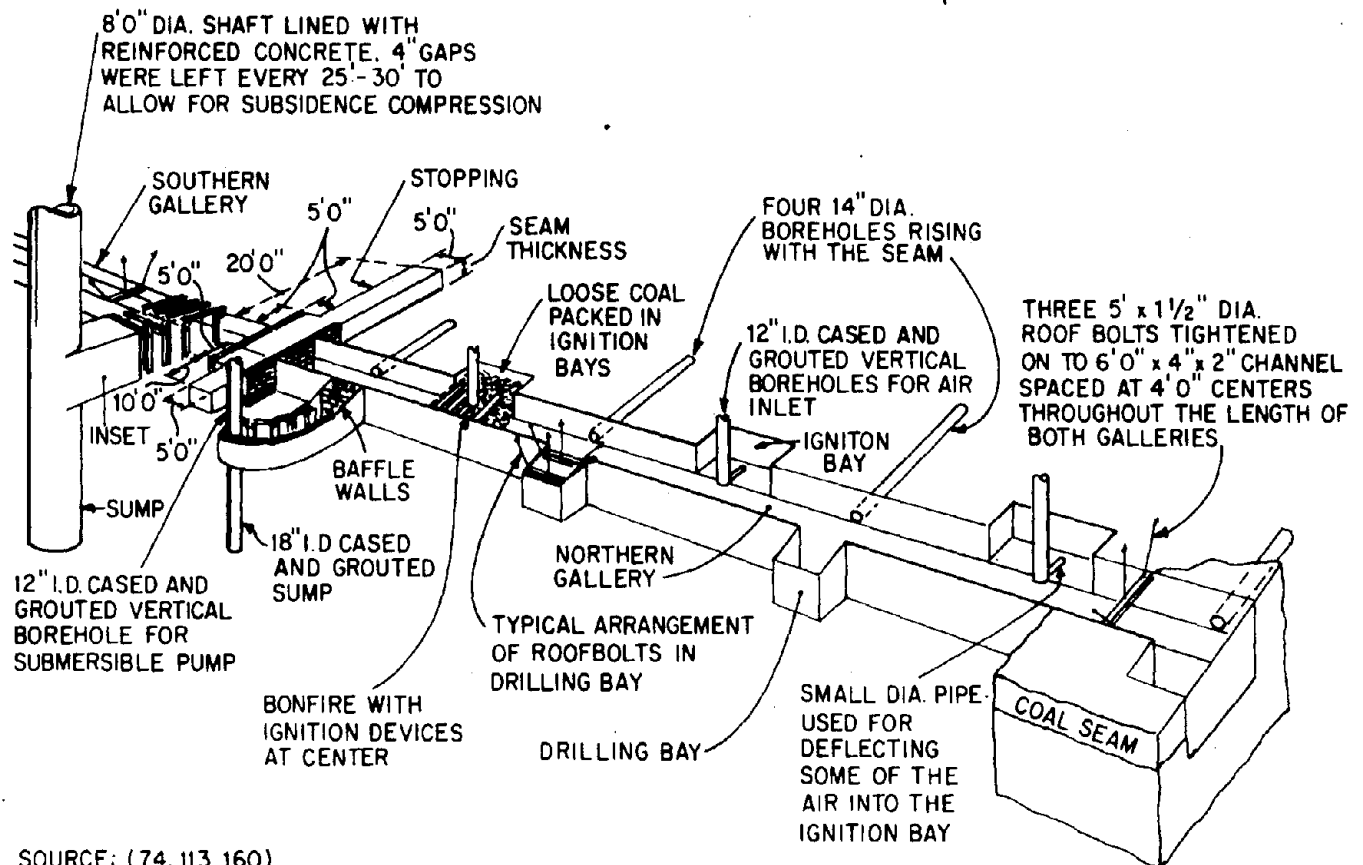
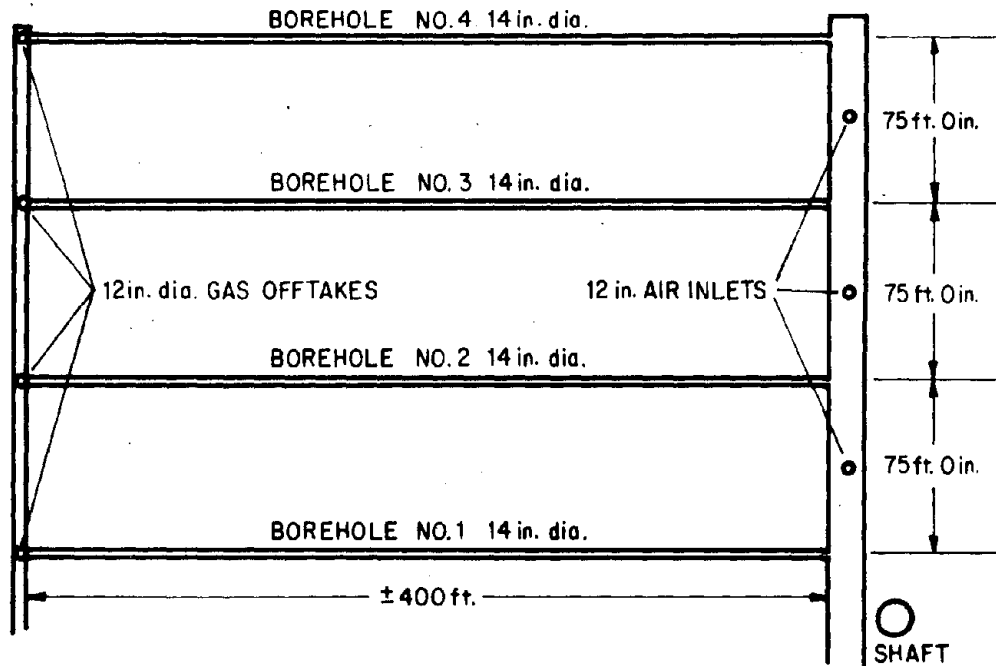
After completion of the 118-day test, the researchers estimated that 84% of the coal had been exhausted, or gasified. The 16% of coal ungasified was largely



SOURCE: A.D.L. & (129)

### STREAM METHOD INSTALLATION AT DJERADA

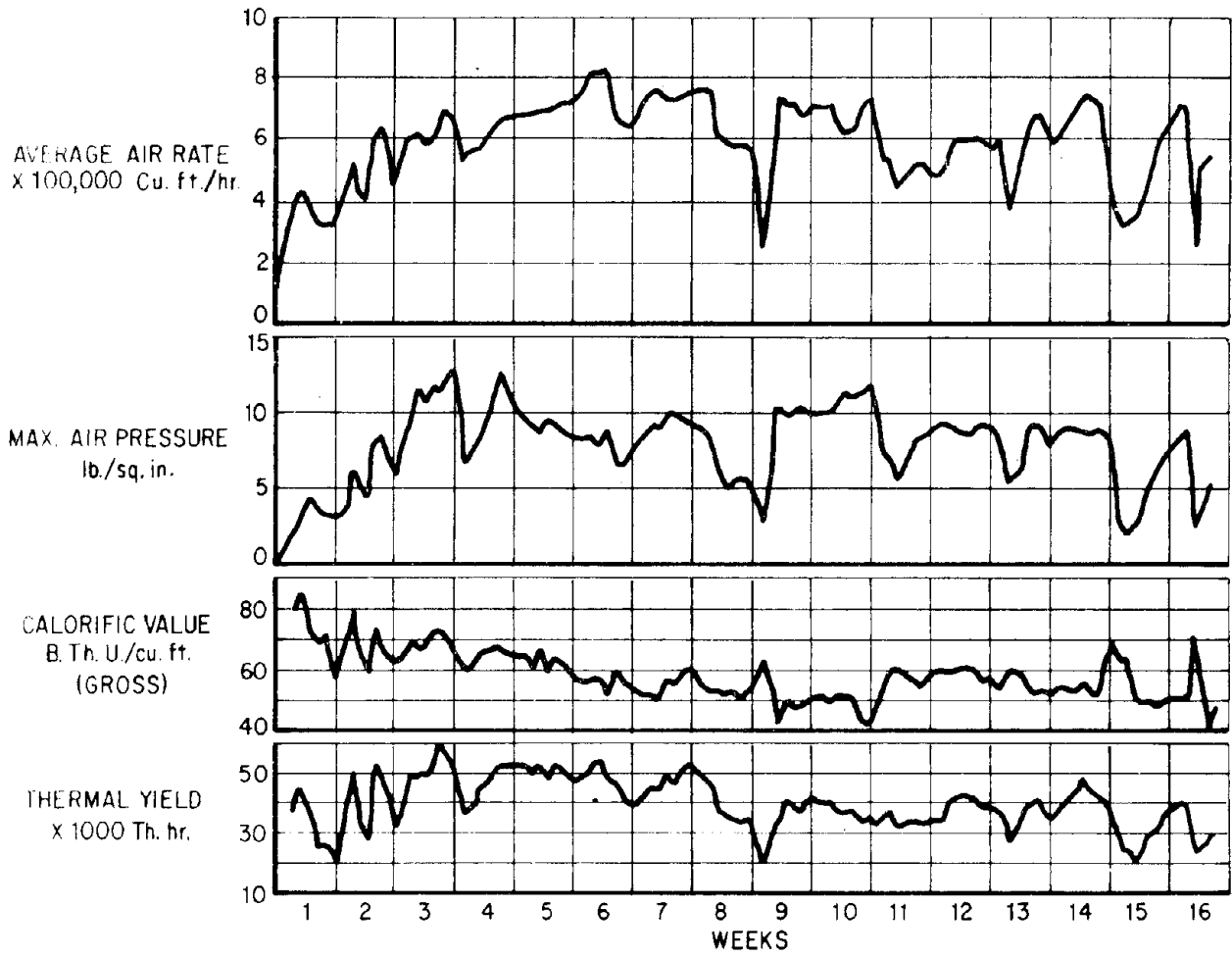
Figure 17



SOURCE: (74, 113, 160)

PICTORIAL VIEW OF THE GALLERY - TRIAL NO. P.5

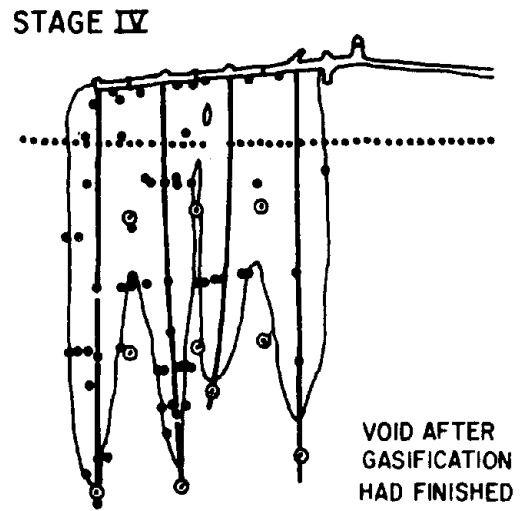
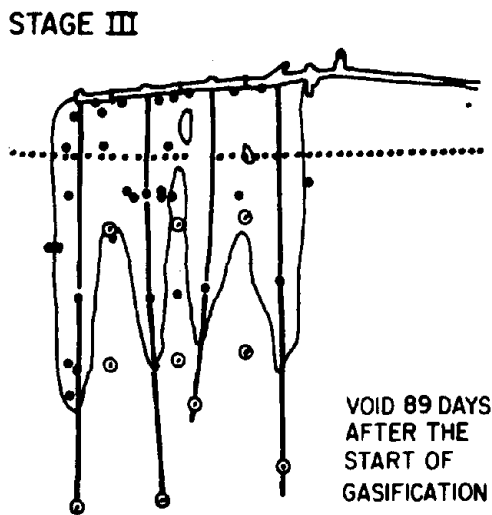
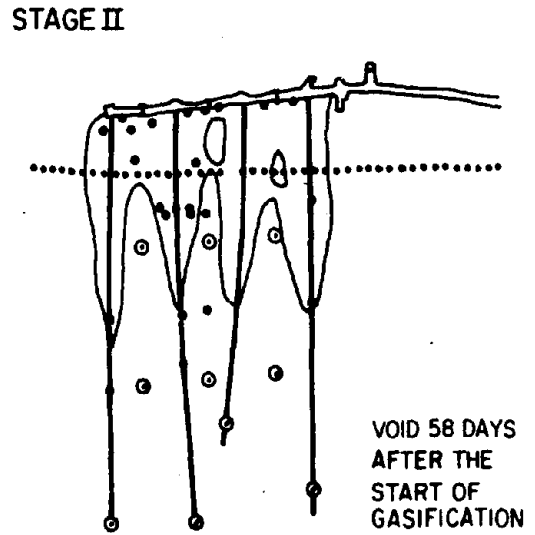
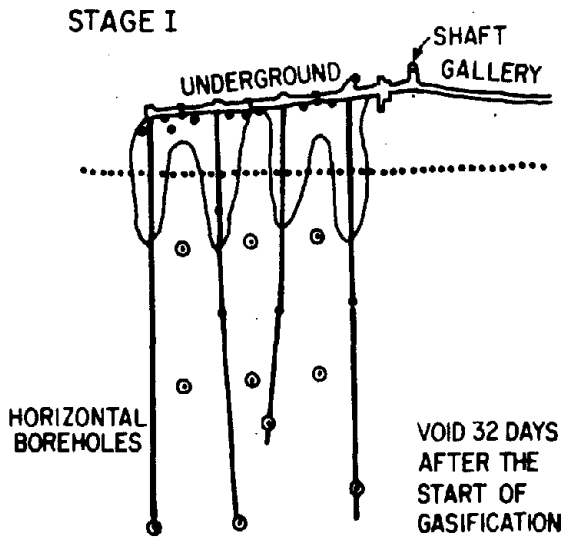
Figure 18



SOURCE: (160)

PERFORMANCE CURVES - TRIAL NO. P.5

Figure 19



VERTICAL BOREHOLES

- ORIGINAL HOLES FOR GASIFICATION
- PROBE HOLES

SOURCE: (160)

**GROWTH OF VOID DURING GASIFICATION - TRIAL NO. P.5.**

Figure 20

accounted for as pillars remaining between gasification boreholes at the gas outlet. The researchers believed that extractions of 90% could be achieved in a commercial operation. There was some evidence that a few pillars had been bypassed by the gasification reactions, and it was thought that a revised spacing of boreholes might prevent this. The work also indicated that at high gas velocities some coke was dislodged from the fire face and brought to the surface. This coke had to be removed in cyclones before the gas could be burned.

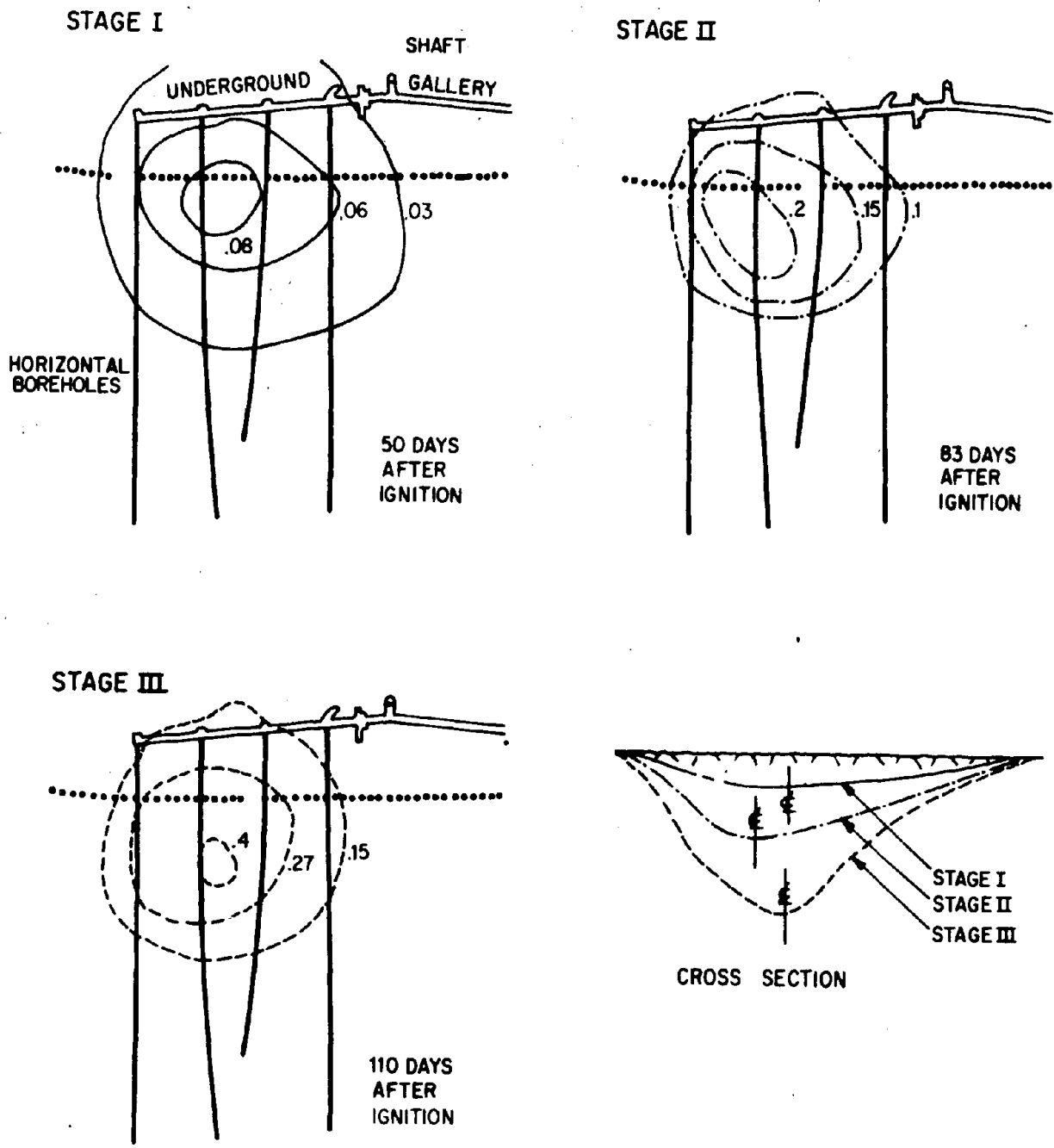
Surface subsidence above the installation, measured during the progress of the test, was small in relation to the seam thickness and appeared not to correlate with the gasification geometry (Figure 21). But surface subsidence did occur even though the coal seam 240 feet below the surface was 2.5 feet thick. The caving of ground above the seam apparently did not affect the gasification results, although this is not absolutely clear from the results in the final report (160).

## B. THE PROBLEM AREAS

The current state of underground coal gasification makes evident the limitations of the technology, most of which are caused by technical problems that have been either difficult to solve or have received inadequate attention. The methods so far developed have been operated on a substantial scale. They can, in fact, produce a combustible gas but not on a continuous basis, or at a constant heating value. Substantial amounts of the fuel value in the coal can be recovered but not at consistently high levels (i.e., 80-90%). Furthermore, none of these methods can be controlled to the extent usually achievable in aboveground processing, so their results are unpredictable. Land subsidence and groundwater contamination problems have not been solved, but this may be attributed to a lack of focus of attention on these problems.

### 1. Combustion Control

Control of the reactions of the coal with the gasifying agent is essential for control of the heating value of the product gases and of the level of recovery of the coal heating value. Ideally, the gas/coal contacting mechanism should be such that the coal in situ is gasified completely, the  $\text{CO}_2$  produced by the reaction of CO with steam is reconverted to CO by reaction with hot carbon, and all free oxygen in the inlet gas is consumed. Furthermore, the mechanism should be such that contacting efficiency is not affected by roof collapse, if this should occur, and its character is retained even when most of the coal in a panel has been gasified. The problem then is to establish and retain such a contact mechanism.



SOURCE: (160)

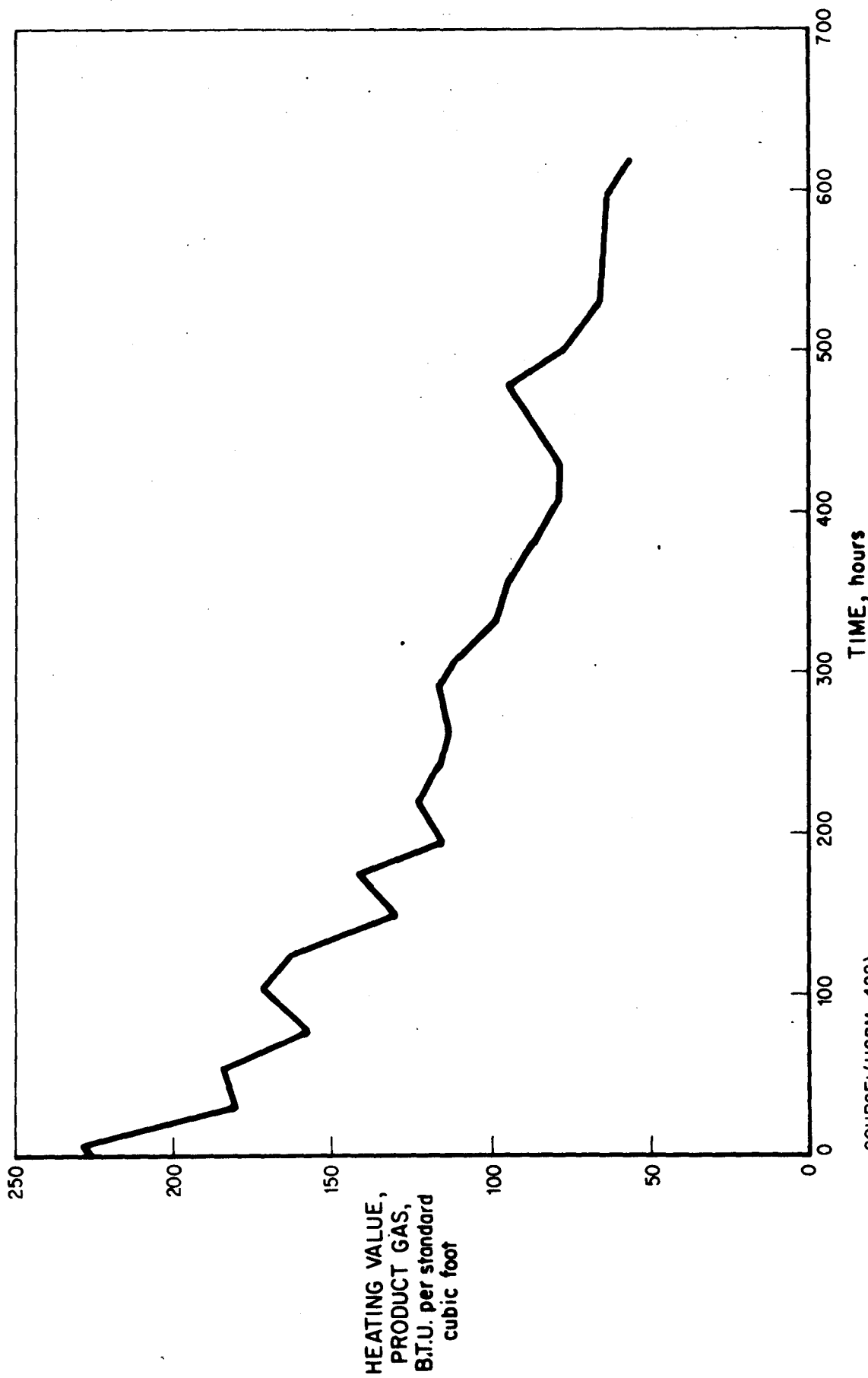
CONTOURS OF SUBSIDENCE - TRIAL NO. P. 5.  
 Figure 21

Actually, gasification runs usually begin with the highest levels of heating value in the gas being produced initially, continue with a gradual loss in heating value as time goes by and as the underground void spaces increase in volume. (See Figure 10.) The trend is a reflection of the increasingly poor contact of gas with the coal face, i.e., too large a combustion volume at the same reactant gas input rate results in inadequate contact between reactants and reduces the reaction rates. A typical set of data (USBM-422) is shown graphically in Figure 22. Heating value is plotted against time for a single air-gasification run between two boreholes during the operations at Gorgas, Alabama. Also, in the same test and in many others it was noted that maximum coal utilization occurred at the oxidizing-gas inlet regions, where oxygen could readily react with the first hot carbon contacted.

Another reason for poor gas quality is the secondary effect of having too large a void combustion volume at the coal face. As the reaction rate decreases, it becomes increasingly difficult to keep face temperatures above the threshold value (900-1000°C) required for effective combustion of coal values. As the combustion chamber enlarges, the inert strata on the roof and floor of the coal seam are uncovered and further increase in void space can take place only along the direction of the coal seam. As the cavity progressively enlarges this way, the roof and floor surface area is increasingly exposed. Through this area heat is dissipated to the strata without a compensating heat release from the combustion of the coal. An increased supply of heat to cope with these increased losses and thereby maintain a sufficiently high temperature at the coal face is required, and this would come about through an increase in the oxygen level in the source. Thus, the ultimate size which the gas-flow channel can reach depends on how long the heat generated in the area can balance the progressively increasing loss to the rock strata. Specifically, this size depends on the ratio of coal surface to strata surface, and this in turn involves the coal seam thickness, and the rate of heat generation, which depends on the rate of air flow.

Roof collapse, if it occurs, can have deleterious effects on gas heating value. Its occurrence causes changes in the character of the void space in the vicinity of the fire front. This is more serious for stream-type processes operating on flat seams than it is for percolation-type processes (regardless of whether forward or backward burning is being employed). In the latter case, the gaseous reactants or products pass through the collapsed rubble and flow problems can only arise, for example, if the collapsed roof material has a low permeability or the character of the collapse can lead to channelling with consequent uneven advancement of the fire face.

The combustion zone temperature should be maintained such that the gasification occurs at temperatures below the fusion point of the ash. If the ash is allowed to fuse, the slag mass can impede coal-gas contact and the decrease in volume can affect roof collapse.



SOURCE: (USBM-422)

HEATING VALUE VERSUS TIME AIR GASIFICATION - SYSTEMS 14-15

Figure 22

Theoretically, it should be possible to regulate the combustion zone temperature by proportioning in the reactant gases, oxygen and cooling agents such as nitrogen, steam, or CO<sub>2</sub>. In practice, however, this is made difficult to achieve by groundwater seepage and reactant gas losses, both of which are aggravated by roof collapse; and by the absence of reliable temperature-measurement techniques which could be used for feedback control for establishing reactant gas compositions. There are no reliable techniques to control leakage in a positive manner.

In summary, then, the problem of providing and maintaining efficient contact on a large scale has not been solved satisfactorily in the currently available technology. The two most serious problem areas are roof collapse and gradual loss in contacting efficiency through enlargement of gas passage cross sections.

## 2. Roof Control

We have noticed little discussion of the roof control problem in the literature and have found little work accomplished in the area of roof control, i.e., the prevention of roof collapse. The procedure generally has been to carry out the gasification process and let the roof collapse as it eventually will when a substantial roof area is left unsupported as a result of the burning away of the coal.

As already noted, uncontrolled roof collapse causes problems not only in the control and successful operation of the gasification process, but also it can result in surface subsidence above the coal deposit, a matter of growing concern especially in the United States.

In some cases, the gasification operations can affect the roof rock with beneficial results. For example, in the experiments at Gorgas, Alabama (USBM-45), the high temperatures developed by the gasification reactions caused the roof rock to become plastic, to expand, and to settle down on the mine floor directly behind the burning coal face. The fusing and expansion of the roof rock apparently sufficed to fill all the space formerly occupied by the rock and the coal. Careful examination after the test of the immediate roof rock affected this way indicated that it was a grayish, compact, silty clay shale containing important amounts of pyrite, carbonaceous matter and altered mica, generally distributed parallel to the bedding and causing the rock to appear banded.

Work in other locations indicates that the Gorgas experience is probably a special case, since most roof rocks are more often not appreciably affected by the gasification operations and temperatures. When the void space reaches a critical point, roof structures cave as blocks and pieces of various sizes, which fill the voids. A result often can be the generation of large semi-open areas in which gases can wander about and not make close contact with the burning coal face.

A Russian analysis (95) of the relationship of underground gasification with the geologic and hydrogeologic conditions of the coal seam concluded that the effectiveness and stability of the gasification process is increased by the presence of unstable rocks (e.g., clayey shales) in the roof, that the effectiveness and stability of the gasification process increases with increasing thickness of the coal seam, and that excess moisture, partings in the coal seam, and fractures in the formations reduce the effectiveness of the process and have a detrimental effect on the gasification process.

The other aspect of importance in roof control is surface subsidence above the coal bed. This is a problem that has not been considered important in many areas where underground gasification has been undertaken, although surface subsidence has been noticed and measured in some cases. For example, in the Moscow Basin where a 9-foot-thick bed of lignite 160 feet deep was gasified, a substantial surface subsidence was noted. Also, as already noted, in Great Britain the subsidence was measured over an area where a 2.5-foot-thick coal bed about 240 feet deep was gasified. Here the maximum subsidence was 0.4 feet in the center of the surface depression.

Russian work has recognized the advantages to be gained from an ability to control the collapse of roof strata over voided spaces. Such work has included investigations of both dry (pneumatic) stowing and slurry (hydraulic) filling for supporting the voided spaces. Laboratory work to select materials for pneumatic stowing, done by the U.S.S.R. Mining Institute (USBM-526) included consideration of sandstones and shales in various sizes. This work indicated that these materials could be used for filling.

The same report mentions a massive cave-in of the roof during gasification at generator No. 1 of the South Abinsk deposit (9-meters thick, steeply inclined). The cave-in disrupted the process. To prevent a recurrence, the workers proposed to support the roof by supplying stowing material underground as the coal was being gasified. It was believed that the use of pneumatic stowing materials in inclined borehole generators resulted in an increase in the quantity of coal gasified as compared to the quantity of coal that can be gasified without filling materials. No mention is made whether or not the proposal was actually implemented.

Studies of hydraulic or wet slurry filling of open spaces were also reported as has mention of the use of clay slurries for filling spaces in inclined gas generators. The results appear to indicate that this slurry filling work was not productive.

For shaftless underground gasification systems (i.e., where no men work underground) the only access is through boreholes. Although roof control methods here are probably limited to pneumatic stowing or hydraulic slurry filling, these can be considered in various ways using a variety of different materials and methods of application.

In summary, methods of roof control are available. The fact that their application in underground gasification systems has not been widespread, or has been unsuccessful is probably the result of inadequate attention to its importance rather than of an inability to solve a difficult problem. Roof control should be considered an important factor in further development of any large-scale underground gasification operation for use in the United States. Avoidance of collapse will be important to reduce the effect of water infiltration and gas leakage on the control of underground combustion.

### 3. Permeability-Linking-Fracturing

Underground gasification of a coal bed requires that the coal have sufficient permeability to permit the oxidizing gas to flow through the bed without an excessive pressure drop. If the coal is not sufficiently permeable, however, the permeability of the coal can be increased by linking or joining two or more locations in the seam. The methods presently used for linking are: pneumatic linking, hydraulic linking with water or slurries, electro-linking, and directional drilling. During early tests in Russia explosives were used in attempts to increase permeability; the explosives were set to detonate ahead of the flame front, but the method was not successful.

The permeability of natural coals varies with their rank. Low-rank coals (e.g., brown coals) have sufficient natural permeability so that underground gasification is practical without linking. Bituminous and higher rank coals, however, require linking.

The problem with the present electro-, hydraulic, and pneumatic linking methods is that they do not increase the permeability of a coal panel uniformly, but form preferred high-permeability paths between the inlet and outlet boreholes. Since such paths usually are not straight, these techniques make it possible for the less-permeable areas of coal to be bypassed during gasification.

The severity of the problem, however, varies with the linking system. For example, in electro-linking followed by immediate gasification the path after linking is already at an elevated temperature – this is an advantage. To illustrate the reverse, the high-permeability path generated between two electro-linked boreholes is not necessarily straight – this is a disadvantage, especially in a panel when multiple electro-links are being established, because there is no way of predicting that direct links will be established between desired pairs of boreholes.

The comparative effectiveness of the various methods is difficult to assess, however, because of the conflicting results that have been reported. The Bureau of Mines has shown that the amount of coal that can be gasified from an electro-linked path is much greater than can be obtained from the backward burning of a hydraulically fractured path. Experience reported by Great Britain has shown the reverse to be true.

Although in an advanced stage of development, fracturing and linking techniques must be improved even further if they are to be applicable to the U.S. situation. If coal is to be made permeable to the degree and to the homogeneity desired, hydraulic fracturing will have to provide greater control than it now does. Electro-linking, on the other hand, will have to be developed to provide enough control to assure direct straight-line paths.

Finally, the technology now used to drill a curved hole in a prescribed path will have to be developed to provide increased borehole diameter and larger penetration into the coal seam.

#### 4. Leakage Control

The control of leakage can be very important, since the loss of a substantial amount of the product gas, or the oxidizing gas, can adversely affect the heating value in the product gas or the recovery of the coal heating value. The severity of the leakage problem varies according to the geological characteristics of the site: i.e., the depth of the coal seam, the permeability of the coal bed, the roof and floor strata, and the faults and fracture zones. Although such characteristics can be identified during the planning stage of the underground gasification operation, the prediction of leakage potentials may still be difficult.

In all the underground gasification operations reported in the literature gas leakage has been a factor. The work to date at fairly shallow depths has shown that to keep leakage at a tolerable level gas pressures will probably have to be limited to 50 psig, or less. Higher pressure levels may be possible at greater depths, or in less-permeable formations. In any case, it is quite evident that underground gasification should never be attempted in a severely faulted or fractured area where leakages might be excessive.

The leakage problem can increase and become serious when roof strata collapse and allow gas to escape into porous sedimentary layers above, especially when gasification is attempted in shallow coal seams. On the other hand, if the roof can be prevented from collapsing, and if gas inlet and exit boreholes are properly prepared and sealed, leakage can be kept low and manageable in non-fractured and non-faulted coal seams.

Some of the variety of leakage problems that have arisen in experimental installations, and the solutions tried, are described in the following examples:

- In the very shallow (25 feet) work at Gorgas, Alabama (USBM-45), numerous surface leaks occurred during the first gasification test. The leak points were filled with gunited concrete so the test could be continued.

- In work at Gorgas involving electro-fracturing and gasification (USBM-422) on a system in a 3-foot coal seam about 180 feet deep, the experimenters noted two types of potential leakage: (1) leakage through the walls of an inlet or outlet borehole, and thence through the strata that were intersected by the borehole; (2) leakage in the reaction zone of the coal seam adjacent to the overlying strata and gases escaping through cracks or fissures. The calculated leakage was based on the nitrogen balance and on the volumes of input air and gas produced. In the linking and gasification trials on various combinations of boreholes, the range of leakages, calculated as a percentage of the injected air, was 14% to 60%. The low 14% leakage occurred in an operation where the injection borehole was on a hillside and one of the boreholes had been grouted. It was speculated that as the coal was removed and some caving took place, the forces exerted on the strata may have been compressive and thus tended to seal the fractures in the strata surrounding the hillside borehole. Had this well been on a hilltop, the forces in the strata induced by caving after removal of coal might have been tensile, and thus might have opened cracks and crevices through which increased leakage would have occurred.
- In the hydraulic-fracturing and backward-burning gasification work at Gorgas (40), leakages of air of 16%, 35%, and 76% were calculated for the three different two-hole systems.
- Another Gorgas experiment consisted of a straight line series of holes connected underground with a man-made gallery (USBM-182) in a 3.5-foot-thick coal bed about 180 feet deep. Gasification was between successive boreholes with calculated leakages of 5% for the ungasified system and up to 60% for systems using specific boreholes. The maximum pressures were about 15 psig.
- The Mechanics Institute of the Soviet Academy of Sciences (USBM-526) concluded that: (1) to reduce leakage it is necessary to maintain as low a pressure as possible in the gasified area; (2) the actual gasification reactions must be carried out at as high a rate as possible; (3) for deeply bedded coal seams, leakages of gas are proportional to the square root of the bounding area of the outgassed space, and for shallow-bedded seams, to the first power of the area of the outgassed space; and (4) of the outgassed areas of various shapes, the least leakage occurs in the area which most approximates a circle.

- Further examples of leakage problems have been discussed in more recent literature. For example, it was recommended (21) that to reduce leakages in the underground gasification of brown coals, boreholes should be linked by hydraulic fracturing so that lower pressures could be used during the gasification process. Another report (63) indicated that at the Podmoskovnaya station in Russia gas was lost through inlet, outlet, and drainage boreholes, through leakage in the surface lines, and through leakage into the underground surrounding rock structure. The losses in the underground areas were 55% and could not be eliminated; operating at a reduced pressure was recommended. Other reports (87, 93, 147, 148) discuss gas losses and one (147) indicated that losses at one Podzemgaz station reached 30% or more. Losses increased when the static pressure in the underground generators was increased. Also as burnt-out spaces increased, the gas losses increased.

In summary, the leakage of reactant gases represents a significant problem. The magnitude of leakage depends on the technique employed, the characteristics of the coal deposit, and on its environment.

## 5. Water Control

Sedimentary-type formations associated with coal seams commonly have strata or layers that contain water, often in large amounts. The coal measures themselves typically contain 1-10% moisture in bituminous-type coals and 30-40% moisture in lignites. Conditions vary, of course, and underground coal mines can be quite dry or can have some considerable water inflow from fractures, or faulted zones, that connect the coal seam with aquifers in the formations above the coal.

Up to a certain point, the presence of water in the seam improves the gas quality, because the water-gas reaction can produce more hydrogen in the effluent gas. But this occurs at the expense of heat, since some of it is used to evaporate the liquid-water flowing into the reaction zone and the water in the surrounding strata. Above that point, water inflow can extinguish the combustion reactions.

As a general rule, it would appear that if underground water conditions permit conventional underground mining, then they will also permit an underground gasification system to be operated. It is easy to install pumps in boreholes to drain aquifers, or keep water under control, as long as the roof can be prevented from collapsing. Thus, the presence of water in the seam probably does not present a serious problem to the gasification process.

Another problem related to water control is the fact that underground gasification can pollute the surrounding groundwater supplies. In work in the U.S.S.R. (168, USBM-719), two groundwater effects were noted. One was the increase in temperature of the water in the surrounding region arising from heat conduction, from the hot zone, and from the leaking hot gases. The other was an increase in the soluble salts content of the groundwater. In a region where the structure was clays and sands, the soluble salts content increased from about 150 to about 550 grams per liter. In a region of sandstones and limestones, this increased from around 500 to about 5000 grams per liter.

In the United States, the potential pollution of groundwater from such a source could be a very serious problem. Measures to prevent or control it would be needed. For example, it might be necessary to pump out affected areas, and to treat the water before discarding it into the drainage system. If roof collapse is avoided, the probability of contamination could be significantly reduced.

## 6. The Control of Underground Gasification

As in any process, the first step in the control of any underground gasification operation is to identify the key operating parameters. The next step is to monitor them so that the progress of the gasification is known and anomalies can be detected. Finally, the appropriate corrective actions must be taken to maintain continuous operation at the desired gasification conditions.

The important operating parameters are:

- the location and the shape of the fire front
- the temperature distribution along the fire front
- the detection of roof collapse and the extent and nature of collapsed roof debris
- the permeability of the coal seam and of possible debris from roof collapse
- the detection of reactant and product leakage and of bypassed coal
- the inflow of groundwater
- the composition of product gas

But the ability to monitor and measure the operating parameters of the underground gasification process is in itself not sufficient to achieve successful underground gasification. The cause and effect relationships must be known so that adequate process control techniques can be developed.

### C. RELATED TECHNOLOGY

Considerable scientific and technological progress has been achieved in many related fields since the last significant experimental work with underground coal gasification was concluded in the United States about 1960. Some of the new technology in these related fields seems to be applicable, or adaptable, to underground coal gasification. (The details are discussed in Appendix C.)

#### 1. The Use of Explosives in Linking

In some early Russian work where dynamite was used to break up coal, the results were inconclusive. A better approach might be to first hydraulically fracture the coal deposit and then to permeate the seam with some type of liquid explosive and detonate. Such a technique would probably make larger volumes of coal permeable and increase the rate of gasification. It might even be possible to perform the fracturing and detonating with the same fluid. If the coal mass to be gasified is to be broken uniformly throughout, the explosive's sensitivity, completeness of detonation, shattering power, and rheological properties should be carefully selected in accordance with the specific application.

A two-component mixture – i.e., a “Sprengel” type – with the desired properties might be very suitable. Since each component by itself is nonexplosive, thus detonation is possible only after mixing. A number of different formulations are being developed, but experience as to their performance is limited. Gelling agents have been incorporated in such mixtures, and this is noteworthy in view of the fact that the performance of hydraulic fracturing fluids can be improved by incorporating gelling agents.

An alternative approach that avoids the need for tailor-made explosive properties is one based on the incompressibility of water. The coal bed is permeated by water alone, after which the detonation of a strategically placed explosive charge produces a shock wave having a steep high-pressure front that the water transmits effectively throughout the coal seam.

It might even be possible to combine several explosive techniques, but considerable experimental work is indicated before linking through explosion may be considered practical. The focus of such work should be on the desired performance of the entire system and the contribution of the component parts to the performance.

NOT REPRODUCIBLE

## 2. The Use of Lasers

Much of the underground gasification technology depends on drilling horizontal or inclined holes underground between given locations. As an alternative, or supplement, to conventional drilling equipment, laser technology has now developed to the stage where high-power units that are available commercially could be considered for drilling straight-line holes through coal seams. For example, smaller powered lasers could be considered for drilling small-diameter holes which then would be used to guide the special mechanical drills needed to drill the larger holes, particularly when the holes are to be offset to desired patterns. The materials required to construct reliable optical systems for controlling the laser beam (e.g., gallium arsenide) are available.

The CO<sub>2</sub>-laser is a good candidate for such drilling, but one disadvantage would be interference with the drilling beam by the coal's decomposition products. It might be necessary to provide for either continuous purging or intermittent drilling alternating with purge. If intermittent drilling proves to be acceptable, even higher powered lasers are available.

Experimental work is indicated, but the focus should be on application and performance rather than on equipment design.

## 3. Large-Scale Use of Oxygen as the Gasification Agent

A potential underground gasification installation in the United States would have to operate on a large scale. The gasifying agent might be enriched air or oxygen-rich gases, in which event large-scale tonnage oxygen plants would be required. Present plants of this type operate efficiently in the range from 1500 to 2000 tons of oxygen per day, a scale not available 20 years ago. The limit on size in a single unit appears to be the maximum available size of steam-turbine-driven air compressors. Larger capacity plants would require multiple units.

## 4. Subsidence and Its Detection

The detection of subsidence of the surface above an underground gasification site would indicate the occurrence of a roof collapse. The amount of subsidence would depend on the depth and thickness of the seam being gasified and the nature of the overlying strata. The amount might be barely detectable, except by the most sensitive of devices. Precise leveling such as used in conventional surveying is limited to a detection accuracy, at best, of a few millimeters in elevation. Recording tiltmeters are perhaps the most suitable. Various types capable of achieving resolutions of a small fraction of a second of an arc are commercially available.

## 5. Monitoring the Combustion Face

Temperature indicator devices can readily be installed in long boreholes that consist of parallel-wired thermocouples, or fusible nichrome links, spaced along the length of the borehole traveling the coal seam. Upon calibration, the accumulated e.m.f.s. generated by thermocouples can be related to the location of the fire face. Likewise, the accumulative resistance changes, as successive nichrome links fail, can be used to locate the combustion face, and also to indicate its probable temperature. Another available method is an electrical one that depends on variations of resistivity between coal deposits and adjacent strata, and variations in current flow that result when a network of electrodes is placed around the fire zone. The lowered resistivity at the fire zone produces an anomaly that can be detected and identified as current flow measurements between pairs of electrodes.

Another possibility is a seismic method in which seismic energy is generated through strategically located explosions or a similar location of nonexplosive devices such as drop hammers and swept-sine-wave sources. The position of the combustion front would be estimated from measurements of reflections, and the isolation and rejection of unwanted results. However, experimental work is indicated. And finally, the position of the flame front could be determined by measuring the attenuation of acoustic energy traveling in coal. Noises generated at the flame front could be detected by multi-pairs of geophones. Knowing the velocities of travel and the geometrical locations of the detectors, one could determine the attenuation. The evaluation process would have to provide for the elimination of spurious signals reflected from other formations, man-made disturbances (e.g., compression equipment at the surface), or microseisms.

## 6. Monitoring Coal Removal

The detection of gravity anomalies, generated by the removal of coal from the deposit by gasification, is theoretically a possible method for estimating the recovery of coal from the seam. However, the field work would have to be so extremely accurate that the usefulness of the technique is questionable.

A more useful technique seems to be the estimation of coal recovery from the carbon balance. This balance could be calculated from analytical measurements of gas compositions and from information regarding the location and movement of the fire front.

## 7. Detection of Leaks

Leakage of reactant gas can readily be calculated on the basis of deficiencies in the balance between oxygen (or nitrogen) fed into an underground gasification system and the amount in the product gases. A preferred method might be to inject a small quantity of an inert tracer gas, such as helium.

Leakages of product gas are not only a waste but represent a potential health hazard because of the toxicity of carbon monoxide. The normal concentration of carbon monoxide or hydrogen in the earth's atmosphere is very low (about 1 ppm). Detection of an abnormally high concentration of CO with a device based on infrared spectrometry appears to be an attractive solution. An alternative might be a remote detection device based on a centrally located laser source of infrared radiation, which would be aimed sequentially at a large number of mirrors or retroreflectors around the periphery of the area to be surveyed. Leakage of CO reaching the surface would increase the absorption of the beam as it travels. Development of such a "searchlight" approach has been limited, and further work would be required.

## 8. Monitoring Product-Stream Components

The technology for measuring components in the product gases is well developed. Alternative, reliable techniques that are available are mass spectrometry, gas chromatography, and infrared spectrometry. Devices could be located above ground in analytical laboratories or control rooms. The choice of technique would depend upon the particular component being measured.



## V. OPPORTUNITIES FOR FURTHER RESEARCH AND DEVELOPMENT

### A. POTENTIAL FOR IMPROVEMENT

#### 1. Productive Capacity

Parallel-operating systems will probably be necessary to reach the capacity levels anticipated for an average-sized U.S. commercial installation — i.e., 3- to 5-million tons per year of coal consumption underground. One criterion for selecting a method (or methods) for further development would be its potential to operate at high unit capacity, thus necessitating fewer parallel units.

High unit capacity depends on increasing the gasification rate within a unit coal volume by providing adequate quantities of the oxidizing gas to the burning face to sustain the gasification reactions and leading away the product gases as they are formed. The key technique to achieve such a goal is to increase the permeability of the coal bed.

Electro, pneumatic, and hydraulic (with or without sand) fracturing methods have generally been tried. Conventional explosives were tried in the early stages of work in the USSR. All of these techniques, except the use of conventional explosives, increased air acceptance by the coal significantly and to a degree that these techniques then become a basis for developing several operable underground gasification methods.

Technology at an early stage of development and practice concerned with the preparation and emplacement of liquid explosives, if combined with fracture linking techniques, might become the basis of a new technical approach to increase the permeability of coal deposits. It would have a potential of raising air acceptance an order of magnitude above current experience, and the results could be an increase in unit capacity of a gasification method based on the technique by a corresponding order of magnitude. Laser drilling might be an alternative, or an adjunct, to conventional drilling in linking boreholes with defined gas passages. The technique is still in a formative stage. Nevertheless its potential could be important if a desired geometry of drilling must be precisely attained as a means of ensuring high unit capacity.

#### 2. Coal Deposit Recovery Level

It is not yet certain that the state of the technology permits one to control an underground gasification process to consistently obtain a desired level of coal deposit recovery. The best reported recovery was the 84% level achieved for Run P.5 in the British work. In choosing a method, or methods, for further development, attention should focus on the features of Run P.5 which point to

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high coal recoveries. The installation and the operation of this run has been reported in detail (160). Study is warranted in more detail, especially since the application of one or more of the techniques (described in Appendix C), could be used to generate knowledge of cause-and-effect relationships.

### 3. Consistency of Product Gas Quality

The state of underground coal gasification technology is such that no operation reported as using air has been capable of yielding a heating value in the gas consistently above about 120 Btu per standard cubic foot. Below this level heating values fluctuate unpredictably, but one could probably count on sufficient control to avoid drops below about 80 Btu per standard cubic foot, the lower practical limit of ready combustibility, without the assistance of a supplementary fuel. Reduction of nitrogen in the product gas through increased use of oxygen in the gasifying agent raises heating value correspondingly. Intermittent heating of a coal bed with air combustion followed by the passage of steam produces higher heating-value gases, but intermittently. Cycles using air alternating with no blast at all seem capable of producing high-hydrogen-concentration product gases during the no-blast part of the cycle. Table 5 is a comparison of heating values of gaseous fuels commonly used in home or in industry in the United States.

The ability to produce a gas of constant heating value at a desired level depends on a number of factors. First, one should have immediate knowledge of the position and expected travel of the combustion face of the coal. Second, one should incorporate in the design of the gasification method devices to correct operating conditions to avoid harmful anomalies in the travel of the combustion front. For example, loss of intimate oxidizing-gas/coal contact and bypass of ungasified coal should be avoided. The phenomena that should be monitored to assure full knowledge of combustion front conditions are roof integrity, completeness of coal combustion, and product gas composition. Active electrical methods, active and passive seismic methods, and acoustic methods (Appendix C) are promising candidates for detection of signals peculiar to the combustion front, which can be evaluated by high-speed data processing to present a continuous picture of the combustion front.

The gasification method itself must then be capable of accepting deliberate changes in the operating conditions that are designed to correct anomalies in the combustion front detected during operations.

Gases approaching the maximum achievable heating value (i.e., the heating value of pure carbon monoxide and hydrogen mixtures) have not yet been produced, but there is a possibility that they might be through more intensive use of oxygen to reduce nitrogen content in the product gases coupled with the recycle of the unwanted carbon dioxide contained in low-grade product gases.

TABLE 5  
ANALYSES AND HEATING VALUES OF GASEOUS FUELS

	Percent by Volume							Calorific Values, Btu/dry ft <sup>3</sup> (60° F, 30 inches Hg)		
	H <sub>2</sub>	CO	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>4</sub> and Illuminants	N <sub>2</sub>	CO <sub>2</sub>	O <sub>2</sub>	Gross	Net
<b>Typical Fuel Gases</b>										
Blast Furnace Gas	3.7	26.3	0.0	0.0	0.0	57.1	12.9	0.0	96.7	94.8
Producer Gases:										
Pittsburgh Coal, Best	12.7	27.5	3.4	0.0	0.8	50.8	4.6	0.2	176.5	167.1
Pittsburgh Coal, Average	15.0	24.7	2.3	0.0	0.8	52.2	4.8	0.2	154	142
Illinois Coal	11.0	25.4	2.5	0.0	0.6	54.0	5.2	0.1	155	146
Coal Gas	48.5	7.4	32.2	1.0	5.6	2.3	2.2	0.8	620	564
Coke-Oven Gas	57.0	5.9	29.7	1.1	3.4	0.7	1.5	0.0	592	523
<b>Blue Water Gases:</b>										
from coal	52.2	32.7	3.1	0.2	0.2	6.8	4.5	0.3	311	284
from coke	49.7	39.8	1.3	0.1	0.0	5.5	3.4	0.2	306	278
Carburetted Water Gas	34.4	31.3	12.0	0.9	5.6	8.2	2.9	0.8	554	507
Oil Gas	50.8	10.2	27.6	—	3.5	5.1	2.6	0.2	548	481
Natural Gas	0.0	0.0	84.5	11.5	0.0	3.8	0.2	0.0	1040	940
Natural Gas	0.0	0.0	94.5	0.5	0.5	4.0	0.2	0.8	963	868
<b>Pure Combustible Gases</b>										
Hydrogen (H <sub>2</sub> )										290
Carbon Monoxide (CO)										341
Methane (CH <sub>4</sub> )										962
Ethane (C <sub>2</sub> H <sub>6</sub> )										1698
Propane (C <sub>3</sub> H <sub>8</sub> )										2433
Ethylene (C <sub>2</sub> H <sub>4</sub> )										1627
Acetylene (C <sub>2</sub> H <sub>2</sub> )										1510

Source: Compiled from p. 90 *Metallurgical Engineering*, Volume 1, Schuhmann, Addison-Wesley Press, Inc., 1952.

The use of alternate air blast-steam run cycles to produce a higher heating value gas is possible and has been demonstrated qualitatively to be possible. In test work when a unit was placed on alternate air blast-steam runs there was a very steady and rapid degeneration in operating results. Heat was lost from the underground system and it became steadily more and more difficult to regain temperature levels.

The control of nitrogen in the product gases is also important not only with respect to the overall thermal efficiency of the system, but also with respect to the ability to meet pipeline-gas specifications should such processing be contemplated (Figure 1). The use of oxygen to enrich air, or in admixture of oxygen with carbon dioxide recovered from the product gases and recycled (Figure 1) could simultaneously raise heating values and reduce their fluctuations.

Large-tonnage oxygen sources are currently available to support large-scale gasification systems. These large sources have been developed during the last 20 years, or since the countries reporting the literature were actively experimenting within underground gasification.

#### 4. Control of Leakage

Leakage can be detected (Appendix C), and control to remedy it has been thought about and acknowledged as a problem. But no solution that is effective with respect to leaks of reactant and product gases has yet been found. However, techniques have been devised that appear to have been partially successful in controlling groundwater influx; thus groundwater control should pose no major problem. In the selection of a method or methods for further development, attention should focus on sealing techniques that can be applied when isolating a block of a coal deposit for gasification. Also, in selecting blocks for gasification, one should avoid geological features (e.g., faults and major fissures) that would be detrimental.

#### 5. Control of Roof Collapse

The literature shows very little work in the control of roof collapse. A modest amount of work employing pneumatic and hydraulic stowing methods has been practiced in the U.S.S.R., but the reported results have not been clear, even as to whether the proposed methods were actually tried. Also, at Gorgas about two carloads of sand were fluidized and pneumatically deposited underground in an effort to control reactant contact. The results were very inconclusive. Not only is roof control important in maintaining gas-coal contact, but also in preventing subsidence at ground surface for environmental reasons.

Stowing appears to be a promising technique for improving underground gasification. The current review by the Bureau of Mines\* could help solve some of the roof control problem.

## 6. Elimination of Underground Labor

Gasification methods that do not require labor to work underground, either before or during the operation, are available. These methods are based on the application of drilling technology, which has sufficiently advanced so that one may now expect to drill from the surface to a given point in an underground coal seam. Thus, the gasification reactions can be initiated without underground labor during any stage. However, there is still room for improvement. For example, one should be able to directionally drill from the surface large-diameter holes that can enter flat coal seams at some depth and at some angle of curvature, and then travel along the coal seam for substantial distances. Such improvements appear to be realizable.

### B. CANDIDATE METHODS

By applying the criteria for U.S. applicability (Chapter III) to the experimental/commercial gasification methods listed in Table 4, especially the criterion of avoiding the need for underground labor, we identified three methods as candidates should experimental work be reactivated in the United States.

The three methods are all shaftless methods, which have already been tried in the past, and for which the literature has recorded the results of experimental work and in some cases in the U.S.S.R. of commercial operations. Modifications would, however, be necessary to provide for positive prevention of roof collapse over voided areas. The means for achieving this modification appear to be at hand through the application and some further development of stowing techniques. Appropriate materials would have to be identified and applied in a way that roof spans would be adequately supported without, at the same time, interfering with the coal face while gas contact occurs.

#### 1. Blind Borehole-Fill System

Three variations of the blind-borehole technique are possible, depending on the coal seam thickness. The methods and their applicability would be little, if at all, affected by the slope of the seam. Actually steeper slopes could make the stowing easier.

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\*We understand this work will be completed in March-April 1972.

For thinner coal seams, say 2 to 10 feet thick, curved boreholes would be drilled traveling perhaps 1000 feet along the coal seam (Figure 23). The borehole would be fitted with a concentric pipe for its entire length. Gasification of the surrounding coal would occur at the end of each borehole when the oxidizing gas entered through the central pipe. The product gas would leave through the annulus. As gasification proceeded and the voided space increased, filling would be carried out by introducing and suspending an inert fill material in the inlet gas stream, which then would enter the voided space at the velocity of the entering gas. Its momentum would send the material toward the far wall thereby filling the cavity. The expectation is that the filling would reach the roof strata so that it could act as a support. A number of such borehole installations would be installed. As one strip of coal was being gasified, the adjacent strip would be started. The gasification of the entire system then would occur in a staggered fashion.

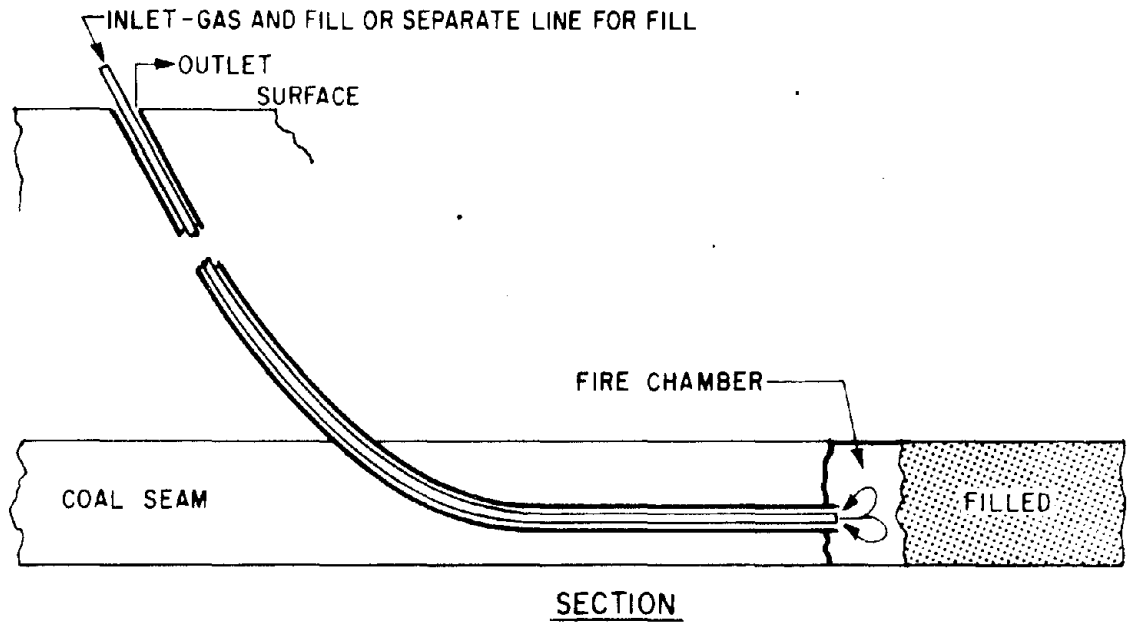
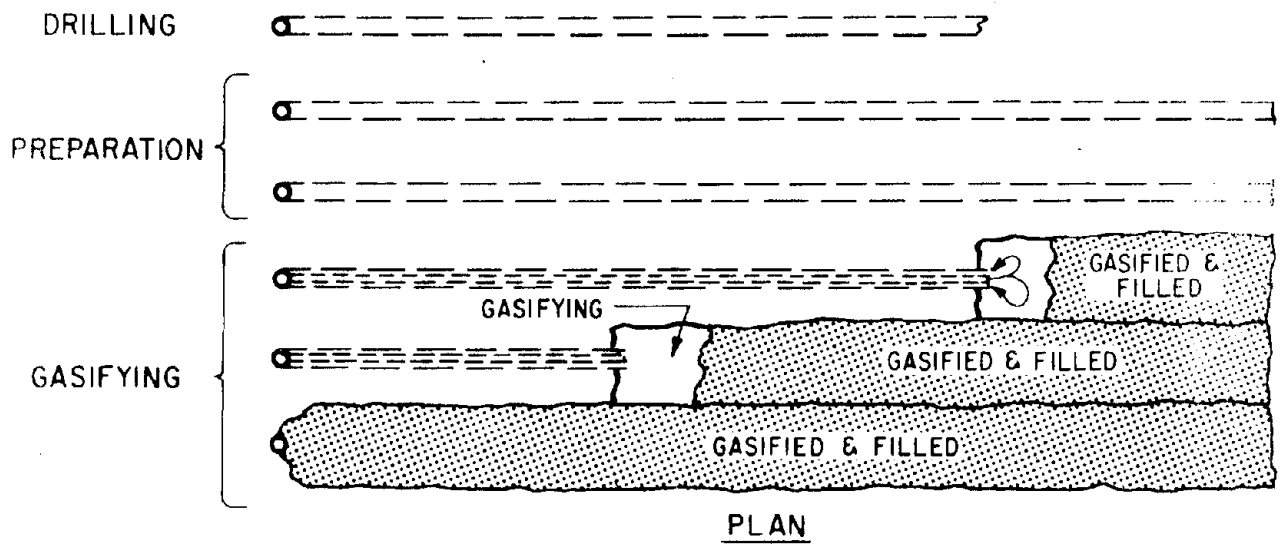
Before such a method could operate successfully, one would need a hole-casing material that would disintegrate at the temperature of the burning coal face and that would resist abrasion by the fill material. Also filling materials would have to be identified and application techniques developed, that would be capable of roof support adequate to prevent collapse. Most importantly, however, an extension of present technology for drilling curved boreholes would be needed to allow the maximum diameter to be increased and travel distances in coal seams to be increased.

For thicker seams, say 10 to 30 feet thick, branching curved holes would be drilled and gasification would take place by a modified streaming method (Figure 24). Separate oxidizing-gas inlets and product-gas outlets would be used instead of annular pipes. As in the case for thinner seams, filling would take place as the reactions proceeded with filling material piling up in the back of the cavity. The development problems also are similar.

For very thick seams, say 30 to 200 feet, or for vertical seams, simple easy-to-install vertical boreholes would be drilled and provided with annular pipes. Filling would be aided by gravity (Figure 25). Vertical holes might be spaced in plan on a square pattern approximately 50 feet apart.

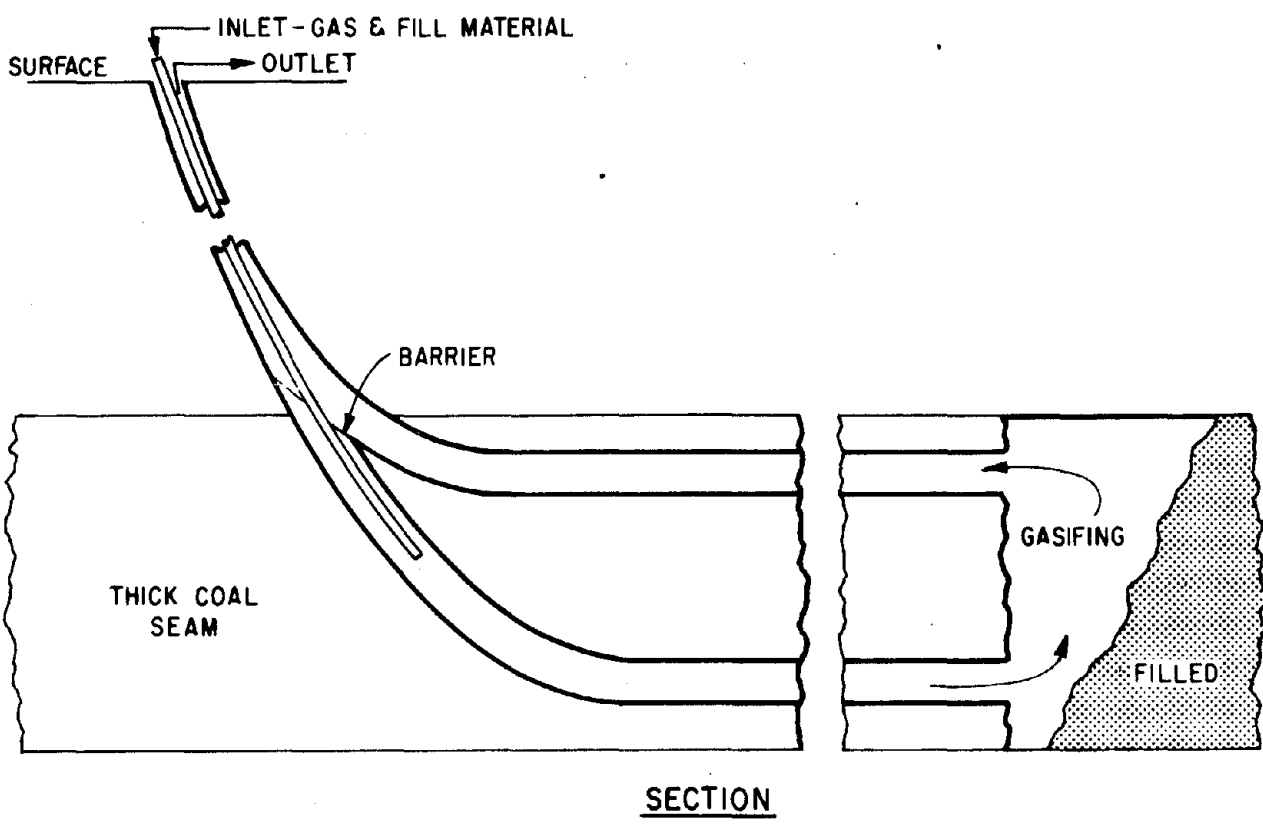
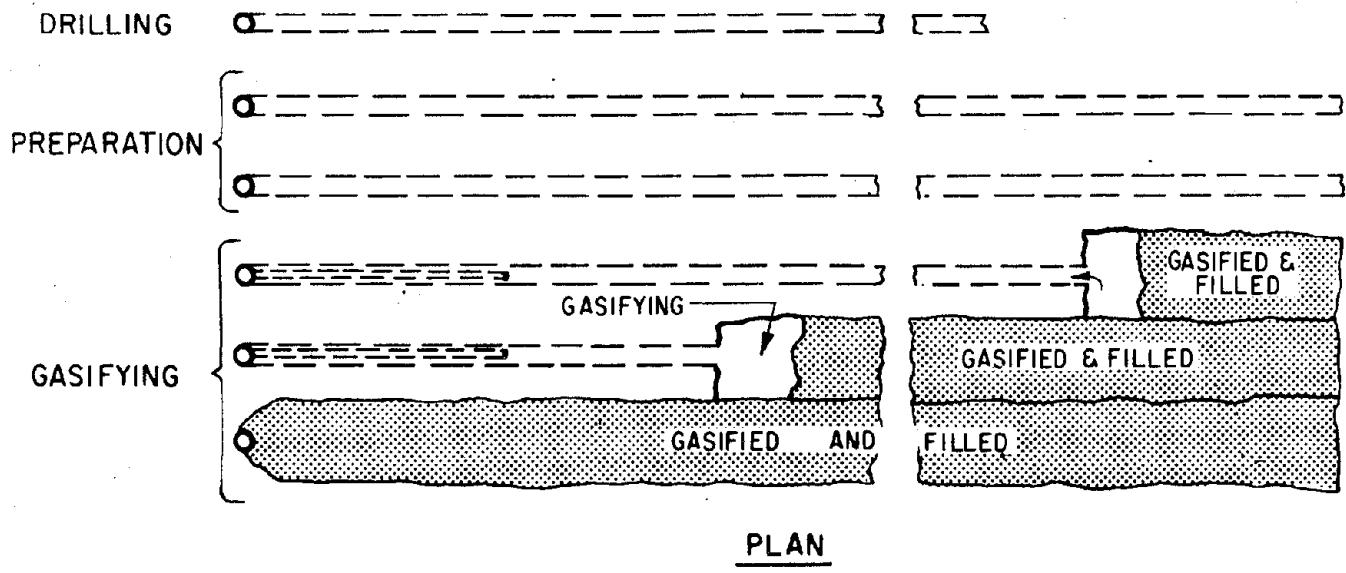
## 2. Shaftless Borehole-Producer Method

Two variations of the borehole producer method are possible, depending on the method of filling the cavity. Both would be applicable to flat and to mildly dipping seams of thickness up to, say, 10 feet.



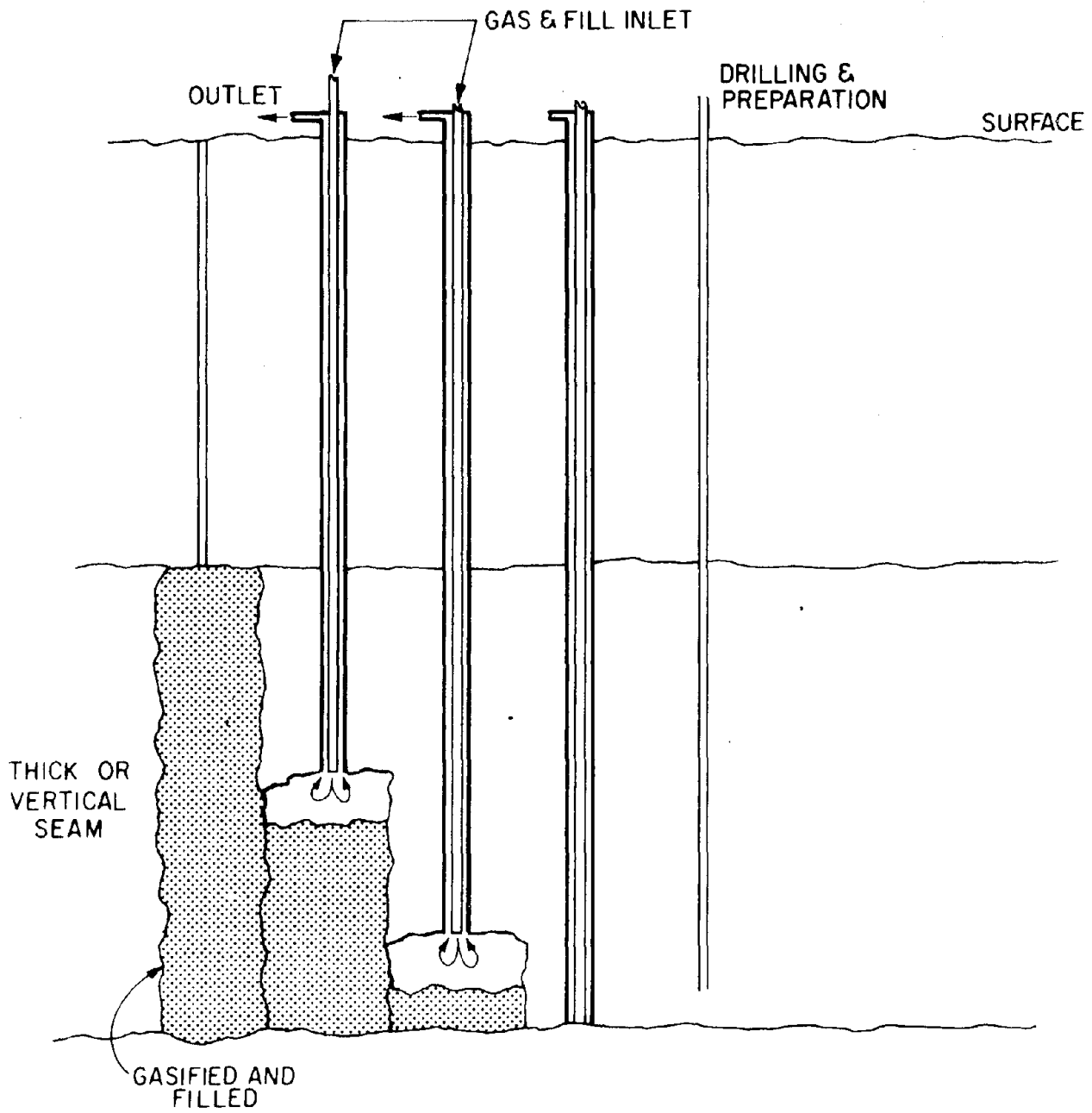
**BLIND BOREHOLE - FILL SYSTEM  
(FOR THINNER SEAMS)**

Figure 23



**BRANCHED BOREHOLE - FILL SYSTEM  
(FOR THICKER SEAMS)**

Figure 24



**VERTICAL BLIND BOREHOLE SYSTEM  
(VERY THICK AND VERTICAL SEAMS)**

Figure 25

a. Two-Borehole, Multiple-Unit, Batch-Filled Method

In the two-hole, multiple-unit, batch-filled method a large number of simple two-borehole systems would be installed and operated in a pattern designed to recover most, if not all, the fuel values in the coal bed. The steps would be as follows:

- (1) Large boreholes (e.g., 14 to 16 inches in diameter) would be directionally drilled from the surface and horizontally for long distances in the seam. A pair of boreholes, perhaps 1000-1500 feet apart, would be joined to form the borehole-producer system. The portion of the boreholes within the strata above the coal seam would be cased to prevent gas leakage and water infiltration.
- (2) The coal between the holes would be ignited and gasified. During gasification, the quantity of oxidizing gas would be continually kept at an optimum level, that is one that corresponds to the continually increasing size of the cavity. The ultimate size of the cavity was to be determined by the size of the boreholes, the coal seam thickness, the pressure and volume of the oxidizing gas, and the level of heating value in the product gas.
- (3) When the cavity reached its maximum size, the reaction would be stopped. At this point the cavity should consist of a completely gasified channel, perhaps 30 to 40 feet in overall width, the sides of which are sections of coked-coal, each section perhaps 8 to 10 feet wide. The roof should be intact, since the voided space opened should not be large enough to cause caving. (See Figure 9.)
- (4) The cavity would now be completely filled through the boreholes with a cement-sand mix of materials having similar properties. The filling technique would still have to be developed experimentally. Drilling of additional small-diameter boreholes from the surface to the cavity might also be required. The filling technique could be a pneumatic method using selected filling materials. A material that expanded as it set would be ideal.
- (5) After the filling had been completed and the material (if a cementing agent is used) had set, the adjacent panel was to be linked and gasified as above. The sequence would be repeated until the entire coal bed had been gasified and the voided spaces filled. This method would provide for recovering the coke left ungasified from the previous operation in the adjacent panel.

#### b. Multiple-Borehole Continuous-Filling Method

In the multiple-borehole continuous-filling method, essentially similar to that proposed by Sears (319), long horizontal holes would be drilled into the coal seam from the surface by directional drilling techniques (Figure 26). A somewhat similar approach was proposed in Russian work for near-surface seams at Kholmogorsk (160).

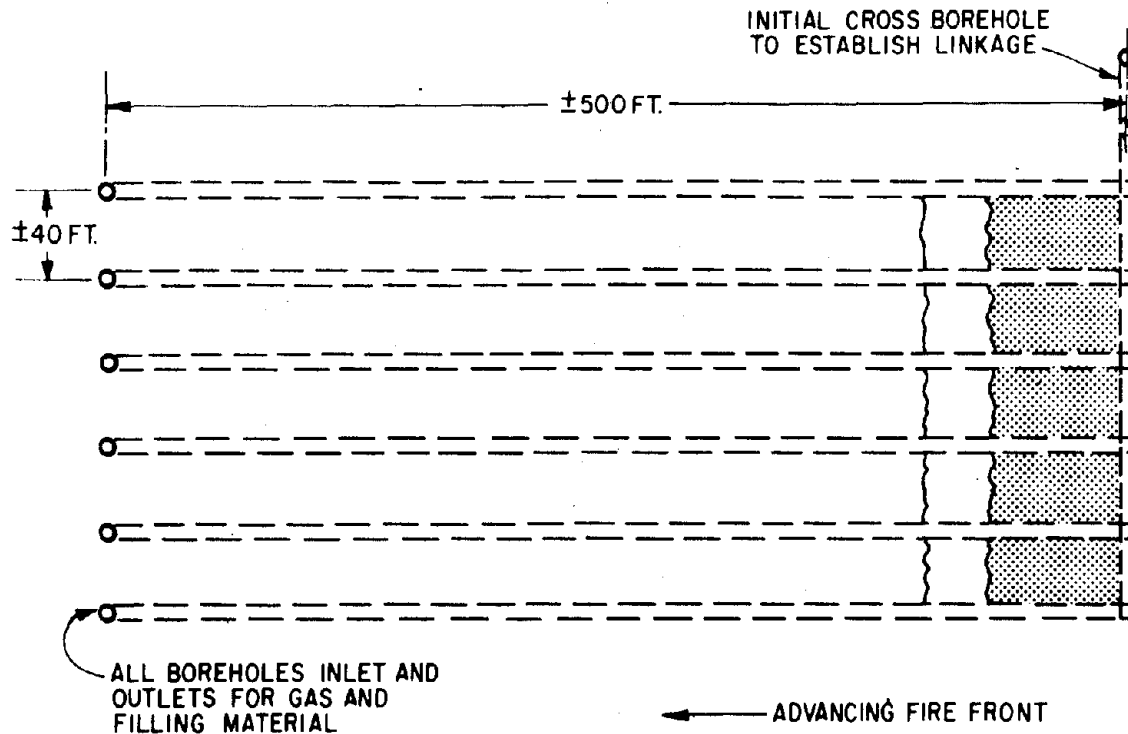
A series of parallel, directionally drilled and cased, boreholes would be prepared, perhaps 30-40 feet apart, and as long as practical (e.g., 500 ft). Positive linkage would be established by drilling one hole directionally in a perpendicular direction to the others such that it intersects a number of the parallel holes near their terminals. For example, some 12 parallel holes could be linked this way by one 500 foot-long cross hole. Alternatively, adequate linkage might be established by simultaneously operating the 12 parallel holes as blind boreholes until the individual cavities joined together. Gasification would take place in a continually advancing broad fire front by selectively using the parallel boreholes as gas inlets or outlets, as required, to keep the fire front under control.

To avoid collapse of roof strata, support would be provided as gasification proceeded by continually feeding filling material suspended in the oxidizing gas as required through the boreholes used as inlets. The amount of filling material suspended would be adjusted to replace the volume of coal burned (less perhaps the volume of ash left behind). The type of filling material best suited to this use would have to be developed. A desirable material might be one that tended to fuse and expand at the prevailing temperature.

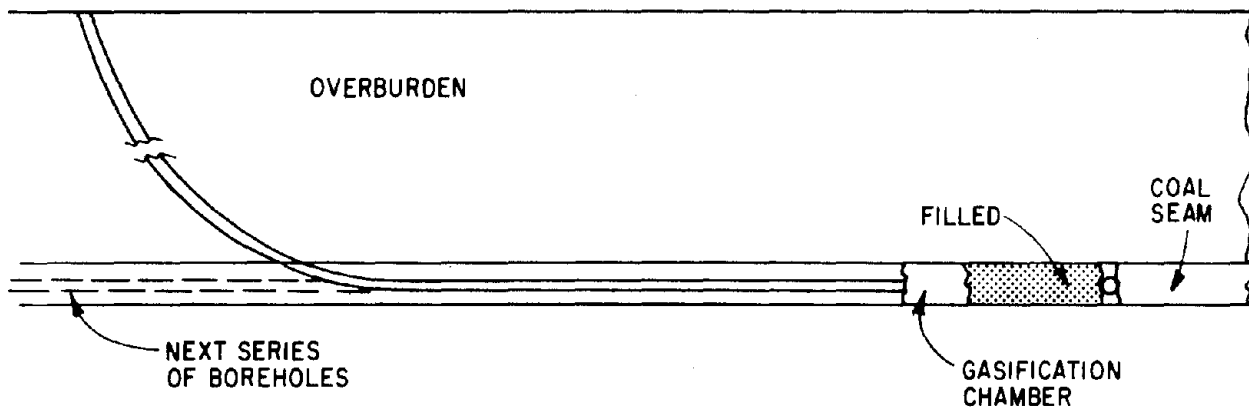
Because of its momentum while traveling in the inlet gas stream, the filling material would have to spray out and away from the fire front and adequately fill the voided space. Proper selection of boreholes as inlets and outlets and control of gas velocities and solids-loading in the gas, should enable the size of the combustion chamber and of gas-coal contact to be controlled, while at the same time preventing roof collapse.

#### c. Shaftless Streaming Method with Stowing

The shaftless streaming method with stowing would be applicable only to sloping seams so that the stowing operations would be facilitated. Ash from the burning coal would fall downward into the voided space as would the stowing materials. The method had been proposed for use in the U.S.S.R. (160), and may actually have been installed and operated there, but probably without the use of stowing for preventing roof collapse and for providing better combustion control.



PLAN



SECTION

**MULTIPLE BOREHOLE - CONTINUOUS FILLING**

Figure 26

Figure 27 illustrates a possible operation on a near-vertical seam. The directionally drilled holes would permit the vertical seam to be developed and gasified with oxidizing gas and fill material introduced and product gas withdrawn through appropriate holes. The filling would be continuous to prevent caving.

### C. TECHNICAL OBJECTIVES

The research and development work indicated for the three candidate methods have in common the following specific technical objectives to be reached for complete feasibility to be established. This listing of the technical objectives represents somewhat of a ranking. As a beginning, no attention should be paid to the second and third objectives unless it becomes clear that the first will be satisfied. Achieving the second and third objectives appears to be about of equal importance. If, at a later stage it becomes evident that achieving all the objectives is not practical for some unforeseeable reason then modifications based on allowing labor working underground in nonhazardous areas during nonhazardous stages of the operation might be considered.

#### 1. Prevention of Roof Collapse

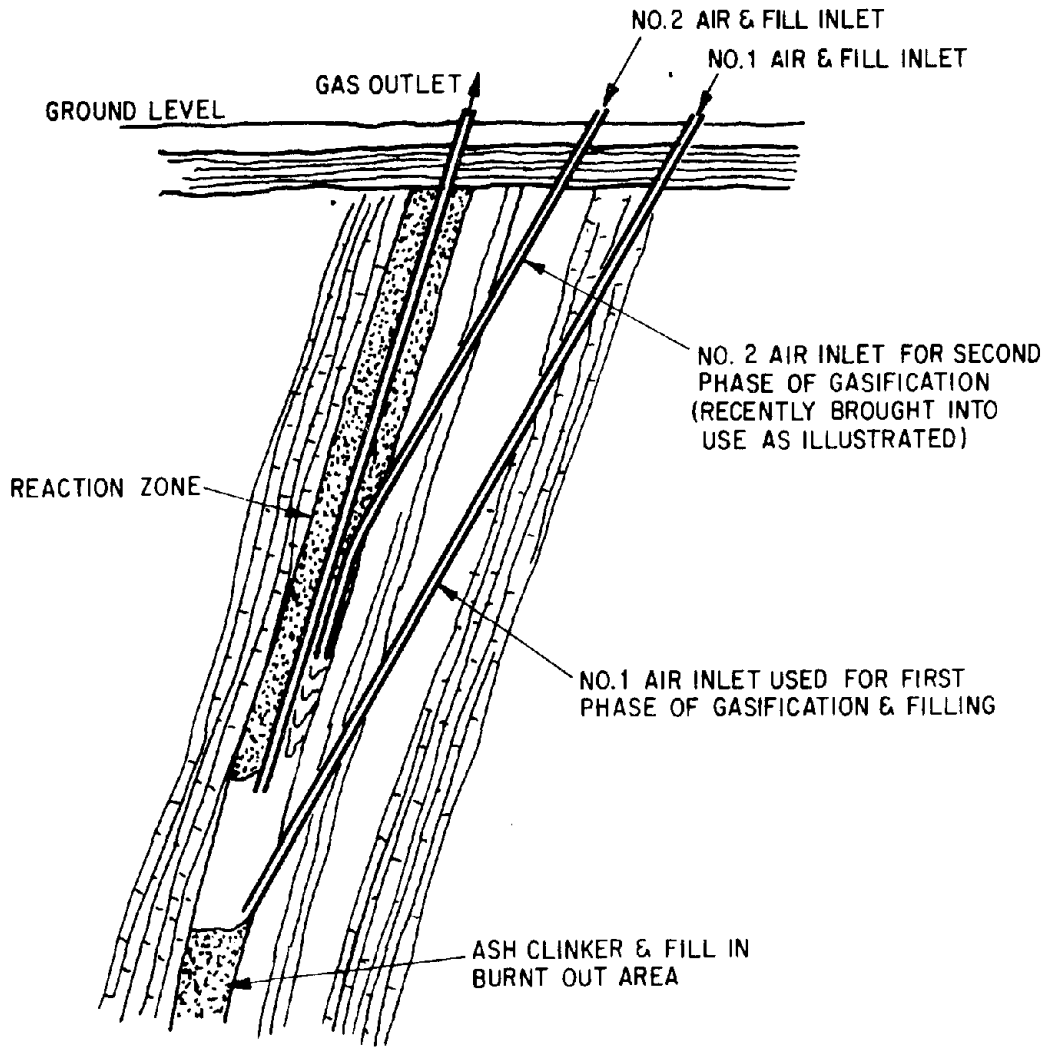
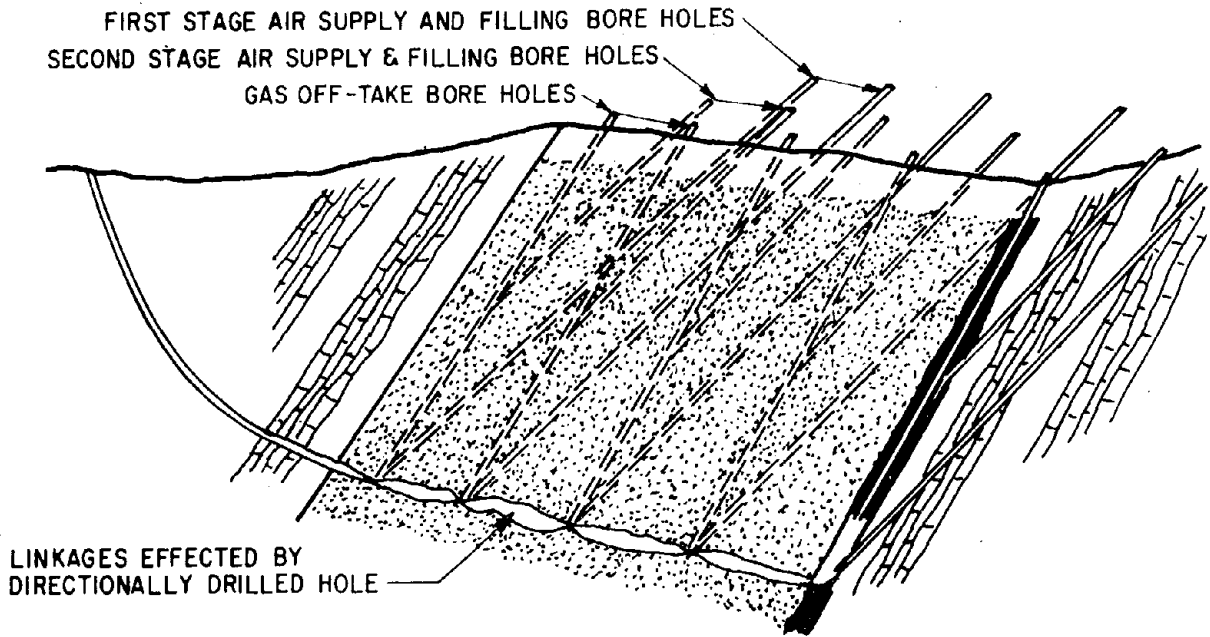
Results must show that positive control of the prevention of roof collapse has been achieved. Control levels would be acceptable when contact between the coal face and the gasification agent could be maintained to the extent that desired heating-value levels in the product gases would be consistently achieved. At such control levels, also, there would be a maximal probability that leakage of gases out of the system and leakage of water into the system from adjacent aquifers would not occur at intolerable rates.

#### 2. Knowledge of Burning-Face Position and Temperature

Results must show that the position and temperature of the burning-face can be reliably estimated. Such estimates could then be compared with predictions of the burning-face positions and temperatures desired to maintain acceptable product-gas quality, product-gas quantity, and recovery of coal values.

#### 3. Control of Operations

Results must show how to incorporate control devices in installations that can be adjusted to eliminate differences detected between estimates and predictions of burning-face locations and temperatures.



SHAFTLESS STREAMING METHOD WITH STOWING

Figure 27

## D. RESEARCH AND DEVELOPMENT PROGRAMS

Table 6 lists the research and development programs that should fit the development needs of the candidate underground gasification methods. The list is comprehensive in that not only does it contain programs aimed at achieving the desired technical objectives, but also it indicates relevant programs and notes the need for work on them at this time.

Table 6 shows that the focus of the work we have recommended is on directional drilling and gasification with continuous stowing, which we believe to be the preferred approach. However, one should also consider electrolinking, hydraulic and pneumatic linking, and explosive shattering techniques as potential backstop linking methods.

### 1. Control to Prevent Roof Collapse

The obvious approach to the work is to control either by completely preventing roof collapse or by allowing only such roof collapse occur as would not adversely affect operations. The latter approach appears difficult to achieve. Even if successful, it still could permit gas leakage, water infiltration, and ground surface subsidence. Thus, attention should be focused on the former approach.

The basic technique should involve filling voided spaces to provide structural support for the roof strata, adequate to prevent collapse, and probably also to prevent sag that could disturb aquifers or open gas escape passages. Two programs to establish and develop such techniques follow:

- Acquire knowledge of the maximum unsupported span of overlying strata beyond which collapse is certain. Such an effort would be largely a research and evaluation of available data on the geology of coal deposits and the structural properties of adjacent overlying strata.
- Determine how to prevent roof collapse and develop new or improved techniques to be used particularly when roof collapse is judged to be imminent. The Bureau of Mines is currently reviewing the state of the art of stowing techniques. Many of the results, expected to be available in early 1972, should be applicable.

### 2. Burning-Face Position and Temperature

The research and development work should involve only the selection of the type of signals to be detected that can be shown to be best suited to the candidate methods, and to the development of data processing techniques that can provide

**TABLE 6**  
**CANDIDATE RESEARCH AND DEVELOPMENT PROGRAMS**

Program	Description	Should Work Be Done at this Time?
Explosive Fracturing		No
<b>Linking</b>		
Electrical		No
Hydraulic		No
Pneumatic		No
Laser Drilling	Aim at yes/no answer only	Yes
Conventional Drilling		Yes
	(a) Directional drilling curved large-diameter boreholes (14-16") for long horizontal distances (1000') in coal seams.	
	(b) Casing and scaling techniques for curved large-diameter holes.	
	(c) Study feasibility and identify methods for drilling branch holes into top and bottom of thick coal seams for a curved hole.	
<b>Roof Control</b>		
Prevention of Collapse	(a) Nonexperimental review study of existing knowledge to determine for different types of coal seams, the maximum size of underground opening before it will collapse.	Yes
<b>Solid Stowing Techniques</b>	(b) Wet and dry stowing techniques through boreholes*	Yes
	(c) Identification of appropriate stowing materials, e.g., sand, clay, fly ash, rock, cemented sand fill and sand and lime.	
	(d) Potential of solid foams and resins for final filling, or in admixture with fill materials noted above.	Yes
	(e) Development of a stowing material that becomes sticky at the temperatures prevailing.	Yes
	(f) Development of a continuous stowing system.	Yes
Controlled Collapse of Roof		No
<b>Combustion Conditions and Control</b>		
Selection of Oxidation Gas Composition	(1) Study temperature-measurement techniques	Yes
Coal Recovery and Process Control	(2) Research on methods of determining shape and location of fire face, and progress of reaction. Includes acoustic, seismic and conductivity techniques.	Yes
Leakage	(3) For areas where leakage may be a problem, it may be desirable to study grouting and chemical scaling techniques. Also for areas where groundwater pollution may occur.	Possibly

\*The Bureau of Mines expects by March 1972 the completion of a review of stowing practices as used in conventional underground coal mining. The results of this review could provide a basis for planning this work. A review of the technology of pneumatic solids transport (Bureau of Mines, IC 8314) could be pertinent to placement work.

the estimates of burning-face position and temperature quickly and reliably. Both of these estimates might be possible from only temperature measurements.

### 3. Control of Operations

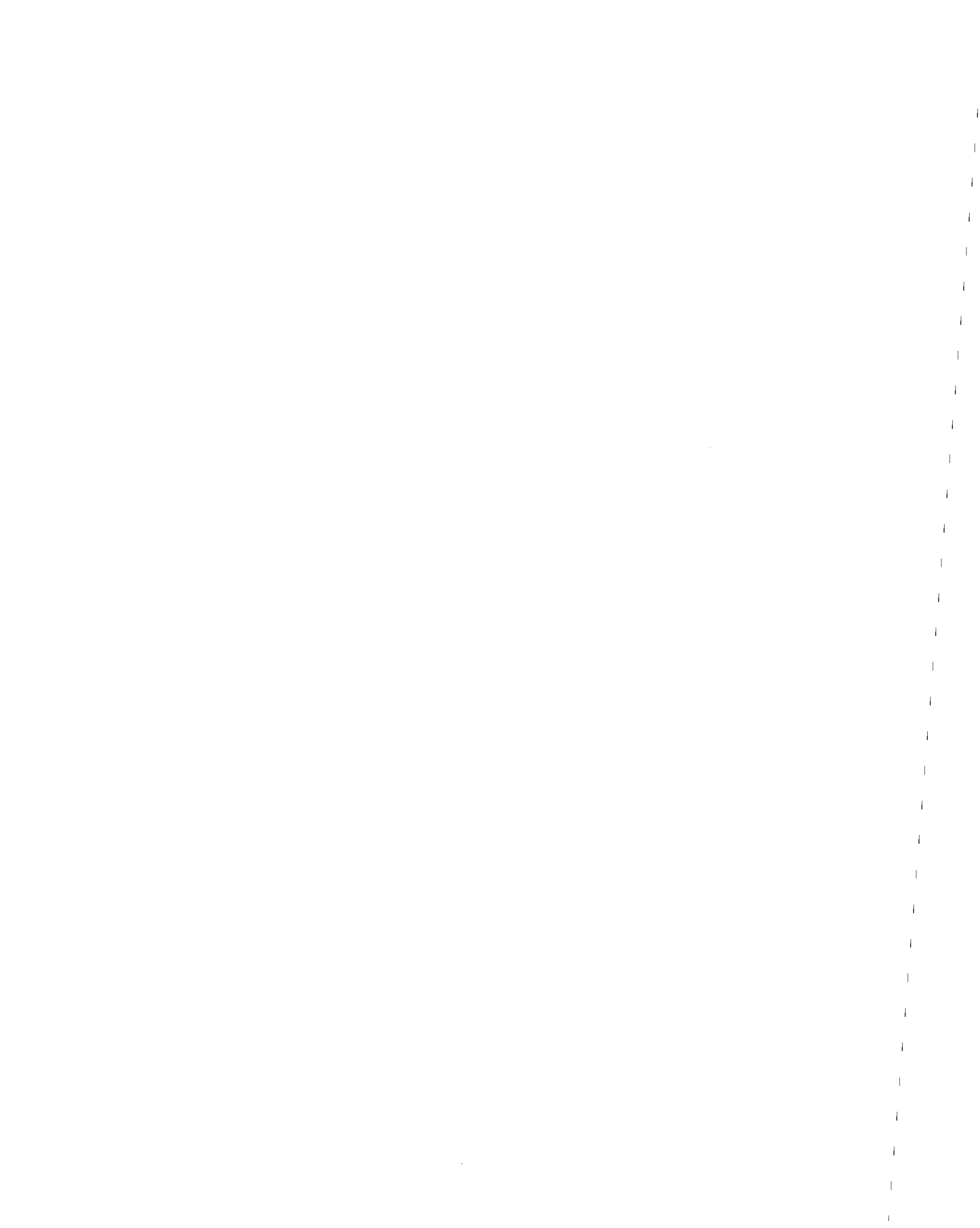
Two approaches to control operations so that of burning-face position and temperature may be reconciled with predictions are:

- *Leakage Prevention.* Work to reduce or eliminate undesirable effects by developing sealing techniques to prevent outward leakage of gases and the inward leakage of water, which are still possible when roof collapse is prevented.
- *Flow and Pressure Regulating Devices.* Little work appears necessary in this area, since devices are readily available and can be provided for in strategic locations when an underground gasification installation is designed. Some experimentation with unusual devices may be warranted as part of experimental installations, however.

### 4. Recycle of Carbon Dioxide

A major reason for erratic and low product-gas heating values is erratic CO<sub>2</sub> content. The heating value of the gas can be stabilized and increased by removing its carbon dioxide content before its utilization, especially when oxygen rather than air is used as the source of oxidant in the gasifying agent. If the recovered CO<sub>2</sub>, instead of steam, is then recycled to the coal with the oxygen two benefits are possible. that is:

- External water requirements are reduced, of probable importance in the western United States.
- Product gases become richer in carbon monoxide. If experimental work shows that such product gases can reach the surface with little or no reversion to carbon dioxide occurring underground through the reaction  $2\text{CO} \rightarrow \text{C} + \text{CO}_2$ , then this reversion might be induced above ground on dust-free gas. The carbon could then be produced as a fine powder, ash and sulfur free. In such a form it could readily be transported to markets as a potential non-polluting boiler fuel. Alternatively, since the nitrogen content would be low, product gases could then reach heating value levels approaching 300 Btu/SCF (Table 5), with little fluctuation even if fluctuations in the CO/H<sub>2</sub> ratio are substantial.



## VI. THE NEXT STEP FOR UNDERGROUND GASIFICATION

### A. SUITABILITY OF U.S. COAL DEPOSITS TO UNDERGROUND GASIFICATION METHODS

Many coal seams in many of the United States probably could be underground gasification candidates. The selection of the most attractive projects would depend upon not only the geographical locations but on many factors, such as the type of coal, its ash content, the seam thickness, the dip of the structure, the presence of faults, the surface topography, the nature of adjacent strata, the presence of partings, and the presence of methane. (See Appendix D for a general description of U.S. coal deposits.)

#### 1. Type of Coal

It is obviously undesirable to gasify coals that could be used for making metallurgical coke. Such coal must be brought to the surface in a solid form, unaltered in character, in order to satisfy present blast-furnace technology and practice. Any other use would be an inferior use of a valuable resource.

In general, most coals in the eastern United States have coking properties, although many areas, such as in Illinois and Indiana, may have non-coking coals. Most western U.S. coals, on the other hand, are lignites, sub-bituminous coals, or high-volatile bituminous coals generally unsuitable for coke making, although some 20 locations in the western states have deposits of coking coals.

Anthracites and semi-anthracite coals are non-coking, and deposits in eastern Pennsylvania and in a much smaller area in Arkansas are possible candidates for potential underground gasification operations.

#### 2. Ash Content

A factor that should enhance an underground gasification application is the ash content of the coal. It should be preferable to utilize high-ash coals by underground gasification since the ash would then be left underground. In general, most United States coals have ash contents of 5-10%, as, for example, the Montana and North Dakota lignites. However, some coal beds in many areas have higher ash content. For example, the coal in the Merrimac seam in Montgomery County, Virginia, contains 15-25% ash, and several seams in Alabama's Plateau field contain around 20% ash.

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### 3. Seam Thickness

It is probably more attractive to gasify a thick seam underground than a thin one, since in a thicker seam more coal is made available per drill hole. The thicker seams occur in the western States, namely: Wyoming, Colorado, and Utah. Thin seams, however, increase in importance when the resource becomes depleted, as was the case in the Belgian work.

### 4. Dip of the Structure

The dip of the structure and coal seam could have a bearing on the particular gasification technique used. For example, steeply dipping seams would be amenable to the shaftless streaming-method with stowing. Steeply dipping beds can be found in many areas, but the best prospects again are in Wyoming and Utah.

### 5. Faulted Areas

Areas where faulting and fracturing is prevalent in the structure are to be avoided, since leakage is likely to be extensive and uncontrollable. The underground gasification of the coal remaining (as pillars, for example) in old mined-out areas is probably also to be avoided, since in such areas the ground has often caved.

### 6. Surface Topography

The nature of the surface topography would affect the ease and cost of development work, drilling holes, and surface installations. In this respect, areas in Illinois, Ohio, and Indiana should attract large-scale underground gasification. Reasonably thick, uniform, persistent, non-faulted or folded coal seams underlying extensive relatively flat surface areas occur at reasonable depths below the surface. Deeper beds, in general, permit higher gasification pressure levels to be used without the risk of excessive leakage.

### 7. Nature of Adjacent Strata

The rock strata enclosing coal seams may be of some importance, although little is known about the effect of gasification temperatures on rocks in general, and on the immediate roof rock in particular. The common rocks involved in adjacent strata are shales, slates, clays, sandstones and occasionally limestones. Limestones occur directly above coal seams in some places in Illinois, in Oklahoma, and probably elsewhere. Limestones are unique since they should decompose to some extent in gasification and form  $\text{CO}_2$  and  $\text{CaO}$ . This may be beneficial since  $\text{CaO}$  may absorb some of the sulfur content that may exist in the gases underground, and also may assist in providing a stable fill for voided spaces. The generation of  $\text{CO}_2$  from the limestone should not be detrimental.

## 8. Partings and Multiple Beds

Another factor is the presence of partings in coal seams. Almost all coal seams, regardless of location, contain partings of inert material which may influence gasification procedures and operations. Partings can be thin, in which case they would only break up and fall to the floor during gasification, or thick (say several feet or more), in which case they could stop the reaction. Special techniques would then need to be developed to handle the problem.

Ultra-thick partings are more precisely multiple-bed coal deposits. The appropriate method would depend on the separation distances between beds. The methods might have to be modified should several beds be gasified simultaneously.

## 9. Presence of Methane

Methane is present in varying amounts in almost all coal seams, but it is generally more prevalent in the higher rank coals. In gassy mines (defined by the Bureau of Mines as those having over 0.25% methane in the return airway) there can be substantial amounts. For example, amounts of 1750-3500 cubic feet per ton of coal mined are known, and a large mine can generate 5 to 20 million cubic feet per day.

Methane can be drained and substantial amounts recovered before mining (usually using boreholes). Not much attention has been given to this potential in the United States, but in Europe in the 1950's some 60 mines practiced methane drainage. The outstanding example was in Belgium, where 13 mines produced 7 million cubic feet of methane per day, thus satisfying 12% of the domestic gas needs of Belgium at the time.

With existing gasification technology, methane content would probably not add to the heating value of the gases produced by underground coal gasification. But, a large number of large-diameter holes drilled for long distances into a coal seam present an ideal opportunity to recover methane by drainage prior to gasification. Methane could be produced as a separate product, or in admixture with the product gases to boost its heating value.

From the viewpoint of eliminating a hazard, gassy coal seams are, of course, more attractive candidates for underground gasification than for conventional underground mining.

## B. THE DECISION FACTORS

The need now is for decision, i.e., whether or not to let the underground coal gasification technology already available continue to lie dormant and accordingly seek to utilize this U.S. coal energy resource in other ways. If the decision should be to rekindle interest and begin new activity, what should the nature of this activity be and what level of effort should be expended on it? A number of factors bear upon such a decision for the United States.

### 1. Elimination of Hazards to People

Since underground gasification of coal is a substitute for bringing the same coal to the surface, the technology eliminates the hazards to the health and safety of the personnel who would otherwise work underground at the coal face. The minimization and regulation of such hazards has been the subject of recent federal legislation, and enforcement has contributed to increases in the production cost of coal mined by underground methods. It is probably too early to assess whether the new legislation can eliminate the hazards entirely, as would be the case if the shaftless underground gasification methods already described as candidates were applied instead.

### 2. Elimination of Hazards to the Environment

Environmental hazards arise from the methods in which coal is mined conventionally, whether by open-pit or underground installations, and from the way coal is conventionally utilized.

Underground gasification produces a gas product which could readily be treated to remove particulates and its sulfur content (Figure 1). Environmentally, then, the treated gas would perform the same as natural gas. Coal itself, however, after combustion in furnances retains residual problems of particulate and sulfur-oxide emissions in stacks.

Waste dumps result from the coal-washing process and contain noncarbonaceous materials unwanted in the coal. These dumps can become quite large, unsightly and hazardous in populated areas. In underground gasification, such waste would remain underground. Moreover, the candidate underground gasification methods would need a filling material which would have to come from the surface. Old waste, fly ash, or other dumped materials, might be acceptable. On the other hand, if such materials are lacking, fill might have to be mined and processed, which could create other environmental problems.

Both conventional underground and surface coal mining methods cause substantial damage to the land. Disruptive damage from open pit and strip mining

of near-surface coal seams is well known. An alternative to gasify such seams underground would eliminate the threat of unsightly abandoned strip pits and disruptions during mining and surface reclamation operations.

Underground gasification would eliminate conditions where uncontrollable and unwanted underground and waste-pile fires could occur. If the candidate methods are to be practical at all, subsurface combustion would be under positive control at all times.

The candidate methods for underground gasification should produce little or no effect on the hydrological character of the strata. The burned-out coal seam will have been filled with probably a low-permeable fill material. The combustion should have been total, leaving little sulfur in the ground. On the other hand, inducing high-temperature combustion conditions could cause heating of aquifers, otherwise unaffected, and an increase in dissolved mineral salts.

Because of emphasis preventing roof collapse, no ground subsidence at all should be experienced with underground gasification, if successful filling techniques are developed. This contrasts with the practices in conventional underground mining, where roof collapse is sometimes deliberately induced in order to achieve high coal recovery.

### 3. Coal Recovery

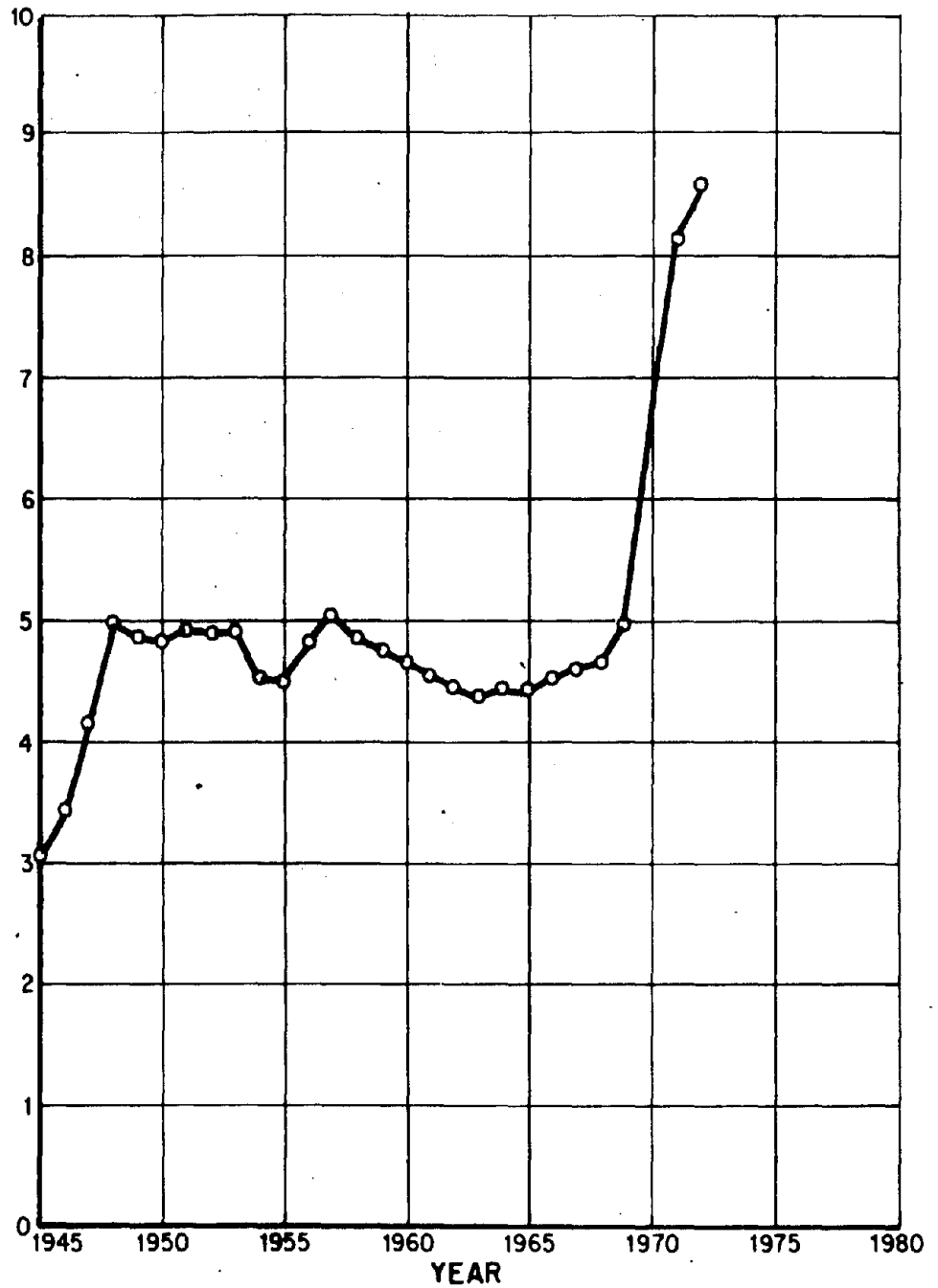
A successful development of the candidate underground gasification methods should result in the recovery of substantially all of the fuel values in the coal in the seam. A recovery in the order of 90% appears reasonable. This would compare with an order of recovery of 60%, which is the current experience in the United States.

### 4. Price of Coal

A review of coal price trends over the post World War II period shows that, for the first time in twenty years, there has been a major rise in the average price of bituminous coal (Figure 28). For spot prices (Figure 29), the 50% increase that took place in 1970 should not be repeated. Instead further, but smaller, increases should be experienced in 1971 and in 1972.

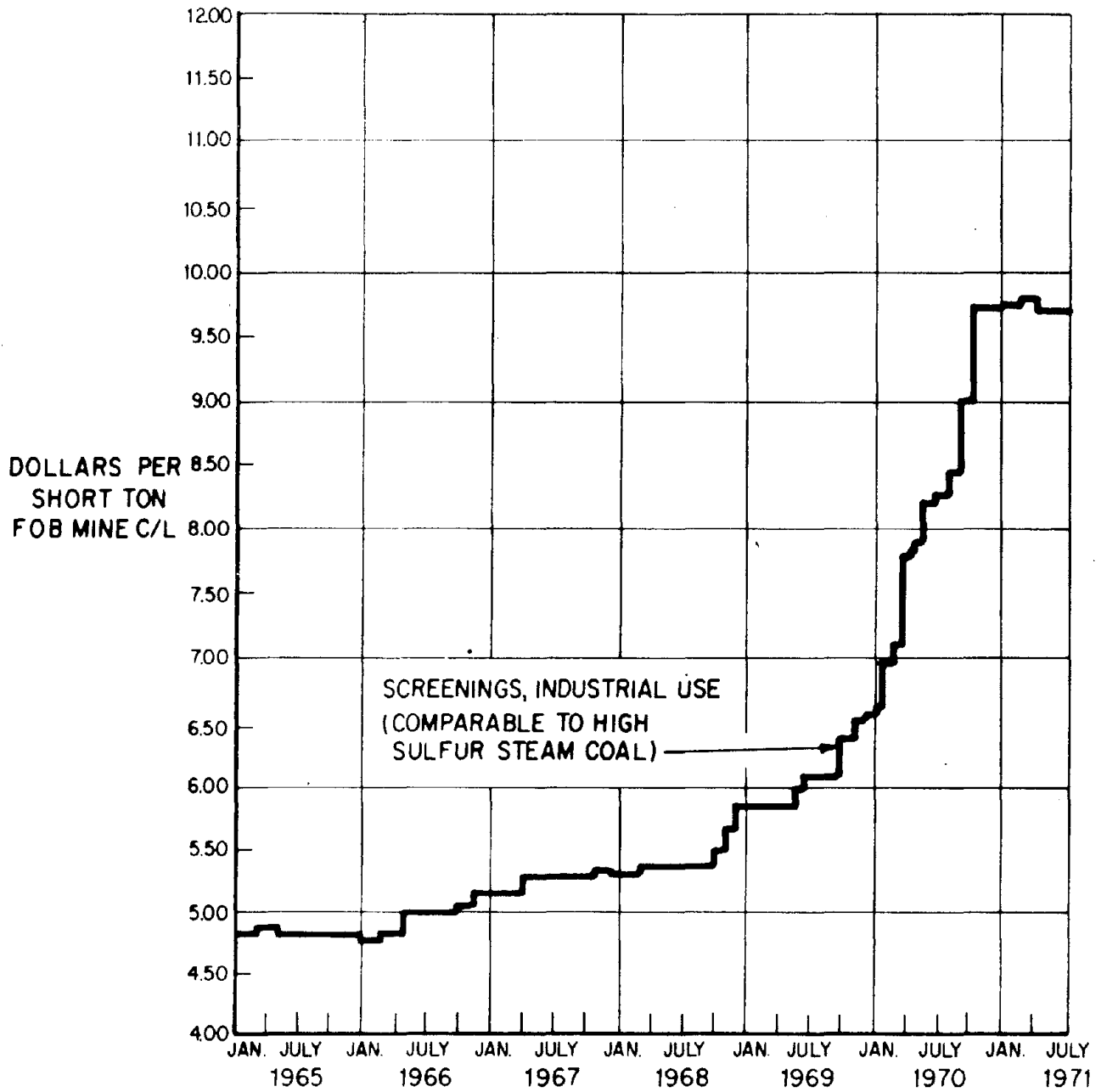
The rise in prices immediately after World War II largely reflected the inflation experienced at that time. While costs of labor and material rose steadily during the fifties and sixties, increases in productivity permitted the coal industry to survive despite a general softening in coal prices due to a shrinking market. In any event, the coal companies were not making much money.

BITUMINOUS COAL  
AVERAGE VALUE  
\$ per net ton f.o.b. mine



SOURCE: 1945-1969 U.S. BUREAU OF MINES,  
1970-1972 ARTHUR D. LITTLE, INC., ESTIMATE

VALUE OF BITUMINOUS COAL, 1945-1972  
Figure 28



SOURCE: U.S. BUREAU OF LABOR STATISTICS

SPOT PRICE TRENDS—U.S. BITUMINOUS, FOB MINE, 1960-1971  
Figure 29

In late 1968, however, a number of events set in motion a basic change in the coal industry. The Farmington mine accident accelerated the enactment of the Mine Health and Safety Act. The production of coal fell behind the growth in demand, particularly of the electric utilities; and the Japanese demand for metallurgical coals became significant in the marketplace. At the same time the rate of increase in productivity slackened, particularly in underground mines. All these factors helped to bring about the resulting price rise. Thus, compliance with the Mine Health and Safety Act, faltering productivity, and the surge in inflation were the major cost-push factors; while the entrance of the Japanese into the market, plus the apparent shortage of steam-coal (and of all fuels), were market-oriented factors that permitted the coal companies to pass on their rising costs and, in addition, improve their profit margins after many lean years.

Currently the supply is more in balance with demand so that future increases, at least over the next few years, will reflect continued increases in production costs, not market conditions. In fact, spot prices will probably begin to decline below long-term contract prices, returning to the situation that existed during the earlier sixties, when contract prices were higher than spot prices. During the seventies, however, large tonnage consumers of coal will cover a much larger portion of their requirements with long-term contracts than they did in the sixties, when they played the spot market. They cannot afford any longer to risk a discontinuity of supply.

##### 5. Share in the Rising Energy Demand

The United States is finding itself facing an increasingly-severe problem of finding new energy supplies to meet growing demand.\* The U.S. reserve of coal is one of two major domestic energy sources (oil shale, of course, being the second) but its potential contribution to bridging the gap between energy supply and demand is limited by a number of factors, particularly those involving environmental effects and stringent safety requirements in underground mines.

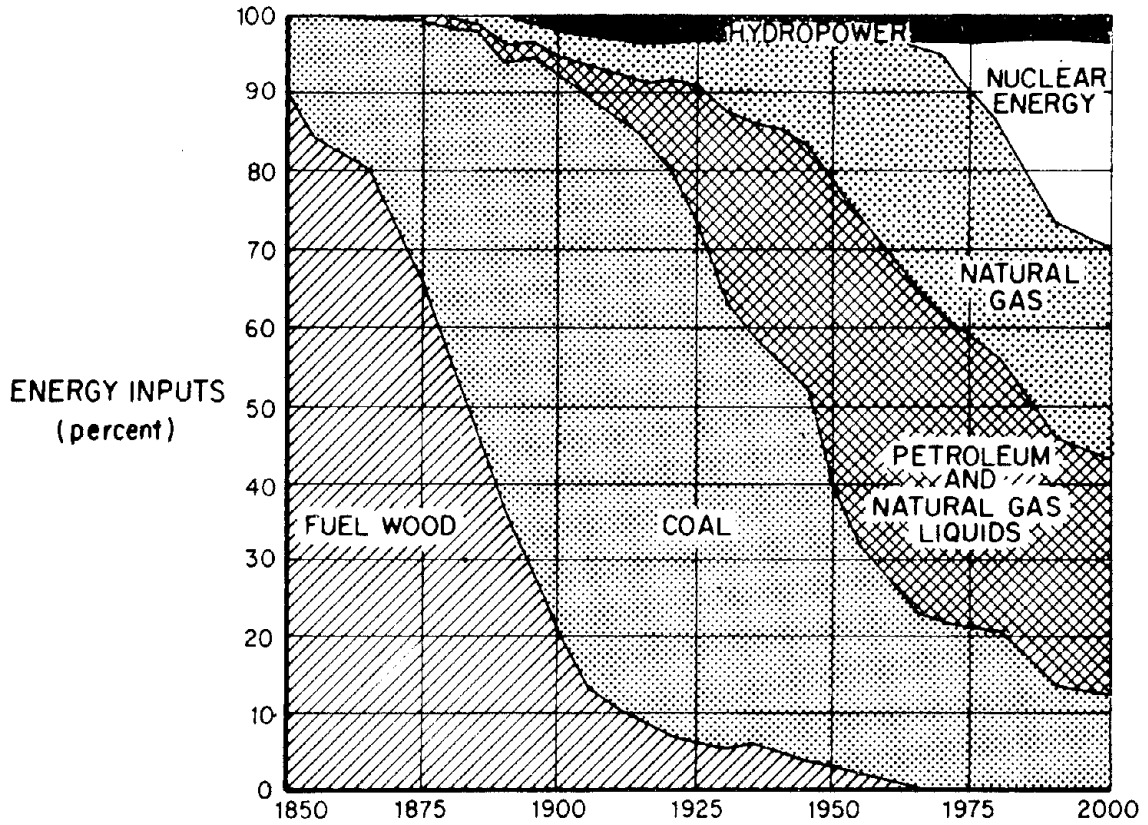
Figure 30 summarizes the proportions of projected increases in U.S. energy consumption in terms of population growth, through projection of past trends for the 200-year period, 1800-2000. The sources of supply for past and future demand, are summarized in Figure 31. Although the basis for the projections

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\*For example, see:

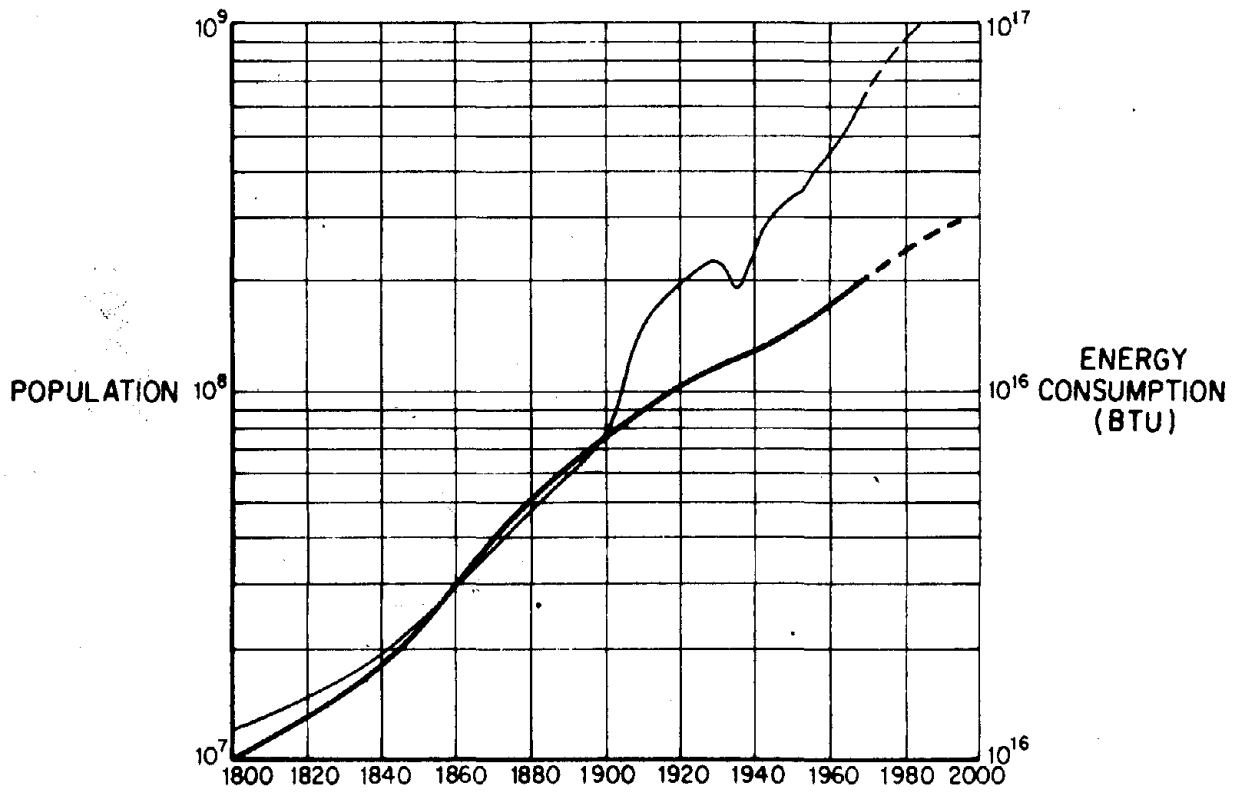
*U.S. Energy Outlook, An Initial Appraisal 1971-1985, Vol. 1, Interim Report of the National Petroleum Council to the U.S. Secretary of the Interior, July 1971.*

*Energy Policy Issues for the United States During the 70's, Arthur D. Little, Inc., prepared for the National Energy Forum for the National Division, the United States National Committee, World Energy Conference, July 1971.*



ENERGY CONSUMPTION AND POPULATION TRENDS  
IN THE UNITED STATES, 1800-2000

Figure 30



**COAL'S SHARE IN ENERGY SUPPLY IN THE UNITED STATES, 1800-2000**

Figure 31

shown in both figures can readily be questioned and argued, less arguable is the forecast of rising energy demand and the reduced share for coal in the total supply.

The significant observation is that the United States is not entirely self-sufficient in the energy sources that are alternatives to coal. It relies heavily on imports of petroleum and the indications are that it will rely more on imports with respect to natural gas supplies in the near future. The U.S. probably cannot support growth of nuclear power generation from domestic uranium sources without the introduction of successful breeder reactors on a large scale. The decreasing share of the U.S. energy market for coal is no doubt the result of the factors already discussed. Whether, or not, technically successful large-scale underground gasification can be introduced to alleviate this decrease would depend in large measure on the competitiveness of the technology to produce marketable energy from coal in comparison with alternative energy sources and conventional coal extraction.

### C. COMPETITIVENESS OF THE TECHNOLOGY

#### 1. Previous Work

Costs for underground gasification have been estimated and discussed in a number of papers (48, 49, 50, 56, 70, 71, 101, 135, 154, 160, 181, 219, 245, USBM-594, USBM-630, USBM-395, USBM-398, USBM-401, USBM-419). The principal ones are the works of Katell and Faber (135), Bakulev (71), Orna (56) and the British work (160).

Katell and Faber (48) in 1961 estimated the cost of underground gasification, using as a basis the USBM work at Gorgas. They compared hydraulic fracturing and electrolinking gasification systems using boreholes. For a three-foot coal seam 200 feet deep with a 1¢ power cost, their cost estimates were 62.1¢ per million Btu for the electrolinking system and 77.1¢ per million Btu for the hydraulic fracturing system. The main reason for the difference in costs was the 38% thermal efficiency\* used for electrolinking and the 15.8% thermal efficiency used for hydraulic fracturing. The costs were based on producing a gas of 100 Btu/ft<sup>3</sup> heating value using air only for gasification, and to supply energy for a 60,000 kw power plant.

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\* Thermal efficiency in the sense used here is the percentage of the heating value of the coal gasified in situ that appears as heating value in the gases resulting from its gasification.

In 1960, Bakulev (71), reported on Russian methods and costs. The production cost was reported in local currency and seemed to be the equivalent of about \$10 per million Btu for the Moscow region plant in 1955. For several new plants, the projected production cost was estimated in local currency to vary between the apparent equivalent of \$1.33 and \$3.14 per million Btu. In 1961, Orna (56) estimated the costs of gasification in Czechoslovakia for various coal thicknesses and depths. For average conditions, he estimated in local currency the apparent equivalent of about \$1.75 per million Btu.

More useful seems to be the British estimate of costs for a commercial-sized plant which was based on their successful P-5 run (160). For a plant to provide  $148 \times 10^6$  therms (1 therm = 100,000 Btu) per year using a combination underground-gasification method, the cost estimated for a specific coal deposit at Newman Spinney was 3.42 pence per therm, equivalent to 40¢ per million Btu. This value is lower than the Katell estimate and the difference may be explainable by the high coal recovery obtained in the British operations. The British used an efficiency of 60% for the purpose of the estimate.

The British cost estimate is now about ten years old. It was based on various assumptions and conditions that may not necessarily be valid today. But it is the one item of cost data of some value in that it is production-oriented in origin, i.e., it represents an indication of a cost of production of gas from underground gasification that has been based on a technically sound set of operating data from a specific installation.

## 2. Coupling Electricity Demand to Underground Product-Gas Energy

Another approach at costs for underground gas is market-oriented, i.e., calculations are made in a backward sequence from the marketplace conditions for marketable energy until a value can be placed on the underground gas in terms of its potential selling price.

We took such an approach using the coupling system shown in Figure 1 and the supply of electricity demand from the product gas. The results of our calculations are shown in Table 7. The calculations are based on data from various sources and on a number of assumptions and these are summarized in Tables 8 and 9, and in Figure 32. The method of calculation should be clear from study of Table 7 and the explanatory notes incorporated.

Briefly, we postulated the price a hypothetical utility management, operating the facilities shown in Figure 1, should be willing to pay for clean, desulfurized gases leaving the gas treatment section at the underground gasification site (Figure 1). We estimated such a price on two bases, depending on how we used judgment to resolve doubt generated by lack of data or information. In Case 1, we were optimistic. Our judgment decisions were made in a way that tended to

POTENTIAL SELLING PRICE RANGE FOR UNDERGROUND PRODUCT CASES  
ELECTRICITY PRODUCTION MODEL

pressure of the steam blast. We selected the first set of data tabulated in Table 8 for the water-gas operation as the basis for estimating the gas analysis after treatment and removal of carbon dioxide. CO<sub>2</sub> removal might be useful to reduce size of equipment. We prorated the product-gas heating-value in proportion to the volume changes when the CO<sub>2</sub> is removed. For Case 2, we estimated the gas composition on the average analysis reported in Table 8 using air in an unidirectional flow for gasification. We estimated product-gas analysis and product-gas heating value from these data in a similar fashion.

C Electricity cost allows for costs of complying with restrictions on chimney emissions and waste-heat dissipation for conventional generation units at market centers. Basic data is Figure 32. Assumption for Case 2 is that inflation will have wiped out indicated generation cost saving projection for 1980. The 1970 data in Table 9, which recognizes the potential of the nuclear power alternative is included for comparison. A 25% contingency is added for Case 1 to allow for more stringent environmental controls now becoming more evident and the AEC's recent (1971) shift to passivity with respect to environmental impact statements for new nuclear power facilities.

C-1 The entry shows the value, based on a postulated bus-bar electricity cost, of the electricity quantity equivalent to 1 million Btu of energy in the form of electricity. The conversion is: 3413 Btu's of energy in electrical form is identical to 1 kwh. Thus, 1 million Btu (e) is equivalent to 293 kwh.

D Based on 300-mile distance market-center to coal deposit and high-voltage transmission line at 500 kV, at 1000 MW loading, and with an 85% load factor. Source is p. 197, 1964 Federal Power Commission National Power Survey, Part II. The basis for Case 1 is an 8 mill cost. For Case 2, 25% contingency is added to provide for inflationary effects and a possible need for buried lines all or part way.

E According to the 1970 (Part III) National Power Survey of the Federal Power Commission, Page 1-136, the basic cost of power plants in the 1975-1980 should be \$120-125 per kw installed. Gorgegno and Zoschak (Supercharging the Once-Through Steam Generator. IEEE-ASME National Power Conference, 1964) report only nominal savings in the capital costs of supercharged boiler/gas turbine installations as compared with the conventional facilities. Thus, the capital cost figure above, unchanged, should still apply and the annual fixed operating, maintenance, administrative, and general charges plus the fixed charges on capital should remain as shown in the National Power Survey reference noted above, i.e., at \$20.37 per kw. In  $d$  annually/million Btu(e) of energy, this annual figure converts to:  $(10^6) (20.37) (100)/(3413) = 590,000d$

If, for Case 1, we assume base loading of the unit at 90% factor, then fixed charges in cents hourly per million Btu(e) become:  $(590,000)/(24)(365)(0.9) = 75d$ . If, for Case 2, we assume peak loading operation only, at 50% factor, the corresponding fixed charge figure becomes 135d.

The supercharged-boiler/gas-turbine cycle shown in Figure 1 is capable of lower rates than conventional cycles. For Case 2, we assume that the heat rate would be same as that reported for the best conventional plant in the FPC 1964 National Power Survey (Page 67, Part I), which was 8588 Btu s/kwh. Thus, the heat rate, as Btu input/Btu(e) output is  $(8588)/(3413) = 2.52$ , i.e., 40% cycle efficiency. For Case 1, we assume that the Figure 1 power cycle could improve the cycle efficiency to 45%, i.e., 2.25 heat rate.

Entry	Note	Description	Case 1	Case 2
1	A	Approach (Objective is Estimation of a Selling Price Per Million Btu in the Product Gas)	Optimistic	Pessimistic
2		Coupling System	Figure 1	Figure 1
3		Basing Point for Price and Gas Composition	Gas Treatment Outlet	Gas Treatment Outlet
4	B	Product Gas Analysis: Nitrogen, Vol. % Carbon Monoxide Hydrogen Methane	13.9 15.3 61.1 9.7	76.4 12.1 9.5 2.0
5	B	Product Gas Heating Value, Btu/SCF	100.0	100.0
6	B	Product Gas Heating Value, Btu/SCF	356.0	97.0
7	D	Bus-Bar Electricity Cost at Market Center		
		a. $d$ /KWH	1.0	0.8
		b. $d$ /10 <sup>6</sup> Btu(e)	293	234
8	E	Transmission Cost, $d$ /10 <sup>6</sup> Btu(e)	23	29
9	E	Generation Cost (less fuel), $d$ /10 <sup>6</sup> Btu(e)	75	135
10	F	Selling Price Available for Fuel (6b)-(7)-(8), $d$ /10 <sup>6</sup> Btu(e)	195	70
11	F	Heat Rate for Power Generation Cycle, Btu/Btu(e)	2.25	2.5
		Selling Price Available for Product, (9)/(10), $d$ /10 <sup>6</sup> Btu	87	28

Note

- A In the optimistic approach, we resolved doubt arising during the calculations in favor of the approach that would yield a higher potential selling price for the product gas. For the pessimistic approach, we reduced the doubt in favor of yielding a lower price for the product gas.
- B Case 1 is based upon producing a gas of high heating-value through the elimination of nitrogen content by the use of a gasification technique involving alternating air/steam blast. Oxygen gasification could also have been selected. Multiple gasification units would be employed, programmed to operate in a staggered manner in order to equalize gas production. A large gas holder installation would be required suited to the operating

NOT REPRODUCIBLE



TABLE 8

## PRODUCT GAS DATA FROM UNDERGROUND GASIFICATION EXPERIMENTATION (U.S.A.)

SUMMARY OF AVERAGE OPERATING RESULTS,  
GASIFICATION WITH AIR, UNIDIRECTIONAL FLOW

	Peak Operation	Entire Operation
Nominal length of system, ft	155	155
Operating life of unit, days	21	59.1
Air input, cfm*	1890	1160
Input pressure, psig	27	30
Leakage of input air from system, percent	5.2	13.8
Gas production, cfm <sup>1</sup>	2160	1170
Composition of dry product gas, %:		
Carbon dioxide	9.7	10.5
Illuminants	0.3	0.3
Oxygen	0.5	0.9
Hydrogen	9.2	8.4
Carbon monoxide	13.1	10.7
Methane	1.5	1.8
Nitrogen	65.7	67.4
Specific gravity	0.94	0.95
Heating value, Btu/cu ft <sup>1</sup>	93	86
Moisture content, Mols H <sub>2</sub> O per mol dry gas	0.11	0.15
Rate of coal utilization, <sup>2</sup> tons of moisture- and ash- free coal per day:		
Completely gasified	11	6
Carbonized only	16	11
Total affected	27	17
Gas produced per ton of moisture- and ash-free coal completely gasified, <sup>1,2</sup> cu ft X 10 <sup>3</sup>	280	290

## GASIFICATION WITH OXYGEN

Operating time, hr	36
Oxygen input rate, cfm <sup>1</sup>	604
Composition of product gas, %:	
Carbon dioxide	47.8
Illuminants	0.3
Oxygen	0.2
Hydrogen	24.5
Carbon monoxide	21.2
Methane	4.1
Nitrogen	1.9
Heating value, Btu/ cu ft <sup>1</sup>	195
Specific gravity	1.0
Moisture content, mols H <sub>2</sub> O/mol dry gas	0.34
Product gas flow, cfm <sup>2</sup>	1335
Oxygen usage: <sup>2</sup>	
Cu ft/M of make gas	452
Cu ft/ml of (CO + H <sub>2</sub> )	990
Cu ft/10 <sup>6</sup> Btu in product gas	2320
Coal utilization, tons of moisture- and ash-free coal per day: <sup>2</sup>	
Completely gasified	33.1
Carbonized only	0

## WATER-GAS OPERATION, AIR-BLOW AND STEAM-RUN

	Air- Blow	Steam- Run	Air- Blow	Steam- Run	Air- Blow	Steam- Run
Individual cycle time, hr	18.8	4.2	6	6	6	6
Input rates:						
Air, cfm <sup>1</sup>	1240		2520		2500	
Steam, lb/hr		1480		1150		1200
Product-gas output rate, cfm <sup>1</sup>	1850	585	2990	250	2580	190
Composition of product gas, %:						
Carbon dioxide	13.0	20.8	16.2	35.8	16.0	40.8
Illuminants	0.3	0.4	0.4	0.6	0.3	0.4
Oxygen	0.3	0.4	0.4	0.3	0.6	0.6
Hydrogen	13.4	47.9	3.5	24.1	2.2	21.0
Carbon monoxide	10.1	12.0	2.1	8.9	1.3	6.9
Methane	3.0	7.6	2.0	7.5	1.2	7.2
Nitrogen	59.9	10.9	75.4	22.8	78.4	23.1
Heating value, Btu/cu ft <sup>1</sup>	112	279	47	195	30	172
Specific gravity	0.91	0.62	1.02	0.92	1.04	0.98
Moisture content, mols H <sub>2</sub> O/mol dry gas	0.19	0.56	0.22	1.23	0.24	1.78
Coal utilization, tons/day <sup>3</sup>						
Completely gasified	10.3	6.3	12.3	4.7	9.3	3.7
Carbonized only	14.4	1.4	22.5	—	19.1	—
Total affected	24.7	7.7	34.8	4.7	28.3	3.7

<sup>1</sup> 60°F, 30 in Hg, dry.<sup>2</sup> Calculated from material balances.<sup>3</sup> Basis, moisture- and ash-free coal; calculated from material balances.

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Source: USBM-422

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TABLE 9

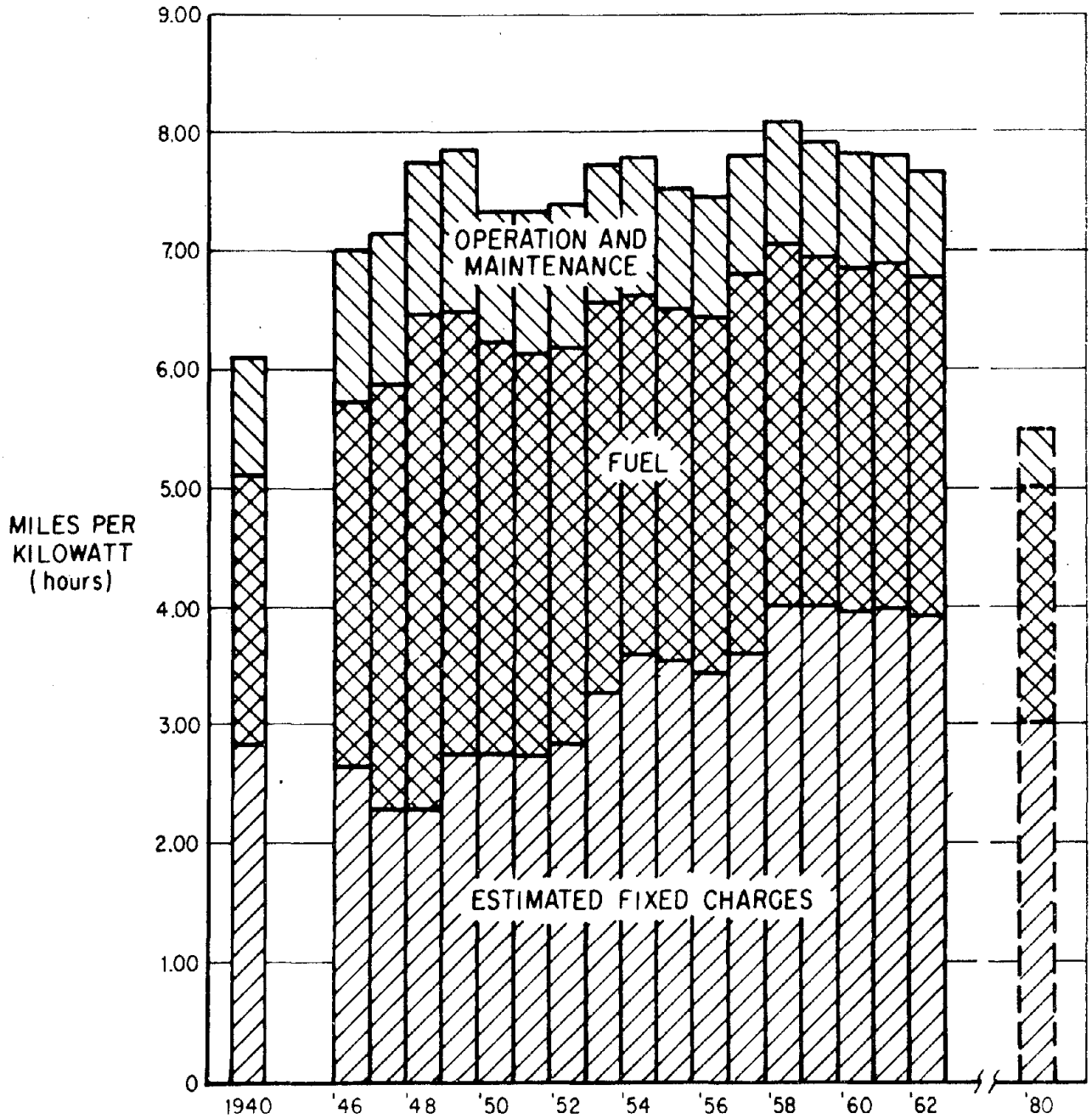
ILLUSTRATIVE COST OF NUCLEAR-POWER GENERATION OF ELECTRICITY<sup>a</sup>

1. Capital Costs <sup>a</sup>	\$/KW		Mills/KWH
Nuclear Steam Supply System	70		
Generating Equipment	50		
Balance of Plant	67		
Interest Charged During Construction	<u>33</u>		
	220		4.4
2. Fuel Cycle Costs <sup>b</sup>	Consumption Costs	Financing Costs	Total
Fabrication (at \$70/kgU)	0.34	0.08	0.42
Uranium Ore (at \$8/lb U <sub>3</sub> O <sub>8</sub> )	0.56	0.18	0.74
Conversion (at \$2.52/kg and Enrichment (at \$265/kg Separative Work)	0.62	0.16	0.78
Spent Fuel Shipping and Reprocessing (at \$45/kgU)	0.19	-0.04	0.15
Plutonium (at \$7.50/g) and Uranium Credits	<u>-0.35</u>	<u>0.08</u>	<u>-0.27</u>
	1.36	0.46	1.8
3. Operation, Maintenance, Insurance			<u>0.3</u>
			6.5 <sup>c</sup>

## Notes:

- a. In an 1150-MWe light water reactor plant ordered in 1970 for startup in 1975. Values are in 1975 dollars and are intended to include all anticipated effects on costs.
- b. Consumption costs include interest during construction on the first core. Cost of money and interest during construction is assumed to be 7 percent per year and total fixed charge rate for nondepreciable capital is assumed to be 14 percent per year. The first three items include a 4 percent sales tax. Total fuel cycle costs are levelized for Pressurized Water Reactor plants over the first ten years of operation at 80% capacity factor. Figures would break down slightly differently for Boiling Water Reactor plants, but total costs would be unchanged.
- c. This single-point estimate of the cost of nuclear-power-generated electricity is comparable to the 6.0-7.0 mills/kwh estimated by the Edison Electric Institute for the light-water reactor starting up in 1975.

Sources: Edison Electric Institute, "Report of Reactor Assessment Panel," Appendix A, May 1970, and Arthur D. Little, Inc., estimates.



SOURCE: FIGURE 42, PAGE 68, PART I, FEDERAL POWER COMMISSION, NATIONAL POWER SURVEY - 1964

**AVERAGE PRODUCTION COSTS, STEAM-ELECTRIC PLANTS  
(Investor-owned utilities)**

Figure 32

increase the maximum price for the product gas that the hypothetical management might justify. In Case 2, we were pessimistic in this respect.

The results we obtained are:

- *Optimism (Case 1).* The product gas could earn as much as 87 cents per million Btu of its heat content in the form it is available at the treatment plant exit. This would compare, for example, with a price for washed coal the hypothetical management might be willing to pay at the mine, which could be 35-40 cents per million Btu (Figure 28, \$8 per net ton), a reasonable level for eastern coals. The conditions postulated for the calculations in Table 7 are applicable to eastern coal supplies to concentrated energy markets (e.g., Illinois coals to Chicago) rather than to western coals. In the west, the distance to concentrated markets would, in general, be much greater than the 300 miles assumed for the calculations in Table 7, and the 87-cent figure would be considerably diminished. For example, if the distance doubled, the figure reduces to about 64 cents (Entry 7 in Table 7).
- *Pessimism (Case 2).* The product gas could earn only 28 cents per million Btu, slightly less than the mine value of conventional coal.

If one were in a position today to estimate realistic production costs based on the candidate underground gasification methods, the upper limit for attractiveness is probably a production cost in the range of 65-70 cents per million Btu, while the lower limit is probably 18-23 cents. The British estimate, with all its limitations, is of interest here, especially if the 40 cent figure could be confirmed by updating cost factors and reviewing the basis for the 60% coal recovery used to estimate it.

Table 7 is offered more as a model for a market-oriented costing approach than as a set of data on which conclusions may be drawn. Many of the assumptions are pure judgment. Costing work in depth is needed in order to reduce the 3 to 1 range of the results to the narrowness that would focus on the real price for the gas.

### 3. Coupling Pipeline Gas Demand to Underground Product Gas Energy

We made a similar attempt to establish a market-oriented price analysis, but this time on the basis of supplying pipeline-gas demand from the product gas. The results of our calculations are shown in Table 10. As before, the calculations are based on data from different sources and on a number of assumptions, and these

TABLE 10

## POTENTIAL SELLING-PRICE RANGE FOR UNDERGROUND PRODUCT GASES

## Pipeline Gas Production Model

Entry	Note	Description	Case 1	Case 2	Note	Explanation
1		Approach (As in Table 7)	Optimistic	Pessimistic	A	Both cases are based on the analysis reported in Table 8 for the gases produced underground when an oxygen and steam mixture is the gasifying agent. Alternatively, a cyclic approach based on the analysis reported in the same table for water-gas operation could have been used, thus avoiding expenditures for oxygen supply at the cost of more extensive underground operations. The analyses are calculated by assuming total CO <sub>2</sub> removal in the treatment section, and neglecting oxygen and illuminant content. Also, the treatment plant would be provided with a CO-Shift stage to adjust H <sub>2</sub> /CO ratio to say 3.25.
2		Coupling System	Figure 1	Figure 1		
3		Basing Point for Price and Gas Composition	Gas Treatment Outlet	Gas Treatment Outlet		
4	A	Product Gas Analysis				
		Nitrogen	3.7	3.7		
		Carbon Monoxide	20.8	20.8		
		Hydrogen	67.6	67.6		
		Methane	7.9	7.9		
5	A-1	Product Gas Heating Value, Btu/SCF	343	343	A-1	In both cases, we calculated product gas heating value from heating values in the component gases as shown in Table 5.
6	A-2	Consumption of Oxygen SCF/million Btu HV	552	552	A-2	In both cases, we reduced arbitrarily the oxygen consumption that was shown in Table 8 as 2320 SCF/10 <sup>6</sup> Btu heating value in gases having the analysis shown in the table, or as 990 cubic feet/1000 cubic ft (CO + H <sub>2</sub> ) produced. Ratio CO <sub>2</sub> /(CO + H <sub>2</sub> ) in Table 8, (47.8)/(24.5 + 21.2) = 1.05. Assume, with high coal recovery, ratio more likely would be = 0.20. Then, Volume of CO <sub>2</sub> /(24.5H <sub>2</sub> + 21.2CO) is (0.2)(45.7) = 9.14. Reduction in Volume of O <sub>2</sub> = Reduction in Volume CO <sub>2</sub> . Thus, % Reduction O <sub>2</sub> /(24.5H <sub>2</sub> + 21.2CO) = (990)(100)/(1-0.933)/ = (47.8 - 9.1)/(47.8) = 80.9%. Volume O <sub>2</sub> /(24.5H <sub>2</sub> + 21.2CO) = (990)(100)/(1-0.933)/ (1000) = 18.9 ft <sup>3</sup> . Heating value of (CO + H <sub>2</sub> ) = (24.5)(290) + (21.2)(341) = 14,334 Btu
7	B	Wholesale Pipeline Gas Cost at Market Center cents/million Btu	100	45		Heating value of total gas (Note A-1) = 34,300 Btu/100 ft <sup>3</sup> . Number of hundred cubic feet per 10 <sup>6</sup> Btu (10 <sup>6</sup> )/34,300 = 29.2. Oxygen Consumption cubic feet/10 <sup>6</sup> Btu in product gas (29.2)(18.9) = 552.
8		Transmission Cost at 1¢/MSCF/100 miles (300-miles), cents/10 <sup>6</sup> Btu	3	3		
9	See Table 11	Methanation Cost at Pipeline Inlet Pressure (1000 psig), cents/10 <sup>6</sup> Btu	4	4	B	Case 1 Coal provides a supplementary pipeline gas source.
10	See Table 12	Compression Cost Gasification Pressure to 1000 psig, cents/10 <sup>6</sup> Btu	10	4		Case 2 Coal provides a base source and the FPC raises wellhead prices 10¢/MSCF.
11	See Table 13	Oxygen Cost, cents/10 <sup>6</sup> Btu	15	8		
12		Maximum Product Gas Cost (7) - ((8)+(9)+(10)+(11)cents/10 <sup>6</sup> Btu	68	26		



are summarized in Tables 11, 12, and 13. Again, the method of calculation should be clear from study of Table 10 and the explanatory notes incorporated.

As before, we postulated the price a hypothetical gas utility management, operating the facilities shown in Figure 1 should be willing to pay for the clean, desulfurized gases leaving the gas treatment section at the underground gasification site. We estimated such a price on two bases, somewhat different than we used in the electricity-demand case. In Case 1, our optimism was based on the prospect that pipeline gas from underground coal gasification would be considered a supplementary source in the same way as for pipeline-gas production from conventionally-mined coal. In Case 2, our pessimism was based on the prospect that the pipeline gas would have to compete at market centers with natural gas purchased at future wellhead prices somewhat above current levels.

- *Optimism (Case 1).* The product gas could earn as much as 68 cents per million Btu of heat content in the form it is available at the treatment plant exit. We based the underground gasification on the use of oxygen, where production costs would be quite sensitive to oxygen consumption, to nitrogen contamination, and to coal recovery. An alternative might be the use of the alternating air-blast/steam-blast cycle. For pipeline gas, the treatment plant would need to be provided with a CO-shift stage to permit adjustment of H<sub>2</sub>/CO ratio, which would not be required if electricity is to be the marketable form. Since we have considered the treatment plant to be part of the underground gasification installation, production-oriented cost estimates in this approach and in the electricity-demand approach are differently affected.
- *Pessimism (Case 2).* The product gas could earn only 26 cents per million Btu.

As before, Table 10 is offered more as a model for a market-oriented costing approach than as a set of data on which conclusions may be drawn. Again, costing work in depth is needed. The range in the two results above is 2.6 to 1.

#### D. JUSTIFICATION TO PROCEED

Earlier, we pointed to the decision whether or not to let the current technology of underground coal gasification lie dormant, or whether to reactivate it. The decision should now be clear. It is to reactivate but on a limited scale. Our appraisal of the technology provides four reasons in support:

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TABLE 11

ALLOCATION OF METHANATION COST  
(Capacity 250-million SCFD Pipeline Gas)

Entry	Description	Table in Source	Value
1	Capital Cost	VIII, p. 67	\$ 11.7-million
2	Sub Total Capital Cost	X, p. 69	\$139.7-million
3	Percentage (1) x 100/(2)		8.4%
4	Annual Total-Plant Operating Expense	XI, p. 70	\$ 39.5-million
5	Total Fixed Charges	XI	\$ 12.3-million
6	Total Labor Supplies, and Related	XI	\$ 9.8-million
7	Proportion Applicable to Methanation		
	a. (3) x (5)		\$ 1.03-million
	b. (3) x (6)		.83-million
	c. Total		\$ 1.85-million
8	Contingency for conclusion re need for development	(c), p. 51	1.25
9	1.25 x (7c)		\$ 2.33-million
10	Ratio Feed Gas Volume/Pipeline Gas Volume	Table II Streams (402), (601)	(3) (22347)/(27484)=2.44
11	Plant Capacity		
	a. Methanator Feed Gas Volume, (2.44)(250)(10 <sup>6</sup> )		610-million SCFD
	b. Feed Gas Heating Value - (11a)x.343		209,000 millions Btu/day
12	Daily Methanation Cost (9)/(300 days)		\$ 7,700
13	Methanation Cost, ¢/10 <sup>6</sup> Btu ( (12)/(11b) ) x100		3.68, say 4.

Source: Engineering Study and Technical Evaluation of BI-Gas Process Air Products and Chemicals, Inc. for Office of Coal Research. Dept. of Interior - Report No. 60, Contract 14-32-001-1204 (1970)

TABLE 12

ESTIMATION OF COMPRESSION COST  
(per Million Btu Heating Value in Methanation Feed Gas)

Entry	Description	Value		
1	Inlet Pressure, atm, abs <sup>a</sup>	4		
2	Compression Discharge, atma	66		
3	Number of Stages	2		
4	Compression Ratio/Stage	4.1		
5	Volume of Inlet Gas, STP ft <sup>3</sup>	2,915		
6	Adiabatic Work to Compress, Btu	29,400		
7	Overall Boiler/Turbine/Compressor Efficiency %	25		
8	Fuel Gas Consumption to Raise Steam, Btu	118,000		
			Case 1	Case 2
9	Cost of Fuel Gas (Table 12, Entry 12) \$/10 <sup>6</sup> Btu <sup>b</sup>		0.70	0.15
10	Cost of Fuel Gas, ¢ per 10 <sup>6</sup> Btu Product Gas Compressed		8	2
11	Installed Compressor Power Capacity, Daily Production			
	a. Gas Quantity for Compression, Table 11, (Item 11b), millions Btu HV		209,000	
	b. Shaft Input Energy (0.7 efficiency), millions Btu/D, ((6)/0.7) x (11a)		8,800	
	c. BHP Input ((11b)/24)/2545		114,000	
	d. Capital Cost @ \$75/BHP Installed		\$11-million	
12	Fixed Charges, Daily			
	a. Capital (11d) x 0.0833/300		\$ 3,000	
	b. Maintenance and Sundry Charges, 15% (12a)		450	
	c. Total		\$ 3,450	
13	Fixed Charges per 10 <sup>6</sup> Product Gas ((12d)/(Entry 11b Table 11)) x 100 Compressed, ¢		2	2
14	Total Compression Cost, (10) + (13), ¢/10 <sup>6</sup> Btu		10	4

a. Pressure level assumed for underground gasification.

b. Assumption, but this should be confirmed by iteration to equal value of low pressure product gas related to selling price found in Table 10.

Source: Arthur D. Little, Inc.



- The technology apparently can be competitive with alternatives that may be considered in the United States to balance future energy sources with energy demands. An exploratory order-of-magnitude market-oriented attempt at estimating selling prices for purified gases from underground coal gasification shows a range of prices into which production costs for these gases must fit. The single data point for production-oriented cost available from past experimental work indicates that a fit is possible. Considerable work in depth, however, is still required to narrow the range indicated in the exploratory market-oriented estimates in order to focus on realistic product gas pricing. No technical reason prevents undertaking this work.
- Candidate underground gasification methods have been identified which fit the criteria for use in the United States. Before estimating realistic production costs for product gases employing these methods would be feasible, further experimental and analytical work is needed.
- The nature of the experimental and analytical work is known; no technical reason prevents the organization of work programs, and the focussing of attention on U.S. coal deposits that would be attractive for underground gasification.
- Numerous coal deposits in the United States, suited to the technology, are available as candidates for ultimate application of improved technology on a large scale.

#### E. THE NATURE OF THE NEXT STEP

Given the decision to reactivate, what should be the nature of new activity? Obviously, it must eventually relate market-oriented selling prices with technology-oriented production costs. Considerable analytical work is required in order to focus on a realistic set of market-oriented product gas prices, while at the same time considerable research and development work is still required in order to enable reliable production-oriented cost estimates to be made. The two orientations together determine profitability and profitability determines the geographical areas in the United States where technological attention should be focused. A feedback loop exists, and the first step in new activity should be to manage it. The technique to do this is phasing.

Thus, the ultimate objective of new activity should be achieving a prototype operation in which significant quantities of gases from underground coal gasification are continuously produced, suitable for conversion into marketable energy forms. This objective should be achieved through three consecutive phases of activity, each designed to minimize the risk of unwarranted expenditures of funds. Only the first phase should be undertaken at this time. The second phase would be authorized only if the results of the first phase justified this.

#### 1. Phase 1

The first phase should be limited to undertaking a small-scale analytical and experimental program to enable production costs to be developed for the candidate gasification methods. These costs should be developed on a parametric basis for use as a tool to explore a variety of local conditions at different possible gasification sites. Individual work efforts to this end should allow for the completion of the following programs:

- A study, preferably limited to office and bench-scale laboratory work, of the prospect that lasers might be used for linking vertical boreholes by drilling passageways between them. Such a study should provide only a preliminary yes or a positive no answer to the feasibility of such a technique.
- A study, limited to office and to interview work, of the technology, methods and feasibility of drilling large-diameter holes that would curve and travel for long distances along coal seams. This should include a study in depth of the current state-of-the-art, and discussions with experts in the field of drilling and drilling-equipment capability. It should result in establishing specifications and design of equipment for such drilling as well as for its control. Problems of casing curved holes, the materials that might be used, and how they could be installed should be identified. The results should permit estimates of cost to be made, but should this not be so, then the work should be extended to test drilling in the field aimed at providing a basis for estimating drilling costs.
- A small study, limited to office and library work, of available information and knowledge about the maximum size of an underground opening one could expect to find in different coal seams and roof structures before the roof collapses. As a part of this work, calculations should be developed from basic information that can predict the optimum borehole size for the gasification of different types of seams at different depths. The objective should

be to compare maximum cavity sizes from structural considerations with maximum cavity size from mass transfer considerations. The parameters that would be involved in the calculations would be seam thickness and depth, heating value of coal, velocity of combustion gases, type of gases, volume and pressure relationships, flow variations needed as the cavity increases in size, and perhaps others.

- A comprehensive study involving office, laboratory, and pilot-plant work aimed at establishing the feasibility of wet and dry stowing techniques to fill underground cavities of the type expected in gasification. The work should include the following major projects:
  - (a) The identification of potential stowing materials and mixtures. Examples of candidates are sand, fly ash, sized rock, cemented sand fill, limestone, small amounts of lime admixed in sand, resins, foams, and expandable shales.
  - (b) Identification of techniques, pneumatic or hydraulic, for example, for placing filling material.
  - (c) Laboratory and/or pilot plant work on promising systems. The aim to develop a filling material that could be fed continually to a gasification system and that would fuse, expand and completely fill cavities under the prevailing temperature conditions expected. Potentially interesting systems should be tried out in the laboratory, pilot plant, or in an available experimental mine.
- An office study of possible temperature measuring techniques for underground gasification systems. A study in further depth of alternative techniques (Appendix C) aimed at location and control of the fire front might be necessary.
- If the results of the work thus far warrant, design and carry out a basic test program for a single blind borehole gasification system using continuous stowing and filling for roof support. This should be done at a convenient location where facilities may already be available, and where a coal seam of known size, shape and characteristics exists. The aim should be to provide the technological basis for estimating the costs of producing product gases of predictable composition on a continuous basis and with recovery of maximum coal quantities.

## 2. Phase 2

If it could be concluded from the results of Phase 1 that a reliable tool is available for economic study of the technology in depth, the overall objective would be to provide justification in Phase 3 for the design, funding, and construction of a prototype underground coal gasification operation at an appropriate location in the United States. The sequence of work in Phase 2 could be somewhat as follows:

- Find a limited number of sites having different combinations of energy market and coal deposit characteristics. For example, consider:
  - (a) New York Metropolitan Area markets for electricity and gas, and Pennsylvania-West Virginia sources for coals.
  - (b) Metropolitan Chicago markets for electricity and gas and Illinois for coal.
  - (c) As the foregoing except Dakota lignites.
  - (d) Metropolitan Los Angeles and markets for electricity and gas and Western coals.
- Set up appropriate schemes such as Figure 1 illustrates for each case and establish energy and material balances to determine quantity of underground gas required.
- Choose a typical coal reserve at each site and design an underground gasification system for it, making an assessment of validity each time an assumption is made to resolve an uncertainty. Here would then begin a selection of further research and development projects, a definition of the work content, and the setting up of program priorities for possible use in designing Phase 3 of the effort.
- Cost out each system to determine profitability from market-oriented pricing and production-oriented costing.
- For each site, compare environmental effects between the underground gasification approach and the alternative method of exploiting the coal deposit. Undertake benefits/cost analyses comparisons between the two. Also, compare intangible benefits if they exist.

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- From the results thus far, and from other nontechnical and non-economic factors, such as alleviation of conditions in a depressed area, constraints imposed by existing institutions involved in energy supply, and compatibility with other governmental programs involving coal, rank the sites for attention and for level of expenditure for development.
- For the site selected, determine whether a prototype installation can be justified.

#### F. LEVEL OF EFFORT

A carefully planned expenditure of about \$2.5 to \$3.5 million over a three-year period should be warranted (Table 14). From \$1.2 to \$2.2 million would probably be spent on equipment and materials, and the balance on the cost of manpower. From \$0.5 to \$1.5 million might be spent during the first year, with the larger amount necessary if costly specialized equipment is needed. The initial expenditure would apply to the work in the first five programs of Phase 1. The final program of Phase 1 would be undertaken only if the results could be judged to justify this.

TABLE 14

#### ESTIMATE OF COST AND DURATION FOR PHASE 1

<u>Programs</u>	<u>Manpower</u>		<u>Equipment</u>	<u>Duration</u>
	<u>Man-Years</u>	<u>Cost \$</u>	<u>\$</u>	<u>Years</u>
First 5	5	250,000	250,000*	1
Final	20	1,000,000	1,000,000	2
Total	25	1,250,000	1,250,000	3

\*Note: This amount might be as high as \$1,250,000 if large amounts of specialized equipment should be required for the laboratory and pilot plant work.



## APPENDIX A

### HISTORICAL BACKGROUND

This Appendix presents a chronological list of events that seem to bear on the development of the technology of underground coal gasification. The events have been gleaned from the literature and sequenced and described to clarify our perspective of the technological developments throughout the world rather than the developments within each particular country. In some instances, the dates of events may be approximate since the various literature sources do not always agree.

1868 Sir William Siemens is apparently the first\* to suggest the underground gasification of waste and slack coal in the mine.

1888 The Russian chemist, D.I. Mendeleev, suggests the underground gasification of coal\*\* when he observes that coal could be ignited underground and converted into illuminating gas. He proposes the use of shafts.

1909 The patent on the subject of underground coal gasification\*\*\* granted to the American Anson G. Betts is apparently the first in the technology. The patentee proposes a method of gasifying coal in the seam by starting a fire at the base of one or more shafts, or boreholes, supplying air and steam through a pipe, and withdrawing the gas formed through the same, or other, shafts or boreholes.

1912 In March, the British chemist William Ramsey presents his ideas for underground coal gasification at a meeting of the International Smoke Abatement Exhibition, and in June at a dinner of the Institution of Mining Engineers. He begins experimental work at Hett Gill, in Durham, but is unable to complete it before the beginning of World War I. His death shortly afterwards ends the effort. His proposals incorporate both the production of combustible gases and their utilization for generation of electricity.

1913 In April, Russian comments (including that of Lenin) in Pravda on the newspaper reports of Ramsey's experiments characterize underground coal gasification as a great task and as a technical revolution. Lenin speaks of the boon the technology offers for the liberation of underground coal miners from drudgery.

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\*Trans. Chem. Soc., 1868, XXI, 279

\*\*"The Future Power on the Banks of the Donets River," Severny Vestik (St. Petersburg), 1888, No. 12, Sec. II, p. 26

\*\*\*British No. 21, 674

- 1920 The Soviet Mining engineer B.I. Belov makes specific recommendations toward a practical realization of the suggestions of Mendeleev in 1888.
- 1925 Professor B.I. Bokiy of the Leningrad Mining School proposes applying underground coal gasification to the thin unworked coal beds of Donbas in the Donets Basin as an aid to the electrification of that region. He proposes a shaftless method. No action is taken on his proposal.
- 1933 The first work in the USSR begins on lignite (Krestorsky), on hard coal (Donbas), and on anthracite (Lisichansk). The first techniques – surface gas generators and hand-loaded gas generators – prove impractical. Emphasis shifts to the gasification of the whole coal seam in situ.
- 1933 The government of the USSR establishes a special state trust, to be known as "Podzemgas," to carry out experimental work aimed at establishing industrial plants. Podzemgas organizes a competition to encourage invention of methods of underground gas production. In 1936, Podzemgas is thought to employ 1500 persons.
- 1934 An experimental underground coal gasification plant at Lisichansk, employing the automatic coal-crushing concept proposed by the Soviet mining engineer I.P. Kirichenko in 1928, produces negative results. Later experiments, employing a new method devised by Kirichenko and V.S. Ton and called the borehole-gas generator method, produce combustible gases with heating values ranging from 84 to 126 Btu per cubic foot when air is used. With cyclic use of air followed by steam blowing, the steam run produces water gas with a heating value of 260 Btu per cubic foot.
- 1936 An underground coal gasification plant at Gorlovka employs a continuous method based on gasifying in a horizontal channel located in an undisturbed coal bed, proposed in 1933 by V.A. Matveyev, P.V. Skafa, and D.I. Filippov of the Donets Institute of Coal Chemistry. It produces combustible gases with heating values ranging from 84 to 115 Btu per cubic foot. Oxygen-enriched air is used for the first time.
- 1936 An experimental coal gasification plant in Kuznetzk (Leninsk), utilizing the large Zhurinsk coal bed and the continuous method tried at Gorlovka, produces gas with a heating value up to 168 Btu per cubic foot. The gas is used to fire a boiler for several months.
- 1937 In November, the success at Gorlovka in obtaining fuel gas from all the experimental underground coal gasification installations leads to systematic industrial consumption for the first time when new coal panels are ignited.

By October of 1938, these panels have supplied 275 million cubic feet of fuel gas, and total production from all installations is 2.75 billion cubic feet, at an average heating value of 94 Btu per cubic foot. About 1.1 billion cubic feet of this production is utilized.

- 1938 In November, a scientific and technical conference convenes in the USSR to summarize the technical progress to date in order to plan further development of underground coal gasification. For reasons of simplicity and low cost the conference directs that future attention be placed on shaftless techniques rather than on the shaft techniques then mostly in use. Also, it recommends building and commissioning in the Donets coal basin, the lower Moscow coal basin, and in eastern USSR a series of industrial stations for underground gasification, the gases to be used for power generation, for chemical works, and for communal domestic purposes.
- 1940 In November, an installation at Krutov for the gasification of Moscow area coals begins operations on four coal panels. The installation uses a filtration method developed by a team from the Energetics Institute of the Academy of Sciences of the USSR, led by A.B. Chernyshev, which differs from earlier methods by eliminating underground operations and underground horizontal piping. The method improves the reliability of underground coal gasification, permits the use of low-pressure air injection into boreholes, and provides better control of the gasification reactions.
- 1940 In December, large-scale production of gas from underground coal gasification starts at Lisichansk on three coal panels, using enriched air (60% oxygen). In the first five months, about 350 million cubic feet of gas are produced. These operations eventually cease in 1946.
- 1941 By July, the beginning of the USSR involvement in World War II, gas is being obtained from five underground gasification installations – three in the Donets coal basin (Schakhtinsk, Lisichansk, Gorlovka), one in the Moscow coal basin (Krutov), and one in the Kuznetzk (Leninsk) coal basin, with at least one industrial use of gas at Gorlovka. War activities stop further development, but interest redevelops and work begins anew after 1945.
- 1944 Wartime activity in Belgium in the underground gasification of coal leads to the formation of a Government-subsidized cooperative society, "Socogaz" (Societe Cooperativ de Gazeification Souterraine) to conduct experimental work on underground gasification at the Bois-la-Dame colliery near Liege.

- 1946 Late in the year, interest in the United States leads to a cooperative agreement between the U.S. Bureau of Mines and the Alabama Power Company to undertake an underground coal gasification experiment at Gorgas (16 miles south of Jasper), Alabama, to determine (a) whether coal in place could be burned successfully, (b) whether the burning could be controlled, (c) the effect of the fire on the coal bed and on the overlying strata, and (d) the yield and the quality of the gas that could be obtained. Preparatory field work begins in November. The coal seam selected is accessible by adits, and overburden can be removed for inspection of the gasified areas after the experiments.
- 1947 In September, the first laboratory and field work in the United States begins on the electrical linking of boreholes. The work is undertaken cooperatively by the University of Missouri and by the Sinclair Coal Company in a coal mine near Hume, Missouri. Work continues through May 1951. The results provide a basis for the design of a pilot plant.
- 1947 First operations at Gorgas begin on 21 January and terminate on 12 March. Sixty-three gasification runs are made with air, with oxygen-enriched air with and without steam, and with oxygen-steam mixtures. The gas flow can be in either direction through the coal. Periodically, some of the gas production is burned in a boiler. The results show that it is not difficult to maintain combustion of coal underground and that coal in place could be completely gasified. The action of high temperatures on the roof strata causes settling in the voided gasified areas and this settling appears to enhance favorably the performance. Further investigation is warranted.
- 1947 In collaboration with Mineraria Valdarno in Italy, Socogaz carries out an experimental underground gasification field test at Banco-Casino on a lenticular lignite seam containing 55% moisture and varying in thickness from 15 to 60 feet. The test produces seven million cubic feet of gas per day with a heating value of 100 Btu per cubic foot. A second experiment at the Colle d'Oro mine of the Terni Company is discontinued when a serious underground leakage problem can not be solved.
- 1948 A new agreement between the Bureau of Mines and the Alabama Power Company covers a second experimental program also at Gorgas but at a new site, one that has better properties in the overlying strata and an isolated coal body. The method of gasification is planned to be essentially similar to that used in the first experiment. The objective of the program is aimed at obtaining fundamental knowledge, while extracting the energy contained in unmined coal.

- 1948 N. Booth reviews the USSR work for the Gas Research Board in the United Kingdom and concludes that underground gasification might be applied in the United Kingdom to thin, steeply sloping seams to make a low-grade gas provided that the gas could be used near the pithead. Constancy in the gas output might be difficult to ensure.
- 1948 Socogaz, Charbonnages de France, and later Charbonnages de Pologne (Poland) enter into an agreement for joint experimentation at the Bois-la-Dame Colliery at Wandre near Liege, Belgium. Interest appears to stem from the wartime work in Belgium by the Germans and the thought that about 50 percent of the coal reserves in Belgium consists of seams too thin to be mined in the usual manner. The experimental work, carried out during the period 1948-50, uses a semi-anthracite bed about 3 feet thick dipping at an angle of 87 degrees, geometrically similar to the seam at Gorlovka. The method employed to burn the seam is sidewise rather than upward, as at Gorlovka; however, the results are considered not to be technically attractive and further work is discontinued.
- 1949 The second experimental program at Gorgas begins in March and lasts until February 1951 when the fires are extinguished by flooding. About 10,500 tons of coal (moisture and ash-free) underlying an area of almost two acres are gasified. This area can be extended at will, with no apparent limit, by drilling new inlet and outlet boreholes at strategic locations. The experiments indicate significant success in promoting gas/solid contact by filling voided spaces with solids. The new boreholes increase the rate of combustion of the coal. The results indicate that underground gasification is capable of the total combustion of coal and the utilization of the thermal energy for power production, and of the partial combustion of the coal to produce either producer gas for power generation or synthesis gas for chemical production.
- 1949 French experimental work culminates in an experiment at Djerada (Morocco) in an almost vertical seam of anthracite. The stream method is used, similar to that at Gorlovka (USSR). Operations are continuous for about five months, but are impaired by infiltration of water into the underground workings from severe rainstorms. An oxygen-free combustible gas is produced. High thermal recovery efficiency is forecast. Post-operation inspection shows that slag has collapsed into the voided space, combustible material content is totally gasified, and free space adjacent to the coal front is small.

- 1949 Late in the year, experimental work begins in the United Kingdom, directed by the Ministry of Fuel and Power. Later, in 1956, responsibility is transferred to the National Coal Board. British work is initially focused on retaining all operations above ground, but this focus shifts in 1953 to introducing shafts and headings to reach coal seams. This shift in focus is the reverse of that in the Russian work. The first site selected (1949) is the mildly caking coal seams at Newman Spinney near Chesterfield, averaging 2.5 feet in thickness and a 1 in 7 slope. The second site (1950) is the non-caking coal seams at Bayton near Bewdley in Worcestershire. The incentive for the work is the desire to extract the values from conventionally unmineable domestic reserves in view of the increasing dependence of the United Kingdom on imported fuels.
- 1949 A department is established to conduct underground gasification of coal in Poland. Polish engineers participate in the Socogaz experimental work in Belgium. Later, work similar to the Belgian's is undertaken in Poland at Lagrissa, and continues for a number of years, the results being reported in the literature in 1957. Oxygen enrichment is employed, as is electrolinking.
- 1951 In June, the first experimental work concerned with increasing coal-bed permeability through electrical methods begins at Gorgas. One of the lower seams at the Gorgas site, is used. The work includes tests to show the improvement achieved in gasification of electrolinked coal for a number of gasification techniques. Large-scale work on the technique is completed in 1952. Subsequent work in the Bureau of Mines Laboratory at Morgantown, West Virginia, is based on simulation and in the field at Gorgas on small-scale experiments.
- 1952 A British delegation visits the Bureau of Mines operations at Gorgas to observe the electrolinking work with the aim of undertaking similar work in the United Kingdom.
- 1953 In February, site preparation begins at Gorgas for experimental work to link coal seams through the use of hydraulic fracturing, a technique used in crude-petroleum production. By June 1955, the work shows that fracturing is possible and that the air acceptance of the coal bed is sufficiently increased to permit actual gasification. Later, additional work is taken with alternative fracturing agents. The fractured coal beds are gasified. Other work is undertaken that demonstrates the feasibility of gasifying several underground paths simultaneously.
- 1954 Experimental work on lignite in a section of the Moscow underground gasification station is directed to the production of carbon monoxide, hydrogen and nitrogen mixtures in the proportions suited to ammonia

production. Varying proportions of steam-oxygen-air mixtures are used for the gasification step. This work continues until 1957. Fluidized-bed gasification of lignite above ground is conducted so the gas mixtures can be compared. An increased heating value in the gases produced underground is noted.

1955 In the United Kingdom, the Scientific Advisory Council to the Ministry of Mines and Power reviews the results of the experimental work, and recommends that it be continued on a larger scale. The transfer of responsibility for the enlarged program to the National Coal Board, the legal owner of the coal reserves of the country, results. The Coal Board accepts the responsibility with the understanding that further work will be aimed at the construction of a pilot plant, and later at the planning of a commercial power station as soon as the pilot-plant results are considered successful. Power-generating facilities will be operated by the Central Electricity Generating Board (then the Central Electricity Authority).

1955 The National Coal Board implements its responsibilities by appointing an Underground Gasification Executive from its staff which is to be advised by a firm of consulting engineers (Sir Alexander Gibb and Partners in association with Messrs. Cremer and Warner) and which is to be assisted by a contractor (Messrs. Humphreys and Glasgow, Ltd.).

1956 By July, at the time of transfer of the U.K. work to the National Coal Board, 52 gasification trials of techniques have been completed, including: linking boreholes by high-pressure air (with and without oxygen enrichment), by electro-methods and by directional drilling methods; and by blind and open borehole gasification methods. Problems on excessive burning of pipes and of inability to distribute flows in a multiple system remain to be solved, and this becomes the first priority in the program of work. The pilot plant is established using the blind borehole method with provision for conversion to the open borehole method. Early 1959 is adopted as the target date for operation of the electricity generation station. Work is concentrated at Newman-Spinney.

1957 An exchange of technical visits occurs: in November-December, a British delegation to USSR installations and to technical institutes; and in April 1958, a USSR delegation to the U.K. installations.

1957 Since World War II, underground gasification of coal in the USSR has progressed to the position shown in Table A-1. For example, earlier, in 1955, the Tula (Lower Moscow) installation had produced about 40 million cubic feet of 90 Btu gas. Labor productivity has increased four or five times

TABLE A-1

## UNDERGROUND GASIFICATION INSTALLATIONS IN USSR, 1957

Station	Location	Coal Type	Gas Output (x 10 <sup>6</sup> cu.m/day)	Power Installed (MW)	State	Notes
Tula	Moscow Coal Field	Brown Coal	1.4		In operation	Experimental
Shatsky	Moscow Coal Field	Brown Coal	—	48	1st Stage completion due early 1958	Electric power gen- eration by gas tur- bines
Angrensk	Uzbekistan (Nr. Tash- kent)	Brown Coal 30 ft. thick 500 ft. cover	—	100 (ultimate 200)	1st Stage completion due 1958	Electric power through steam boilers
Gorlovka	N. Donbass	Bituminous	—	—	Closed down since war	Damaged beyond economic repair
Lisichansk	Donbass	Bituminous	0.6	—	In opera- tion	Experimental
Yuzhno- Abinsk	Kuzbass	Bituminous High Volatile , 23 ft. thick	0.4	—	In opera- tion (devel- opment stage)	Semi-experimental
Kamensky	Donbass	Semi- Anthracite	—	—	Due for completion 1960	Semi-experimental
Stalinsk	Kuzbass	Semi- Anthracite	—	400	Construc- tion not yet started	Plans awaiting authorization (steam boilers and flue-gas turbines)
Kholmogorsk	Kuzbass	Bituminous High-Volatile	—	1200	Construc- tion not yet started	Plans in hand

Source:

and production cost decreased commensurably. At Lisichansk, under geological conditions different than at Tula, process improvements have been made, and experimentation on drilling techniques continues. At Yuzhno-Abinsk, burning in thick, steep beds is being studied and reliable operation is reported.

- 1957 In May, the Soviet Academy of Sciences holds a conference on the position and the future technical development trends with regard to the underground gasification of coal. Differences in points of view are reported. Considerable controversy is generated with regard to conducting economic evaluations of the technology at the stage of technical development so far achieved. Terpigorev indicates the following: (1) theoretical research on shaftless gasification schemes; (2) model techniques and complex calculations; (3) extension of shaftless methods to gasification of shales; (4) research into roof and fire-zone control under various geological conditions; (5) investigation and testing of surface methods for automatic control of the process; (6) working out a system for gasifying coal beds in series; (7) investigation of the reaction of electric current on coalbeds; (8) study of methods of producing synthesis gases; and (9) investigation of the economics of large industrial stations. The opposite points of view in the economic evaluation controversy appear to be Bakulev in favor of immediate attention to this, and Chukhanov in favor of additional technological development beforehand.
- 1958 Kovalenko in the USSR estimates an increase of underground gas production from coal from the currently expected 27 trillion cubic feet for 1958 to 450 trillion cubic feet by 1965.
- 1958 High government agencies in the USSR endorse a plan for work in the underground gasification of coal to begin in 1959, and to continue through 1965. The plan provides for improving existing technical procedures and developing new and more-effective methods to correct the deficiencies of past work, namely: high cost of gas production at a low heating value; and considerable losses of coal, gasifying agents, and product gas. Progress and the scale of work so far is considered to be insufficient. Chukhanov's viewpoint at the 1957 conference seems to have won.
- 1958 It becomes apparent that the necessity to supply power in the United Kingdom from the underground gasification of coal is not as urgent as previously thought. At best, it could only be competitive with conventional power sources. The Ministry of Power agrees with a National Coal Board decision to terminate its work on the completion of trial 61 and trial P.5, which include operation of the pilot power plant. Plans for the later construction of a 60,000-kw generation plant are cancelled. Trial 61 is

established to incorporate the more successful features of the previous blind borehole trials to lead the way to full pilot development. Trial P.5 is established to use the general lines of the Russian work on open boreholes.

- 1959 Experimental work in Czechoslovakia near Chomutov in northern Bohemia is reported. The borehole method is used in a seam 4-12 feet thick and containing a reserve of 1 million tons. Free water in the seam is detrimental and reduces the heating value of the gas. Gas is to be used to power a 1.5-mw electricity generator. A larger generator is planned for 1961.
- 1959 In April, the pilot electricity-generating station at Newman-Spinney begins operating on gas produced from Run P.5. The official test takes place on 6 June. The plant operates on both Run 61 and Run P.5 gas, and is finally shut down on 17 August. The plant generates a total of about 3.5 million kwh during the operations, consuming 238 million SCF of gas at an average heating value of 58.8 Btu/SCF; the design heating value is 75 Btu/SCF; the heating value of the gas fluctuates from 84 to 40 Btu/SCF. Supplementary oil firing is required to maintain ignition. Coal extraction is about 84% in Run P.5 and less than 50% in Run 61 when it is shut down, but a potential for further recovery remains.
- 1959 The U.S. Bureau of Mines terminates its experimental work on the underground gasification of coal. Because of limited budgets its work had been concentrated on attractive short-range projects.
- 1959 There are reports of USSR plans to build two gasification stations at Stalinsk, each to have an annual capacity of 280 billion cubic feet of gas. Plant No. 1 will produce 138-Btu gas for a steel mill. Plant No. 2 will supply a 241-MW electricity generating station. A third plant, with a capacity of 125 billion cubic feet, will be built to supply a 100-MW station.
- 1960 Experimental work in the United Kingdom ceases. The results of the completed experiments indicate that further experimental work is desirable, but the economic situation in the country with respect to electricity supply apparently cannot justify its continuation.
- 1963 A review of the USSR fuel gas industry, in the Gas Journal issue of 14 August refers to underground gasification as a source of low-heating-value gas inefficiently produced. This review also traces the growth of the natural gas industry in the USSR and its current reserves beginning with the discovery in 1940 of large gas reserves near Saratov.

- 1964 Mining Review states (page 299) that natural gas and oil products are rapidly increasing in importance in the Soviet fuel balance, and that the six underground coal gasification stations directed by Podzemgas organization were being operated mainly for experimental purposes, although the increase in gas production from this source had been scheduled to rise from 3400 million cubic meters in 1957 to 8300 million in 1965.
- 1966 The number of articles appearing in the Russian literature begins to drop markedly as follows: 26 in 1965, 5 in 1966, 16 in 1967, 4 in 1968, 2 in 1969, and none since.
- 1969 According to a news report in the issue of the Mining Journal (British) of 3 January 1969, the USSR coal industry is reported to be undergoing modifications to increase productivity 50% by 1975, but their nature is not specified. Later news items in the same journal, appearing at intervals through April 1971, mention expansion of conventional open pit and underground mining to increase Soviet coal output for power generation. Unusually large (15 million annual tons) open pit and unusually deep underground operations are reported.
- 1970 For the first time, the current literature contains no papers from Russian or other sources referring to work on the underground gasification of coal in the USSR, ending the gradual reduction in the volume of literature from the USSR on the technology from the 26 items noticed in 1965. This absence of Russian literature continues into the first months of 1971.
- 1970 In June, a delegation of representatives of the US Federal Government, US coal-mining industry, and US coal mining equipment manufacturers visits the USSR in June to exchange information on items of interest to the coal industries of both countries. The report of their findings makes no mention of activities in the USSR with respect to the underground gasification of coal.
- 1970 The USSR, in October, begins to import natural gas from Iran on a projected scale of 10,000 million cubic meters per year.
- 1971 The US Atomic Energy Commission (Division of Peaceful Nuclear Explosives) includes underground breakage of coal preparatory to in-situ gasification in its Plowshare program. Non-experimental work reported (Appendix B) in June, based on the coal in the Powder River Basin of Wyoming and on an analysis of four patterns of potential underground nuclear explosions, concludes that underground breakage of coal is probably technically feasible.

- 1971 In August, the USSR Ministry of the Coal Industry declines to arrange a visit by ADL representatives to exchange technical views on the underground gasification of coal. This contrasts with its earlier willingness (in 1957) to cooperate technically with the British effort.
- 1971 The September 10 issue of the Mining Journal (page 224) reports a major expansion of conventional coal mining in the Donets coal basin, where underground gasification work had begun in 1933. Coal output in 1975 is planned to be 50% greater than in 1970.
- 1971 In October a check of major US libraries (including the Library of Congress) reveals that the Russian journal *Podzemnoi Gazifikatsii Uglei* (Underground Gasification of Coal)\* appears to be in a state of limbo. The last issue available at the Library of the US Congress is Volume 13 (1965). The library has no record either of subsequent issues or that the publication has ceased. The latest listings for this journal in the Chemical Abstracts Accession List is for the year 1965. ADL found no references to this journal after 1965 for inclusion in Appendix B.
- 1971 In October, reports summarized in the magazine Coal Mining and Processing (page 11) tell of the construction in the USSR in the Donbas coal basin of a conventional underground coal mine to produce 16,000 tons per day from four faces worked by remotely controlled cutter-loaders. The total work force will be 900.

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\* Officially, *Trudy, Vsesoyuznyi Nauchno-Issledovatel'skii Institut Podzemnoi Gazifikatsii Uglei*.

## APPENDIX B

### THE TECHNICAL AND PATENT LITERATURE SINCE 1960

#### 1. INTRODUCTION

Our review of published information on the subject of *underground* gasification of fossil carbonaceous material covered U.S. and foreign sources. In selected countries we reviewed not only the technical literature but the patent literature as well. When the relevance of a particular reference was not clear, we resolved the issue by including it in our bibliography. (See Section 2.)

##### a. The Technical Literature

An early survey of the literature in 1945 by L.J. Jolley and N. Booth\* covered the literature published primarily from 1934 through 1945, but included four earlier references published between 1868 and 1919. This bibliography listed 123 references. Two later reviews of the literature appeared in 1963. One was the bibliography in Chapter 21 of the book, *The Chemistry of Coal Utilization*, edited by Lowry, authored by Elder, and published by Wiley. The second was *Underground Gasification of Coal, 1945-60: A Bibliography*, by John P. Capp, Robert W. Lowe, and Dorothy W. Simon, published by the US Bureau of Mines as Information Circular 8193. This annotated bibliography contained 734 literature references and 92 patent references.

Our review of the literature covers the period 1960-71. For this review, we relied heavily on the following major abstracting and indexing services: *Chemical Abstracts*, *Chemisches Zentralblatt*, *Engineering Index*, *Fuel Abstracts* and *Current Titles*, *Referativnyi Zhurnal - Khimia*, and the published *Lists of Bureau of Mines Publications and Articles*. We made intensive efforts to obtain copies of all original publications cited in this bibliography. However, some were not available and others could not be obtained within the time limits set for the project. Finally, to report the technical contents we used available abstracts. The initials in parentheses at the end of an abstract indicate the source: thus, BuM = Bureau of Mines; CA = *Chemical Abstracts*; CZ = *Chemisches Zentralblatt*; EI = *Engineering Index*; FA = *Fuel Abstracts*; and RZ = *Referativnyi Zhurnal - Khimia*.

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\* Fuel in Science and Practice, 24 (2), 31-7 (May-June 1945); 24 (3), 73-9 (1945) (Number 9 in the bibliography published by the Bureau of Mines).

While we believe that our bibliography is comprehensive, we lay no claim to its being complete. No one abstracting or indexing service, nor even a combination of the best of them, insures completeness. Moreover, the need to rely on index terms in a literature search in itself precludes completeness. Furthermore, *Chemisches Zentralblatt* ceased publication in 1970, and there were several gaps in our collection of *Fuel Abstracts* for 1961 and 1963.

#### **b. The Patent Literature**

We enlisted the services of two firms who specialize in the searching of patent literature, and with whom we have had long-standing relationships. The countries we selected for search were Great Britain (the United Kingdom), Japan, Poland, the USSR, the United States, and West Germany. The firm of Invention, Inc. (Arlington, Virginia), searched the patent literature in the United States, while the firm of Octrooi-en Merkenbureau Koerts (The Hague, Holland) searched the patent literature of the other countries.

#### **c. Format**

In general, we followed as closely as practical the format used in the USBM bibliography (IC 8193) with respect to numbering of references in the technical literature and arrangement by year of publication. Within each year, we listed the references alphabetically by name of the principal author as cited in the literature. For the year 1960, we listed references only when they did not already appear in the USBM bibliography, since many times literature in one year may not be abstracted until the following or later years.

For the patent literature, we listed the countries searched alphabetically and the patents found in each country in ascending numerical order.

A list of abbreviations for the journals cited in the bibliography appears in Table B-1. Table B-2 lists foreign articles not listed in our bibliography, which we translated in order to provide background information in depth.

TABLE B-1

LIST OF ABBREVIATIONS  
USED FOR JOURNALS

Cited in the Bibliography

Advan. Chem. Ser.	Advances in Chemistry Series
Amer. Gas J.	American Gas Journal
Anal. Chem.	Analytical Chemistry
Anal. Chem. Ann. Rev.	Analytical Chemistry Annual Review
Atomwirt. Atomtech.	Atomwirtschaft, Atomtechnik
Ber. Bunsenges. Phys. Chem.	Berichte der Bunsengesellschaft fuer Physikalische Chemie
Brennst. Waerme-Kraft	Brennstoff-Waerme-Kraft
Brit. Chem. Eng.	British Chemical Engineering
Brit. Coal Util. Res. Assoc. Mon. Bull.	British Coal Utilization Research Association Monthly Bulletin
Bur Mines Bull.	Bureau of Mines Bulletin
Bur. Mines Inform. Cir.	Bureau of Mines Information Circular
Bur. Mines Rep. Invest.	Bureau of Mines Report of Investigations
Bur. Mines TPR	Bureau of Mines Technical Progress Report
Can. Inst. Min. Met. Bull.	Canadian Institute of Mining and Metallurgical Bulletin
Chem. Eng.	Chemical Engineer
Chem. Eng. Progr.	Chemical Engineering Progress
Chem. Eng. Progr. Symp. Ser.	Chemical Engineering Progress, Symposium Series
Chem. Technol.	Chemical Technology
Chemik	Chemik (Gliwice)
Coke Gas	Coke and Gas
Colliery Engineer	Colliery Eng.
Cost. Eng.	Cost Engineering
Dokl. Akad. Nauk SSSR	Doklady Akademii Nauk SSSR
Erdoel Kohle	Erdoel und Kohle
Freiberg. Forsh.	Frieberger Forschungshefte
Gazif. i piroliz topl.	Gazifikatsiya i piroliz topliv
Geol. Surv. Bull.	Geological Survey Bulletin
Gidroteoterm. Usloviya Verkh. Chastei Zemnoi Kory	Gidroteotermicheskie Usloviya Verkhnikh Chastei Zemnoi Kory
Gor. Tverd. Top. Tr. Vses. Konf.	Gorenie Tverdogo Topliv Trudy Vsesoyuznyi Konferentsia
Hydrocarbon Process. Petrol. Refiner	Hydrocarbon Processing and Petroleum Refiner
Ind. Eng. Chem.	Industrial and Engineering Chemistry
Int. J. Rock. Mech. Mining Sci.	International Journal of Rock Mechanics and Mining Science
Izv. Sib. Otd. Akad. Nauk SSSR	Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR

TABLE B-1 (Cont'd)

Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Khim. Nauk	Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR. Seriya Khimicheskikh Nauk
Izv. Vyssh. Ucheb. Zaved. Geol. Razved.	Izvestiya Vysshikh Uchebnykh Zavedenii Geologiya i Razvedka
J. Chem. Eng. Jap.	Journal of Chemical Engineering of Japan
J. Petroleum Technology	Journal of Petroleum Technology
J. Fuel Soc. Jap.	Journal of the Fuel Society of Japan
J. Inst. Eng., Calcutta	Journal of the Institution of Engineers, Calcutta
J. Inst. Fuel	Journal of the Institute of Fuel
J. Mines Metals Fuels	Journal of Mines, Metals, and Fuels
J. Petrol. Technol.	Journal of Petroleum Technology
Kemer. Knizh. Izd.	Kemerovskoe Knizhnoe Izdatel'stvo
Khim. Tverd. Topl.	Khimiya Tverdogo Topliva
Koks, Smola, Gaz	Koks, Smola, Gaz
Kompleks. Ispol'z. Khim. Prod. Podzemn. Gazif. Kuznets Uglei, Kemerovo	Kompleksnoye Ispol'zovaniye Khimicheskikh Produktov Podzemnoy Gazifikatsii Kuznetskikh Uglei
Mater. Geol. Polez. Iskop. Sev.-Vostoka Evr. Chasti SSSR	Materialy Po Geologii i Poleznym Iskopaemykh Severo-Vostoka Evropeiskoi Chasti SSSR, Sbornik Statei
Mater. Pyatoi Knof. Mladsh Nauch. Sotrudn. i Aspir. Lab. Gidrogeol. Probl. Akad. Nauk SSSR,	Materialy Pyatoi Konferentsii Mladshykh Sotrudnikov i Aspirantov Laboratorii Gidrogeologicheskikh Problemy Akademia Nauk SSSR
Midwest Eng.	Midwest Engineer
Min. Congr. J.	Mining Congress Journal
Montan Rdsch.	Montan Rundschau
Petrol. Refiner	Petroleum Refiner
Podzemn. Gazif. v Kuzbasse, Kemerovo	Podzemnoi Gazifikatsii v Kuzbasse, Kemerovo
Podzem. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop.	Podzemnaya Pererabotka Topliv Akademia Nauk Trudy Instituta Goryuchikh Iskopaemykh
Pr. Gl. Inst. Gorn.	Prace Główny Instytutu Gornictwa
Pr. Ustava Vyzk. Paliv	Prace Ustawa pro Vyzkum a Využití Plynných Tuhých Paliv
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo	Problemy Podzemnoi Gazifikatsii v Kuzbasse, Kemerovo
Proc. A.I.Ch.E.	Proceedings of the American Institute of Chemical Engineers
Proc. Amer. Power Conf.	Proceedings of the American Power Conference
Przegł. Gorn.	Przegład Gorniczy
Referat. Zh. Khim.	Referativnyi Zhurnal Khimia
Riv. Combust.	Rivista dei Combustibili
Rep. Progr. Appl. Chem.	Reports on the Progress of Applied Chemistry

TABLE B-1 (Cont'd)

Sb. Pererab. Tverd. Topl., Kemerovo	Sbornik Pererabotka Tverdykh Topliv, Kemerovo
Sb. Probl. Hidrogeol.	Sbornik Problemy Hidrogeologii
Sb. Razvitiye Proizvoditel'nykh sil Bol'shogo Turgaya, Moscow	Sbornik Razvitiye Proizvoditel'nykh sil Bol'shogo Turgaya, Moscow
Sb. Statei Vses. Zaoch. Politekh. Inst.	Sbornik Statei Vsesoyuznogo Zaochnogo Politekhnicheskogo Instituta
Soc. Petrol. Eng. J.	Society of Petroleum Engineers Journal
Tech. uroven a ekon ucinnost vyroby	Technicheska uroven a ekonomicheska ucinnost vyroby
Trans. Inst. Chem. Engr.	Transactions of the Institution of Chemical Engineers
Trans. Soc. Instr. Tech.	Transactions of the Society of Instrument Technology
Tr. Donetsk. ind. inst.	Trudy Donetskogo industrial'nogo instituta
Tr. Inst. Goryuch. Iskop., Akad. Nauk SSSR	Trudy Instituta Goryuchikh Iskopaemykh, Akademia Nauk SSSR
Tr. Lab. Hidrogeol. Probl. Akad. Nauk	Trudy Laboratorii Hidrogeologicheskikh Problemy Akademiya Nauk
Tr. Tatar. Neft. Nauch. Issled. Inst.	Trudy Tatarski Neftyanoi Nauchno- Issledovatel'skii Institute
Tr. vses. n-i. in-ta ispol'z gaza v nar. kh-va i podzemn. khraneniya nefti, nefteproduktov i szhizh gazov	Trudy vsesoyuznogo nauchnogo instituta ispol'zovania gaza v narodnom khoziistve i podzemnogo khraneniya nefti, nefteproduktov i szhizhenie gazov

**TABLE B-2**  
**TRANSLATIONS\***

The following articles, which are not listed in our bibliography, were translated to provide background information for this project:

**1934**

1. Kirichenko, I.P.  
FIRST SURVEY OF THE WORK IN THE AREA OF UNDERGROUND GASIFICATION  
Ugol, No. 101, 90-101 (1934)

**1935**

2. Kirichenko, I.P. and V.S. Ton  
UNDERGROUND COAL GASIFICATION AT THE LISICHANSK MINE  
Gornyi Zhurnal 111 (7), 10-9 (1935)
3. Sazonov, N.I.  
SUMMARY OF THE FIRST EXPERIMENTAL RESULTS OF SUBTERRANEAN GASIFICATION OF COALS  
Khim. Tverd. Top. 6, 17-28 (1935)
4. Sazonov, N.I.  
RESULTS OF EXPERIMENTS ON UNDERGROUND GASIFICATION OF COAL  
Khim. Tverd. Top. 6, 861-9 (1935)

**1938**

5. Buyalov, S.I.  
PRINCIPLES OF UNDERGROUND GASIFICATION  
Ugol, No. 11, 17-24 (1938)

**1939**

6. Kulebakin, V.S.  
UNDERGROUND GASIFICATION OF COAL – ADVANCED SOVIET TECHNOLOGY  
Avtomatika i Telemekhanika 4, 3-6 (1939)

**1956**

7. Silin-Bekchurin, A.I. and K.F. Bogoroditskii  
THE INFLUENCE OF WATER UPON UNDERGROUND COAL GASIFICATION  
Dokl. Akad. Nauk SSSR 109 (4), 832-3 (1956)

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\* Translator: David H. Kraus – Asst. Prof. of Information and Computer Science, Georgia Institute of Technology, Atlanta, Georgia 30332.

1957

8. Bogoroditskii, K.F.  
NATURE OF HYDROGEOLOGICAL STUDIES OF COAL DEPOSITS SUBJECTED TO GASIFICATION  
Podzemn. Gazif. Uglei No. 1, 65-7 (1957)
9. Fedorov, N.A.  
SOME PROBLEMS OF CONDUCTING THE PROCESSES OF UNDERGROUND GASIFICATION OF COAL  
Podzemn. Gazif. Uglei No. 1, 16-21 (1957)
10. Garkusha, I.S.  
RESEARCH DATA AND IMMEDIATE TASKS OF THE ALL-UNION SCIENTIFIC RESEARCH INSTITUTE FOR GASIFICATION OF COAL  
Podzemn. Gazif. Uglei No. 1, 10-15 (1957)
11. Kulish, E.D.  
INDUSTRIAL EXPLOITATION OF NEAR-MOSCOW STATION PODZEMGAZ  
Podzemn. Gazif. Uglei No. 2, 27-31 (1957)
12. Leonovich, K.M.  
RELATION BETWEEN AERODYNAMICS OF GAS-BLAST STREAMS AND TECHNICAL PARAMETERS OF UNDERGROUND GASIFICATION OF COAL  
Podzemn. Gazif. Uglei No. 1, 32-8 (1957)
13. Nusinov, G.O.  
METHOD OF CALCULATING BLAST, COAL AND GAS LOSSES IN THE PROCESS OF UNDERGROUND GASIFICATION OF COAL  
Podzemn. Gazif. Uglei No. 1, 22-8 (1957)
14. Pechuk, I.M.  
THE ACTION AGAINST PENETRATION OF GASES FROM THE UNDERGROUND GAS-GENERATOR IN PIT NO.1 AT THE MINING ENTERPRISES OF THE SKURATOVUGOL TRUST  
Podzemn. Gazif. Uglei No. 2, 100-5 (1957)
15. Strollo, I.S.  
UNDERGROUND GASIFICATION OF THICK SLOPING AND STEEP STRATA OF THE KUZNETSK BASIN COAL PROPOSED IN A CONTEST UNDER THE SLOGAN "PERSPECTIVNYL"  
Podzemn. Gazif. Uglei No. 1, 60-4 (1957)
16. Terpigorev, A.M. and M.P. Korsh  
SCIENTIFIC RESEARCH ON UNDERGROUND GASIFICATION OF COAL CONDUCTED AT THE INSTITUTES OF THE ACADEMY OF SCIENCES, USSR, OVER THE PERIOD 1950-1955  
Podzemn. Gazif. Uglei No. 1, 3-9 (1957)

1957 (Continued)

17. Zyalova, G.P.  
THE ANGREN COAL AS A RAW MATERIAL FOR UNDERGROUND GASIFICATION  
Podzemn. Gazif. Uglei No. 2, 110-3 (1957)

1958

18. Lavrov, N.V. and V.M. Martynova  
DETERMINATION OF CHEMICAL EFFICIENCY OF UNDERGROUND GAS GENERATORS  
Podzemn. Gazif. Uglei No. 4, 5-7 (1958)

1959

19. Al'tshuler, M.M. et al  
ECONOMIC EFFECTIVENESS OF EMPLOYING ENRICHED BLAST (AIR) IN UNDERGROUND GASIFICATION OF COAL  
Podzemn. Gazif. Uglei No. 1, 67-71 (1959)
20. Babkin, V.G.  
THE STRUCTURE OF DEGASIFIED FIELD AND THE COMPLETENESS OF DEGASIFICATION OF A COAL SEAM  
Podzemn. Gazif. Uglei No. 2, 22-5 (1959)
21. Bogoroditskii, K.F.  
SOME DATA FORECASTING THE EFFECT OF THE PHYSICAL CHEMICAL STATE OF UNDERGROUND WATER ON COAL DEPOSITS TO BE GASIFIED  
Podzemn. Gazif. Uglei No. 2, 34-8 (1959)
22. Fedorov, N.A.  
INVESTIGATION OF SOME PROBLEMS OF SHAFTLESS PREPARATION OF COAL BEDS FOR GASIFICATION  
Podzemn. Gazif. Uglei No. 1, 26-30 (1959)
23. Gubergrits, M. Ia. and V. Kh. Brodskaia  
STATE OF THE ART AND PERSPECTIVES OF DEVELOPING THE UNDERGROUND GASIFICATION OPERATION OF COMBUSTIBLE SHALE NEAR THE BALTIC  
Podzemn. Gazif. Uglei No. 1, 3-9 (1959)
24. Lavrov, N.V. et al  
ULTRASONIC CLEANING OF THE DUST COVERED GASES AND PERSPECTIVES OF ITS APPLICATION IN UNDERGROUND GASIFICATION OF COAL  
Podzemn. Gazif. Uglei No. 1, 18-22 (1959)
25. Leshchiner, R.E.  
ECONOMICS AND TECHNICAL PROGRESS IN UNDERGROUND GASIFICATION OF COAL  
Podzemn. Gazif. Uglei No. 4, 64-8 (1959)
26. Mirakov, S.G.  
THE POSSIBILITIES AND NEEDS OF UNDERGROUND GASIFICATION OF COAL IN THE GEORGIAN REPUBLIC  
Podzemn. Gazif. Uglei No. 2, 69-70 (1959)

1959 (Continued)

27. Petrenko, I.G.  
STUDY OF THE UNDERGROUND GASIFICATION PROCESSES OF SOLID FUEL  
USING ISOTOPES  
Podzemn. Gazif. Uglei No. 3, 61-4 (1959)
28. Terpigorev, A.M. and M.P. Korsh  
REALIZATION OF D.I. MENDELEEV'S IDEA REGARDING UNDERGROUND GASIFICATION OF COAL  
Zhurnal Prikladnoi Khimii 32, 705-10 (1959)
29. Tiutin, F.G.  
GAS AS AN INDICATOR OF MECHANICAL STRENGTH OF COAL BEDS DURING  
HYDROFRACTIONATION  
Podzemn. Gazif. Uglei No. 2, 51-5 (1959)
30. Yudin, I.D. and M.V. Rewa  
SOME TECHNOLOGICAL METHODS APPLIED AT THE SOUTHERN-ABINSK STATION  
PODZEMGAZ  
Podzemn. Gazif. Uglei No. 1, 13-5 (1959)
31. Zagredel'naya, V.S. and S.T. Kazachkova  
GASIFICATION OF COAL DEPOSITED IN SANDY ROCKS  
Podzemn. Gazif. Uglei No. 2, 19-22 (1959)
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Podzemn. Gazif. Uglei No. 2, 43-4 (1959)

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1960

- ( 1) Al'tshuler, V.S., N.V. Lavrov et al  
UNDERGROUND GASIFICATION OF COAL UNDER HIGH PRESSURE  
Tr. Inst. Goryuch. Iskop., Akad. Nauk SSSR No. 13, 75-82 (1960)\*

A laboratory study was made of the semicoking of Lisichansk stone coal 2-3 mm and 3-5 mm in size and the gasification of the coke obtained at pressures of 1, 20, and 50 A employing steam-oxygen (70 liters per minute) and steam-air (100 liters per minute) blast. The optimum pressure proved to be 20 A. The gas yield was 335.3 liters per kilogram of coal; the calorific power was 4523 kcal/kg. (RZ)

- ( 2) Antipova, N.G., et al  
INSTRUMENTS FOR AUTOMATIC CONTROL OF UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 3, 97-123 (1960)\*

- ( 3) Blackwood, J.D.  
THE KINETICS OF CARBON GASIFICATION  
Coke Gas 22, 293-7 (1960)

A discussion of the reaction of C with CO<sub>2</sub> and dissocd. gases, including the effect of pressure, nonlinear effects, development of rate equation, effect of H, pretreatment history of C, gasification with at. species, action of active centers, rate-controlling process, and general gasification. (CA)

- ( 4) Bogoroditskii, K.F.  
USE OF GAS-CHEMICAL CALCULATIONS TO DETERMINE THE DEGREE OF FLOODING OF COAL SECTORS THAT ARE TO BE GASIFIED  
pp. 212-6 in Sb. Probl. Gidrogeol. Moscow. Gosgeoltekhizdat (1960)\*

To arrive at an approximate estimate of the quantity of gravitational water and possible regulation of the water regime of an

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\*Original article not available

1960 (Continued)

- (4) *underground* coal gasifier, a method is proposed and examples are given of the calculation of the water balance of an *underground* gasifier. The following methods are recommended for regulating the water cycle of an *underground* gasifier: the drainage of the water, increasing the coefficient of decomposition of the steam by increasing the supply of blast containing oxygen, forcing out of the water by increasing the blast pressure, and others. (RZ)

- (5) Brushtein, N.Z., and G.O. Nusinov  
GASIFICATION OF COAL WITH PREFERRED DEGASSING OF THE COAL IN THE DIRECTION OF THE COAL PILLAR AND WITH PRELIMINARY THERMAL PREPARATION OF THE COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 58-60 (1960)\*

A new technological system of *underground* gasification with preferred degassing of the coal bed in the direction of the coal pillar and with preliminary thermal preparation of the coal with the heat of hot gasses were tested under laboratory conditions and under natural conditions. The object of this technique is to increase the degree of (de) gasification of coal. It was established that the gasification of the coal improves the more the coal is heated, which reduces the final moisture content of the coal pillar and changes the crack content of the coal pillar and makes it possible to gasify coal with a high ash content. Tests and experimental sectors of the Podmoskovnaya and Shatskaya stations of Podzemgaz have shown that when this technique of gasification is used, the gasification of coal improves and quality of the gas produced is also improved, which effects the positive influence on the technico-economic indices. (RZ)

- (6) Derman, B.M. and V.A. Nikolayeva  
THE INFLUENCE OF PRELIMINARY THERMAL PROCESSING ON A COMPOSITION OF GAS IN UNDERGROUND GASIFICATION OF COAL IN A FILTRATION CHANNEL  
Tr. Inst. Goryuch. Iskop., Akad. Nauk. SSSR No. 13, 44-7 (1960)\*

Under laboratory conditions it was shown that preliminary thermal processing of brown coal columns at temperatures greater than 350°C increases the calorific power of the gas produced by gasification employing oxygen blast, from 1500 to 2200 kcal/nm<sup>3</sup> and increases the CO content of the gas in the relationship CO/H<sub>2</sub> (RZ).

1960 (Continued)

- ( 7) Dziunikowski, Kazimierz  
INDUSTRIAL EXPLOITATION OF COAL DEPOSITS BY UNDERGROUND GASIFICATION  
Przegl. Gorn. 16 (5) 269-75 (1960) (In Polish)

Survey with data on the technico-economic parameters of the process based on the experience of *underground* gasification stations in the Soviet Union and in England. (RZ)

- ( 8) Dziunikowski, K.  
PRINCIPLES FOR INTERPRETING PHYSICOCHEMICAL PROCESSES IN UNDERGROUND GASIFICATION OF COAL BY AIR AND THEIR EXPERIMENTAL ILLUSTRATION  
Pr. Gl. Inst. Gorn., Komun. (Katowice) Ser. A, No. 246, 1-15 (1960)

The use of O rather than air for *underground* gasification of coal is recommended, because the heating value of the gas produced and efficiency deteriorate with the use of air. The heat content of particularly the N in the product gas on using air results in a lowering of the temperature in the gasification zone and a heat loss greater than to the surrounding terrain. (CA)

- ( 9) Dziunikowski, K.  
UNDERGROUND GASIFICATION OF COAL BY AIR: INTERPRETATION OF PHYSICOCHEMICAL PRINCIPLES  
J. Inst. Fuel 33, 337-43 (July 1960)

A description is given of the principles involved in *underground* gasification processes for coal, and some of the physicochemical processes occurring are interpreted. Four experiments were carried out on the *underground* gasification of coal by air in a 1-m. seam. The results of these tests (divided into 10-hr periods) was: The initial calorific value of the gas is over 1000 kcal/standard cu. m., but this gradually decreases to 700-800 kcal/standard cu. m; this latter value would be expected in industrial gasification of coal with air. Partial combustion of H is continuous, increasing in the final period. However, after a period of gasification with pure O, steam was decomposed and the gas contained 10% H, with a calorific value of over 2000 kcal/standard cu. m. for the first few hours, after air was substituted for pure O. A formula is given for calcg. the effective efficiency factor; this was about 0.6. In the thermal balance the sensible heat of the gas is an appreciable

1960 (Continued)

- ( 9) factor. It is greater than that of useless losses to the surrounding  
(cont'd) rocks and is more than 20% of the heating value of the gasified  
coal. Useful losses to the surrounding rocks (recovered in gasifica-  
tion ) are about 5-6%. (CA)
- (10) Garkusha, I.S. et al  
RESULTS OF THE WORK OF PODZEMGAZ STATIONS IN 1959  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 2, 3-17 (1960)\*
- (11) Garkusha, I.S. and M.M. Al'tshuler  
METHOD OF DETERMINING THE NATIONAL-ECONOMIC EFFEC-  
TIVENESS OF UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 3, 80-138  
(1960)\*
- (12) Kindermann, Gerhard C.  
PRESENT STATUS OF UNDERGROUND GASIFICATION IN THE  
USSR  
Erdoel Kohle 13 (9), 664-7 (1960) (In German)  
  
A survey. (CA) (Original article translated.)
- (13) Klosky, Simon  
INDEX OF SELECTED GASIFICATION PATENTS I. UNITED STATES  
PATENTS  
Bur. Mines Bull. 581 (1960)  
  
Includes abstracts of more than 500 patents issued between 1867  
and 1955 on coal-gasification processes. Part II includes United  
Kingdom and other patents and Part III, European patents.  
Parts II and III published in 1962. (BuM)
- (14) Kochergin, N.I.  
BASIC TECHNICAL PROBLEMS IN THE FIELD OF UNDERGROUND  
GASIFICATION OF COAL  
Tr. Donetsk. ind. inst. 38, 19-27 (1960)
- (15) Kononov, V.I.  
CHARACTERISTICS OF THE HYDRODYNAMIC AND HYDRO-  
CHEMICAL CONDITIONS OF UNDERGROUND WATERS IN THE  
MOSCOW AND LISICHANSK AREAS OF UNDERGROUND COAL  
GASIFICATION  
pp. 20-2 in Sb. Mater. Pyatoi Konf. Mladsh. Nauch. Sotrudn. i Aspirantov.  
Lab. Hidrogeol. Problem, Akad Nauk SSSR, Moscow (1960)\*

1960 (Continued)

- (16) Kosec, W.  
UNDERGROUND GASIFICATION OF COAL  
Technicke Prace 12 (11), 987-9 (1960)\* (In Slovak)

The composition in (% by volume) of the gas produced in an experimental *underground* gasification installation in Borislav(a), Czechoslovakia is given: CO<sub>2</sub>, 18%; CO, 6%; H<sub>2</sub>, 17%; O<sub>2</sub>, 0.7%; CH<sub>4</sub>, 3%; N<sub>2</sub>, 55.3%; the calorific power of the dry gas was 850 kcal/nm<sup>3</sup>, of the raw gas 400 kcal/nm<sup>3</sup>; moisture content 400 g/nm<sup>3</sup>, tar content 1.3 g/nm<sup>3</sup>, phenols 3.1 g/nm<sup>3</sup>, mechanical impurities 0.4-2 g/nm<sup>3</sup>. The method of cleansing the gas H<sub>2</sub>O, tar, and mechanical impurities is described. A drawback in the method is the loss of a considerable amount of heat (temperature of the gas leaving the borehole approximately 350°). (RZ)

- (17) Kreinin, E.V., and I.L. Farverov  
THE PROBLEM OF ACHIEVING EFFECTIVE HYDRODYNAMIC CONDITIONS FOR THE FIRE FILTRATION CROSSCUTTING OF BOREHOLES  
Tr. Inst. Goryuch. Iskop., Akad. Nauk. SSSR No. 13, 125-30 (1960)

It is recommended that crosscutting be carried out first to the blast borehold and then to the gas removal borehole. The direction of crosscutting blast is changed after it has reached the center of combustion at the moment the crosscutting center has begun to move along the coal seam. (RZ)

- (18) Nusinov, G.O., N.Z. Brushtein, and N.S. Miringof  
DEPENDENCE OF GAS QUALITY ON THE MOISTURE CONTENT OF GASIFIED COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 3, 13-8 (1960)\*

- (19) Petrenko, I.G. and E. Belyanova  
METHOD OF STUDYING THE MOVEMENT OF GASES IN THE UNDERGROUND GASIFIER EMPLOYING RADIOACTIVE ISOTOPES  
Tr. Inst. Goryuch. Iskop. Akad. Nauk. SSSR No. 13, 144-62 (1960)

The methodology and principle conditions are described for employing radioactive isotopes to study the gas streams in an *underground* gasifier. (RZ)

1960 (Continued)

- (20) Pitin, R.N. and K.I. Cheredkova  
THE INFLUENCE OF THE CONCENTRATION OF OXYGEN IN THE  
BLAST ON THE RATE OF MOVEMENT OF THE ZONES IN THE  
CROSSCUTTING STAGE OF UNDERGROUND GASIFICATION  
Tr. Inst. Goryuch. Iskop., Akad. Nauk. SSSR No. 13, 61-70 (1960)

Using a laboratory model of a single crack (fissure) it was shown that with countercurrent crosscutting the beginning of the gasification zone moves with the specified minimum amount of oxygen; when the amount of oxygen in the blast is increased from 21-34 to 100%, the rate of movement of the gasification zone increases by a factor of 12-30 for brown coal and by a factor of 300 for wood. (RZ)

- (21) Pitin, R.N.  
SOME PROBLEMS OF REDUCING THE LEAKAGES OF BLAST AND  
GAS IN UNDERGROUND GASIFICATION OF PODMOSKOVNAYA  
BROWN COALS  
Tr. Inst. Goryuch. Iskop., Akad. Nauk. SSSR No. 13, 115-24 (1960)

To reduce gas leakages during *underground* gasification it is recommended that the boreholes be crosscut after preliminary hydraulic fracture of the coal seam and with reduced pressure at the gas removal boreholes, it is also recommended that the gasification be carried out with maximum intensity of outgassing and with the minimum admissible static pressure. (RZ)

- (22) Pitin, R.N. and Yu. A. Ponnik  
DISTRIBUTION OF BLAST DURING THE CROSSCUTTING PROCESS  
IN UNDERGROUND GASIFICATION OF FUELS  
Tr. Inst. Goryuch. Iskop., Akad. Nauk. SSSR No. 13, 131-43 (1960)\*

The authors study the distribution of blast in the fuel (coal) seam during crosscutting employing a model which they developed by the electro hydrodynamic analog method. (RZ)

- (23) Ragunath, Singh  
UNDERGROUND GASIFICATION OF COAL  
Commet 9, 70-7 (1960)

Described is the principle of *underground* gasification and prospects of using it in India. (RZ)

1960 (Continued)

- (24) Rauk, J.  
INDUSTRIAL USE IN GAS TURBINES OF GAS FROM UNDERGROUND GASIFICATION OF COAL  
Przegl. Gorn. No. 10 and 11, 535-9 (1960)\*
- (25) Reznik, M.G.  
SOME PROPERTIES OF COKE RESIDUES THAT FORM DURING UNDERGROUND GASIFICATION OF COAL  
Tr. Donetsk. ind. inst. 38, 29-37 (1960)
- Studies of the coke residues that were extracted during the opening of the *underground* gasifier at Lisichansk showed that there was a distinct increase in the yield of volatile substances in a direction perpendicular to line of the fire front. At a distance of 20 centimeters from the reacting surface, the yield of volatile substances reached 6%. A similar relationship was noted with respect to specific electrical resistance. (RZ)
- (26) Semenenko, D.K.  
THE YIELDS (PRODUCTION) OF BOREHOLES SITUATED IN SERIES IN A NONHOMOGENEOUS COAL BED, AND GAS LOSSES  
Tr. Vses. Nauch Issled. Inst. Podzemn, Gazif. Uglei No. 3, 27-47 (1960)\*
- The yield of gas boreholes and *underground* gasification of coal and in homogeneous coal beds is calculated. A number of recommendations is made for reducing the loss of gas as the result of leakages. (RZ)
- (27) Silin-Bekchurin, A.I. et al  
ROLE OF UNDERGROUND WATER AND OTHER NATURAL FACTORS IN THE UNDERGROUND GASIFICATION  
Tr. Lab. Hidrogeol. Problem. Akad. Nauk SSSR NO. 23, (1960) 127 pp
- (28) Toekhiko, Yamazaki  
PROCESSING OF COAL BY CHEMICAL METHODS  
Nippon Kogyo Kaishi 76 (869), 769-72 (1960)

Several different methods of extracting coal are presented: hydrogenation cracking and destructive hydrogenation of coal, the working of coal beds with superheated steam at high temperature and pressure in combination with gasification and the use of

1960 (Continued)

- (28) oxygen. As a variant of *underground* gasification, a method employing *underground* nuclear reactors is examined, and also a method of cracking coal in a colloidal state under the action of a concentrated alkalized solution under pressure. It is noted that the most effective and economical method is the method of *underground* destructive hydrogenation (liquation) of coal which gives the best yield of valuable components of coal. The advantage of this method is that its effectiveness increases as the depth of working increases and there is a possibility of simultaneously obtaining methane and other fuel gases. Hydrogenation cracking takes place at a temperature of approximately 450°C and pressure greater than 200 atmospheres. It is shown that it is effective to use this method with boreholes deeper than 1000 meters. A method is described for making [drilling holes] boreholes. A method of working coal by converting it in the bed into a plasma state at a temperature of approximately 10,000°C is also examined. (RZ)

- (29) Zagredel'naya, V.S., T.M. Sukhotinskaya, and I.D. Yudin  
INVESTIGATION OF THE DYNAMICS OF GAS FORMATION AND  
OF THE INFLUENCE OF VARIOUS FACTORS ON THE PROCESS OF  
UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 50-5 (1960)\*

The dynamics of gas formation was studied on the basis of the data of the Podzemgaz (*Underground Gasification Trust*) stations and using models. The influence of the quantity of blast, ash content, moisture content, and other factors on the composition of the gas was determined. (RZ)

- (30) Agroskin, A.A. and N.S. Miringof  
KINETICS OF THERMAL DECOMPOSITION OF COMBUSTIBLE SOLIDS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 4, 3-10 (1961)\*
- (31) Al'tshuler, M.M. et al  
ECONOMIC ANALYSIS OF THE ACTIVE PODZEMGAZ STATIONS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 107-14 (1961)\*
- (32) Al'tshuler, M.M. et al  
WORKING OUT THE TECHNICO-ECONOMIC INDICES FOR PLANNING INDUSTRIAL STATIONS OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 114-29 (1961)\*
- (33) Al'tshuler, M.M. and R.E. Leshchiner  
PROSPECTS FOR THE DEVELOPMENT OF UNDERGROUND GASIFICATION OF COAL IN SIBERIA AND FAR EAST  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 5, 91-9 (1961)
- It was found expedient to construct, in place of the proposed open pit mines, the following *underground* gasification stations: in the Kholbol'zhinsky and Lake Gusinoe deposit in the Buryat ASSR, in the Chitin region, the Bikin and other regions. (RZ)
- (34) Antipova, N.G. and E.M. Belyanova  
DEVELOPMENT OF MEANS AND METHODS FOR AUTOMATIC CONTROL OF THE PARAMETERS OF GAS AND BLAST MEDIA  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 98-101 (1961)\*
- (35) Arimasa, Baba  
UNDERGROUND GASIFICATION OF COAL  
Doréku 11 (62), 203-5 (1961)
- (36) Averitt, Paul  
COAL RESERVES OF THE UNITED STATES – A PROGRESS REPORT – JANUARY 1, 1960  
Geol. Surv. Bull. 1136 (1961)

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\*Original article not available

1961 (Continued)

- (37) Balfour, A.E.  
UNDERGROUND GASIFICATION OF COAL  
Colliery Guardian 203 (5254), 782-6, 788, 790 (28 December 1961)
- Blind borehole and alternative methods; instruments for temperature, air and gas volume and pressure measurement, and for gas analysis; special instrumentation techniques, including use of remote-reading inclinometer, remote-reading compass and coal-sensing device; problems of intersection of vertical and horizontal boreholes; detection of leaks in *underground* air piping. (EI)
- (38) Balfour, A.E.  
UNDERGROUND GASIFICATION OF COAL  
Gas World 154, 438-42 (7 October 1961)
- Leaks in the piping in an *underground* coal gasification plant in Newman Spinney, England, were detected by the use of Kr<sup>65</sup>. (CA)
- (39) Brushtein, N.Z. and S.P. Golger  
TESTING OF THE UNDERGROUND GASIFICATION OF COAL EMPLOYING STEAM-OXYGEN-AIR BLAST  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 64-6 (1961)\*
- Experiments were conducted at the Podnoskovnaya station with a blast rate of 900-1400 nm<sup>3</sup>/hr with a 55-70% concentration of oxygen in the blast. The composition of the gas obtained (in %) was: CO<sub>2</sub>, 28.2; CO, 15.0; H<sub>2</sub>, 35.0; CH<sub>4</sub>, 1.9; N<sub>2</sub>, 16.5; H<sub>2</sub>S, 2.8; the calorific power of the gas was lower, 1735 kcal/nm<sup>3</sup>. (RZ)
- (40) Capp, J.P., K.D. Plants, M.H. Fies, C.D. Pears, and L.L. Hirst  
UNDERGROUND GASIFICATION OF COAL: SECOND EXPERIMENT IN PREPARING A PATH THROUGH A COAL BED BY HYDRAULIC FRACTURING  
Bur. Mines Rep. Invest. 5808 (1961)
- Involves the use of hydraulic fracturing to increase air acceptance of a coalbed for the introduction of combustion air and the removal of product gases. (BuM)
- (41) Capp, John P., Robert W. Lowe, and Everett F. House  
UNDERGROUND GASIFICATION OF COAL: OPERATION OF MULTIPLE-PATH SYSTEM  
Bur. Mines Rep. Invest. 5830 (1961)

1961 (Continued)

- (41) Indicates the feasibility of simultaneously burning several paths through a coalbed to develop a multiple-path *underground* gasification system. (BuM)
- (42) Charbula, Karel  
UNDERGROUND GASIFICATION OF COAL  
Tech. uroven a ekon. ucinnost vyroby No. 3, (1961) 90 pp (In Czech)
- (43) Esfandiary, Mary S.  
FOREIGN LITERATURE ON COAL: A GUIDE TO ABSTRACTS AND TRANSLATIONS  
Bur. Mines Inform. Cir. 8063 (1961)
- Describes sources available used to obtain information on foreign coal technology. (BuM)
- (44) Farberov, I.L.  
SHORT SURVEY OF THE OPERATION OF THE FUEL MINERAL PRODUCTS OF THE ANSSSR OF THE UNDERGROUND PROCESSING OF FUELS  
Tr. Inst. Goryuch. Iskop., Akad. Nauk. SSSR 16, 248-61 (1961)\*
- (45) Gun'kov, B.M.  
PULSATING FLOW IN PROCESSES OF CHEMICAL TECHNOLOGY  
Tr. Inst. Goryuch. Iskop. Akad. Nauk SSSR 16, 83-101 (1961)\*
- (46) Gvozdev, A.P., V.V. Sokolov, and M.I. Shapiro  
UTILIZATION OF THE GAS PRODUCED BY UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 102-6 (1961)\*

Data are given on the industrial and the domestic use of gas produced by *underground* gasification of coal produced at active stations. The advantages of converting industrial furnaces from coal to gas produced by *underground* gasification are noted. Complete burning of the gas is achieved with a coefficient of air excess of 1.10-1.12. In experiments in burning *underground* gasification gas with the calorific power of 794 kcal/m<sup>3</sup> a boiler efficiency of 0.88 and the [efficiency] of the electric station of 0.275 was achieved, while with natural gas (calorific power of 8533 kcal/m<sup>3</sup>), under the same conditions, the figures are 0.92 and 0.285 respectively. (RZ)

1961 (Continued)

- (47) Hokao, Zenjiro  
UNDERGROUND GASIFICATION OF COAL BY OXYGEN  
Nippon Kogyo Kaishi 77, 970-4 (1961)
- Use of O instead of air for *underground* gasification of coal was studied. A calorific value of  $> 1000$  kcal/cu. m resulted. (CA)
- (48) Katell, Sidney and John H. Faber  
ESTIMATED COSTS OF GASIFYING COAL IN PLACE  
Gas Age 128, 40-4 (14 September 1961); (Bur. Mines Inform. Cir. 8020 1961)
- Presents a study based on electrolinking and hydraulic fracturing experiments. Provides an economic analysis. Develops a basic cost formula for any *underground* gasification system. (BuM)
- (49) Kazak, V.N., I.K. Korolev, and D.K. Semenenko  
LOSSES OF COAL UNDERGROUND  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 69-71 (1961)\*
- Data are given on coal losses *underground* during *underground* gasification and the reasons which govern the magnitude of the losses are discussed. It is shown that the magnitude of losses depends essentially on the distance between boreholes; at the Podmoskovnaya station the losses amounted to 21% with the network of boreholes 25 x 25 meters, while the losses were 52% with a borehole network of 25 x 40 meters. Losses of coal also are a function of its ash content, permeability, and the nature of the rocks which cover and underline the coal seam. Data are given on the losses of coal *underground* in the industrial gasifiers of the Podmoskovnaya station in the years 1951 through 1958. The losses varied from 8 to 50%. The coal losses at Lisichansk and South Abinsk stations were smaller and varied between 2 and 30%. (RZ)
- (50) Leshchiner, R.E.  
ECONOMIC EFFECTIVENESS OF UNDERGROUND GASIFICATION OF COAL IN VARIOUS REGIONS OF THE SOVIET UNION  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 4, 93-105 (1961)\*

1961 (Continued)

- (51) Leshchiner, R.E.  
FACTORS FOR IMPROVING THE TECHNICO-ECONOMIC INDICES OF UNDERGROUND GASIFICATION OF COAL BY INCREASING THE CAPACITY OF THE PODZEMGAZ STATIONS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 4, 105-14 (1961)\*
- (52) Leshchiner, R.E.  
ECONOMIC PROBLEMS CONCERNING THE ENERGY REQUIREMENTS OF THE UNDERGROUND GASIFICATION STATION  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 5, 80-90 (1961)\*
- (53) Lichtig, Ignaz  
CONVERSION OF COAL TO FLUID FUELS: ABSTRACTS OF SELECTED GERMAN PATENT APPLICATIONS  
Bur. Mines Inform. Cir. 8065 (1961)
- German patents have been particularly useful in this field because both processes for the complete conversion of coal to fluid fuels originated in Germany and were thoroughly investigated there because of the shortage of indigenous fluid fuels. Patents cover chemical processes and apparatus, furnace installations, gas production by degasification of fuels, wet methods of producing fuel gas, production of fuel gas by carbureting, and purification of distillation gas and of acetylene. (BuM)
- (54) Nusinov, G.O.  
BASIC PARAMETERS OF THE TECHNOLOGY OF UNDERGROUND GASIFICATION OF BROWN COAL  
Referat. Zh. Khim. No. 4, M133 (1961)
- Author's summary of doctoral dissertation for Degree of Technical Sciences, Institute of Combustible Minerals, Soviet Academy of Sciences, Moscow, 1960.
- (55) Nusinov, G.O., N.Z. Brushtein, M.A. Kulakova, and N.S. Miringof  
EXPERIMENT IN EMPLOYING HYDRAULIC FRACTURE OF A SEAM IN THE BROWN COAL DEPOSITS OF THE PODMOSKOVNYI BASIN  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 5, 3-12 (1961)\*

1961 (Continued)

- (55) (cont'd) The results of experiments in the application of hydraulic fracture of a coal seam between boreholes at the Podmoskovnaya and Shatskaya *underground* gasification stations are discussed. In many cases it was established that the new method has an advantage over the methods of electrolinking and filtration cross-cutting. (RZ)
- (56) Orna, Bernard  
UNDERGROUND GASIFICATION OF COAL IN CZECHOSLOVAKIA  
Colliery Guardian 202 (5214), 363-4 (23 March 1961)
- Czechoslovak interest in *underground* gasification is in connection with seams that cannot be mined, and in connection with isolated deposits where there is little coal and opening of mine employing classical methods would be uneconomical; consideration is also given to gasification of coal left over in old mines which cannot be extracted by normal methods. (EI)
- (57) Perry, Harry and Carl C. Anderson  
FUEL TECHNOLOGY IN THE UNITED STATES  
J. Inst. Fuel 34 (249), 421-39 (October 1961)
- Surveys the entire fossil fuel situation in the United States; history, reserves, technology, and present and future uses of coal, petroleum, and natural gas. While the use of petroleum and natural gas will continue to increase as population and per capita consumption increase, it is believed that coal will claim a larger proportional share of the energy market, particularly in generating electric power. (BuM)
- (58) Pitin, R.N., and Yu. A. Ponnik  
AERODYNAMIC EFFECTIVENESS OF HYDRAULIC FRACTURE OF A COAL SEAM DURING UNDERGROUND GASIFICATION  
Tr. Inst. Goryuch. Iskop., Akad. Nauk. SSSR 16, 284-94 (1961)\*
- (59) Rauk, J.  
ROOF CONTROL DURING UNDERGROUND GASIFICATION OF COAL IN THIN INCLINED SEAMS  
Przegl. Gorn No. 3, 163-70 (1961)

1961 (Continued)

(59) Differences in *underground* gasification of coal with air and with comp. pure O are discussed together with their influence on the behavior of mine roofs. The steadiness of the process would minimize the possibility of carrying out the reaction in empty spaces remaining after gasification and in roof gaps. Increased concentration of oxidizing agent in the flame zone intensifies the process. Gasification with air in thin seams reduces the possibility of roof control. (CA)

(60) Reznikov, A.D.  
INDUSTRIAL SCALE RESULTS ON ELECTRICAL-CARBONIZATION/GASIFICATION AT THE MOSCOW UNDERGROUND-GASIFICATION STATIONS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 4, 47-52 (1961)\*

(61) Rotter, Dietrich  
STATUS AND PROBLEMS OF UNDERGROUND GASIFICATION OF COAL  
Bergakademie 13 (11), 706-11 (1961) (In German)

The author considers experiments on the *underground* gasification of coal in different countries, paying particular attention to work being carried out in the Soviet Union. The different methods – and their variants are described in detail. Finally, the author considers the gas losses, the quality of the gas, and its suitability for various applications (FA) (In German)

(62) Russell, Paul L.  
NUCLEAR BLASTING AND ITS POTENTIAL FOR STRIPPING OVER-BURDEN  
Proceedings of the 27th Mining Symposium and 39th Annual Meetings of the Minnesota Section of the AIME, pp. 145-51 (10-12 January 1961)

Nuclear cratering experiments have demonstrated the ability of nuclear explosives to move vast volumes of earth and rock. Their compact size for very high energy yields permits emplacement at less cost than equal energy yields of chemical explosives. Phenomenology of nuclear cratering and possible application to overburden removal for open-pit mining is discussed. Limitations and hazards are considered. All cratering explosions result in the release of radioactivity to the atmosphere; however, this release is generally small compared with that of above-ground explosions of

1961 (Continued)

(62) similar yield. Most of this radioactivity falls out locally and, unlike  
(cont'd) above-ground detonations, only a very small quantity is believed to enter the worldwide fallout system. Extensive research on reduction in radioactive contamination indicates that current technology is such that cratering tests in selected areas should not significantly raise radiation levels beyond our borders and therefore should present no danger. (BuM)

(63) Semenenko, D.K.  
INVESTIGATIONS OF BLAST AND GAS LOSSES, AND METHODS FOR REDUCING GAS LOSSES  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 67-9 (1961)\*

Tests conducted at the Podmoskovnaya station of Podzemgaz (*Underground Gas Trust*) have shown that in *underground* gasification there are gas losses through blast, drainage, and exhaust boreholes, through leakages in the communication lines, and from the gasifier into the surrounding rock massif. The losses in the underground part of the gasifier come out to 55%, the remaining 45% of the losses can be eliminated. A list of measures is given for eliminating gas losses, in particular it is recommended that a pressure of 0.3 or less A be maintained in the *underground* gasifier. (RZ)

(64) Semenenko, D.K.  
STUDY OF GAS CIRCULATION IN COAL BEDS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 4, 33-46 (1961)\*

(65) Shmarev, A.P. and S.N. Yatrov  
GROUP METHOD OF UNDERGROUND GASIFICATION OF COAL EMPLOYING HYDRAULIC FRACTURING OF THE SEAM  
Sb. Statei Vses. Zaoch. Politekh. Inst. No. 26, 69-76 (1961)\*

Concepts are presented on intensification of the *underground* gasification of deeply bedded coal seams by hydraulic fracturing of the seam and simultaneous operation of a group of blast and gas removal boreholes, regulation of the combustion process and other measures. (RZ)

(66) Yurchenko, V.P. and V.G. Artamoshkina  
FOREIGN EXPERIMENTAL WORK IN UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 5, 100-11 (1961)\*

- (67) Al'tshuler, M.M., G.N. Mikhaylova, and E. Yu Chernyak  
 TECHNICAL-ECONOMIC ANALYSIS OF THE OPERATION OF  
 PODZEMGAZ STATIONS AND STONE COAL DEPOSITS, 1960  
 Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 6, 108-14 (1962)
- (68) Al'tshuler, M.M. and R.E. Leshchiner  
 SOME QUESTIONS OF THE ECONOMICS OF CHEMICAL PROCES-  
 SING OF THE GAS PRODUCED BY UNDERGROUND GASIFICATION  
 Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 83-96 (1962)

Data are given for determining the technical-economic indices of process gas production for  $\text{NH}_3$  synthesis based on *underground* gasification of coal, with application to the Dzhanyspay deposit of the Turday basin of the Tselinnyi district; it is assumed that the gas of *underground* gasification of the coal has a composition as follows (% by volume):  $\text{CO}$ , 15.2%;  $\text{H}_2$ , 35.4%;  $\text{CO}_2$ , 29.0%;  $\text{O}_2$ , 0.3%;  $\text{H}_2\text{S}$ , 2.4%; unsaturated hydrocarbons, 0.5%;  $\text{CH}_4$ , 1.9%;  $\text{N}_2$ , 15.2%; gas of this type is produced by enriched blast containing 60% oxygen and  $300 \text{ g/nm}^3$  steam. The economic indices of purifying the gas of *underground* gasification of coal by different methods are examined. Figures are given on the cost of producing  $\text{NH}_3$  from the natural gas of the Gazli deposit by catalytic steam-oxygen-air conversion; from the gas of *underground* gasification of coal; and from the gas of continuous steam-oxygen gasification of the coke of Karaganda coal. (RZ)

- (69) Al'tshuler, M.M., Yu. D. Kalmanova, G.N. Mikhaylova, and E. Yu Chernyak  
 TECHNICO-ECONOMIC ANALYSIS OF THE OPERATION OF POD-  
 ZEMGAZ STATIONS FOR 1961  
 Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 80-7 (1962)

The trends of scientific research on developing new methods for *underground* processing of fuel are discussed. The following promising trends are pointed out: the extraction of humic and other acids from the coal in the bed by alkalized solutions, *underground* dissolution of coals in organic solvents, processing with gaseous reagents, *underground* burning [of the coal] to produce high pressure steam, thermal processing employing atomic energy, and still other processes. (RZ)

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\*Original article not available

1962 (Continued)

- (70) Al'tshuler, M.M.  
METHOD FOR CALCULATING THE COST OF GAS PRODUCED BY  
UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 104-7 (1962)

- (71) Bakulev, G.D.  
AN ECONOMIC ANALYSIS OF UNDERGROUND GASIFICATION OF  
COAL  
Bur. Mines Inform. Cir. 8069 (1962)

Represents a translation of a Soviet publication. The objective of the work described was to investigate the present and future economic problems involved in the *underground* gasification process. Briefly discusses the history and early development of the process. (BuM)

- (72) Balfour, A.E.  
UNDERGROUND GASIFICATION OF COAL: SOME FEATURES OF  
INSTRUMENTATION  
Trans. Soc. Instr. Tech., 14 (1), 50-6 (March 1962)

Blind borehole and alternative methods; instruments for temperature, air and gas volume and pressure measurement, and for gas analysis; special instrumentation techniques, including use of remote-reading inclinometer, remote-reading compass and coal-sensing device; problems of intersection of vertical and horizontal boreholes; detection of leaks in *underground* air piping. (EI)

- (73) Baxter, J.S.  
LONG BOREHOLES IN COAL  
Colliery Eng. 39 (462), 320-6 (August 1962)

Studies in use of radioactive detector methods of proving relative positions of 2 boreholes *underground* at Newman Spinney coal mines, England; radioactive material was introduced into one hole and scintillation counter into another; calibration of equipment; effect of background radiation; effect of pyrites within coal seam on shielding counter from radiation. (EI)

- (74) Baxter, J.S.  
UNDERGROUND GASIFICATION TRIALS  
Colliery Eng. 39 (466), 511-6 (December 1962)

1962 (Continued)

- (74) Features necessary for successful *underground* gasification of coal seams at Newman Spinney near Chesterfield, Derbyshire; dimensions and design of stopping, pumping, ignition and gasification of system, entrainment of solids in gas stream, control of gas quality and volume, results of 7 week gasification operation. (EI)  
(cont'd)
- (75) Bogdanova, V.V. and V.G. Smirnov  
INDUSTRIAL-SCALE TESTS ON HYDRAULIC DISRUPTION OF THE AOUGR. -40 SEAM (MOSCOW BASIN)  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 69-73 (1962)\*
- (76) Capp, J.P. and K.D. Plants  
UNDERGROUND GASIFICATION OF COAL WITH OXYGEN-ENRICHED AIR  
Bur. Mines Rep. Invest. 6042 (1962)
- Describes tests with oxygen-enriched air conducted in an Alabama coal field. During the best gasification period, which extended for 2-1/2 days, 780,000 std cu ft of 124-Btu gas was produced. In other periods the heating value at times was almost 300 Btu per std cu ft, but sustained production of such gas was not achieved. Approximately 12 million Btu per foot of nominal path was recovered at the surface. Work done in cooperation with the Alabama Power Company. (BuM)
- (77) Fedorov, N.A. et al  
HYDRAULIC DISRUPTION OF COAL AT DEPTHS EXCEEDING 250 M  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 6, 66-78 (1962)
- (78) Fedorov, N.A.  
THE NATURE OF GAS FORMATION DURING COUNTERFLOW CROSSCUTTING OF BOREHOLES  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 3-4 (1962)

The change in the ratio  $O_f O_d$  of the  $O_2$  content in the gas of *underground* gasification and in the blast is investigated as a function of the distance between boreholes, according to the data of the Lisichansk station. In the case of blast furnace combustion of the coal  $O_f O_d = 0.88$ . Under conditions of countercurrent crosscutting of boreholes  $O_f O_d$  is less than 0.88. This explained by

1962 (Continued)

- (78) the adsorption of O by the coal and by the expenditure of the  
(cont'd) hydrogen-containing components of the gas in combustion. (RZ)

- (79) Fedorov, N.A.  
REACTION RATE OF COAL DURING COUNTERCURRENT MOVE-  
MENT OF THE COMBUSTION CENTER IN SLIT CHANNELS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 5-7 (1962)

In countercurrent movement of the combustion center, the oxygen of the air reacts with the particles of coal that are catching fire and those already ignited. In this case, the total rate of reaction of the coal is linearly dependent on the Reynolds number (Re). It is concluded that in a case of countercurrent movement of the combustion center in a slit (slot) channel, the reaction processes of oxygen with the coal particles that are being ignited take place in a region close to the kinetic [region], and the total processes (that is including the reaction with the coal that has already been ignited) takes place in a region approaching the diffusion [region]. (RZ)

- (80) Fedorov, N.A., et al  
COMPOSITION OF AND MEANS OF USING THE LIQUID PRODUCTS  
OF UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 95-103 (1962)

300-350 g/cm<sup>3</sup> of water condensate and up to 3 g/m<sup>3</sup> of tar were separated from the gas of the *underground* gasification of brown coal at the Shatskaya station. The characteristics of the tar were as follows: specific weight 0.966-0.982, viscosity at 20°C, 1.92°E, phenol content 9-10%, bases 2.8-3.6%, up to 300°C, 66.7-67.6% boils away. The following group composition of the neutral mass was found (in %): unsaturated hydrocarbons 14.4-32.0, aromatic [compounds] 14.0-32.0, paraffins and naphthenes 30.0-36.0, neutral oxygen compounds 20.0-22.0. We give the results of experiments in applying the phenols of the tar for synthesizing resols of neutral oils as softeners of rubber, and the use of the water condensate as a fertilizer. (RZ)

- (81) Gershevich, E.G., A.A. Kashkin, Ye. V. Kreyenin, and M.K. Revva  
BASIC RESULTS OF THE WORK OF THE SOUTH ABINSK STATION  
OF PODZEMGAZ FOR 1961  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 87-91 (1962)

1962 (Continued)

- (82) Glivicky, Oldrich  
RESULTS OF UNDERGROUND GASIFICATION OF BROWN COALS  
IN THE NORTH BOHEMIAN BASIN (CZECHOSLOVAKIA)  
Bergbautechnik 12 (2), 99-101 (1962) (In German)

In Czechoslovakia attempts are under way to gasify nonworkable brown-coal seams *below ground*. The results of tests carried out near Chomutov are described. A detailed description of the geological conditions is followed by an account of the gasification process and its difficulties and an analysis of the gas yield. (FA)

- (83) Golger, S.P.  
STUDY OF GASIFICATION AT A DEPTH OF 300-400m. AT THE  
LISICHANSK-UNDERGROUND GAS STATION  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 6, 11-19 (1962)

A description is given of the preparation, ignition, and operation of an *underground* gas generator at a depth of 350m. The average operating characteristics of the generator for a 6-month period were as follows: degassed, coal, 3479 tons; yield of high-grade gas with a calorific value of 800 kcal/cu m, 7.78 million cu m; yield of gas from 1 cu m of coal, 3.34 cu m; gas waste and blast - 10%. The gas compn. (in % by vol.) was: H<sub>2</sub>S 1.5, CO<sub>2</sub> 21.0, CO 4.5, H<sub>2</sub> 16.0, CH<sub>4</sub> 3.2, and N 53.5. The temperature of the gas at the exit was 200-50°. A number of recommendations are given on operating a gas generator at a depth of 300-400m. (CA) (Original article translated.)

- (84) Hokao, Zenjiro  
ON THE REDUCING REACTION IN UNDERGROUND GASIFICATION  
PROCESS OF COAL  
Nippon Kogyo Kaishi 78 (884), 99-104 (February 1962) (in Japanese)

Author took  $\beta = \text{CO}/\text{CO}_2$  as index of reduction; laboratory experiments indicate that it is desirable to get  $\beta = 1.0$  in process of gasification ideally; but it is not possible in actual *underground* gasification because of heat losses; reducing temperature is about 650 C. (EI)

- (85) Hokao, Zenjiro  
ON REMOVAL VELOCITY OF COMBUSTION REACTION ZONE IN  
PROCESS OF UNDERGROUND GASIFICATION OF COAL

1962 (Continued)

- (85) Nippon Kogyo Kaishi 78 (887), 385-90 (May 1962) (in Japanese)  
(cont'd)

Equation for removal velocity of combustion reaction zone as function of particle size is based on assumption that combustion of coal is thermal decomposition of coal particles; it is shown that when particle size of coal is not small, removal velocity is very low. (EI)

- (86) Hokao, Zenjiro  
SOME FACTORS THAT AFFECT THE RATE OF PROPAGATION OF  
THE COMBUSTION ZONE IN THE UNDERGROUND GASIFICATION  
OF COAL  
Nippon Kogyo Kaishi 78, 593-7 (1962) (In Japanese)

The rate of propagation of the combustion zone is investigated as a function of the amount of oxygen introduced, the diameter of the gasification channel, density of the coal particles. The theoretically and experimentally obtained relationships make it possible to control the propagation rate. (CZ)

- (87) Kashkin, A.A., D.K. Semenenko, and S.A. Khenkina  
GAS LOSSES AT THE SOUTH ABINSK STATION OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 12-21 (1962)

An analysis is made of the possible reasons for the observed abrupt variations in time of relative losses of gas and static pressure in the gas generators (gasifiers) of the South Abinsk station. These gasifiers are situated at a relatively shallow depth on inclined seams and are covered with thin (7-8) Quaternary deposits. It was concluded that the gas losses could be decreased by increasing the gas removal which could be accomplished, in particular, by increasing the transmissive capacity of the gas removal boreholes, by increasing the number of such boreholes at each gasifier, and by employing devices that will make it possible to reduce the pressure at the heads of the gas removal boreholes or even to create a vacuum in them. (RZ)

- (88) Kirichenko, I.P., R.N. Pitin, I.L. Farberov, and N.A. Fedorov  
SOME PROBLEMS OF SHAFTLESS EXTRACTION AND UNDER-  
GROUND PROCESSING OF FUELS AND OTHER USABLE MIN-  
ERALS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 3-10 (1962)

1962 (Continued)

- (89) Klosky, Simon and Zane E. Murphy  
INDEX OF SELECTED GASIFICATION PATENTS. II. UNITED KINGDOM, AUSTRALIAN, CANADIAN, AND SOUTH AFRICAN PATENTS  
Bur. Mines Bull. 581 (1962)

Includes abstracts of patents issued in these countries between 1917 and 1956 on coal-gasification and processes. Part I includes U.S. patents, and Part III European patents. Part I published in 1960. (BuM)

- (90) Klosky, Simon and Zane E. Murphy  
INDEX OF SELECTED GASIFICATION PATENTS. III. BELGIAN, FRENCH, GERMAN, ITALIAN AND SWEDISH PATENTS  
Bur. Mines Bull. 581 (1962)

Includes abstracts of patents issued in these countries between 1914 and 1955. Part I includes U.S. patents; Part II includes United Kingdom, Australian, and South African patents. Part I published in 1960. (BuM)

- (91) Koranda, J.J. Koutnik, and V. Peer  
UNDERGROUND GASIFICATION OF COAL  
Pr. Ustava Vyzk. Paliv 5, 5-33 (1962)\*

- (92) Korolev, I.V.  
THE EFFECT OF THE THICKNESS AND THE STRUCTURE OF A COAL BED AND THE QUALITY OF THE COAL ON THE INDICES OF THE UNDERGROUND GASIFICATION PROCESS ACCORDING TO THE OPERATIONAL DATA OF THE GASIFIERS OF THE PODMOSKOVNOYA STATION OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 27-32 (1962)

Analysis of the operation of *underground* gasifiers of the Basovskiy and Gosteyevskiy deposit showed that when the coal seams are thicker, the calorific power of the gas produced is higher but the intensity of the process is reduced. The degree of gasification decreases with increasing thickness of the interlayers of rock and with increased ash content of the coal. It is recommended that the following norms be followed in *underground* gasification in the Podmoskovnaya basin: thickness of coal layer equal to a greater than 1.3 meters, ash content equal to a less than 40%, content of rock traces (interlayers) less than 30% of the total thickness of the coal patches. (RZ)

1962 (Continued)

- (93) Korolev, I.V.  
EFFECT OF THE OCCURRENCE OF KARSTS IN COAL DEPOSITS  
ON THE UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 47-51 (1962)

In observing the losses of gas and blast at the Basovo deposit it was noted that these losses increase as the gasifier approaches sink holes (karsts). The magnitude of the losses decreases if the rock in the vicinity of the karst is flooded. (RZ)

- (94) Korolev, I.V.  
RELATIONSHIP OF THE INDICES OF AIR CROSSCUTTING OF  
BOREHOLES IN PODMOSKOVNAYA BASIN TO THE CLEAVAGE IN  
THE COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 61-8 (1962)

Analysis of the operation of the active *underground* gasifiers has shown that the rate of crosscutting increases when the air crosscutting of boreholes is conducted in the direction of the basalt cleavage. (RZ)

- (95) Korolev, I.V.  
INTERRELATION OF THE UNDERGROUND GASIFICATION OF  
COAL ON THE GEOLOGIC AND HYDROGEOLOGIC CONDITIONS  
AT COAL DEPOSITS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 51-8 (1962)

Analysis of the operation of *underground* gasifiers has shown that the effectiveness and stability of the *underground* gasification process is increased by the presence of unstable rocks in the roof (i.e., clayey shales) and that the effectiveness and stability are the higher the thicker the coal beds are. Excess moisture, foreign interlayers (interlayers of rock), tektonic destruction (dislocation) reduce the effectiveness of the process and have a detrimental effect on gasification condition. (RZ)

- (96) Kreinin, E.V.  
THE HYDRODYNAMICS OF GAS FLOW IN A LAYER OF COAL  
FINDS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 7-15 (1962)

Employing a laboratory apparatus, the hydrodynamics of a stream of gas in a layer of coal particles 330 centimeters deep was

1962 (Continued)

(96) investigated. Viewing the layer of coal as a system of channels a  
(cont'd) relationship was established between the coefficient and resistance  
( $\xi$ ) of the coal finds and  $Re$  in the layer and in the arbitrary  
channels. The data obtained were processed in the form of the  
relationship  $\xi KaH = f(Re_{KaH})$ . (RZ)

(97) Kreinin, E.V.  
EFFECT OF THE HYDRODYNAMICS OF THE STREAM OF GAS ON  
THE SHIFTING OF THE COMBUSTION CENTER IN A LAYER OF  
COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 15-21 (1962)

The movement of a center of combustion was studied in a vertical quartz tube 26 millimeters in diameter and 500 millimeters long in which on a grid (also of quartz) was a layer of coal (fractions 0-0.63 and 0-1.6 mm), air was supplied from above. An empirical relation was obtained between the rate of linear displacement of the combustion center in the coal layer and the Reynolds number ( $Re$ ). It was established that the critical  $Re$ , at which  $w$  is practically independent of the hydrodynamics of the stream, is a function of particle size. (RZ)

(98) Kreinin, E.V.  
THE EFFECT OF THE BULK SPEED OF CROSSCUT BLAST ON THE  
INDICES OF THE PROCESS OF FIRE FILTRATION CROSSCUTTING  
OF BOREHOLES  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 10-12 (1962)

Artificial pillars of coal, made from South Abinsk coal (Class 0-2 mm) were tested under laboratory conditions employing different flow rates of blast and pillars of different thickness. It was found that the blast intensity (specific consumption of blast) increases as its bulk state is increased. (RZ)

(99) Kreinin, E.V., A.S. Zabrovskiy, and E.G. Gershevich  
ANALYSIS OF THE OPERATIONAL FACTORS OF ACTIVATING IN-  
CLINED GAS REMOVAL BOREHOLES AT THE SOUTH ABINSK  
STATION OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 91-5 (1962)

Methods of connecting inclined boreholes with gasification channels are examined (gasifying methods, air crosscutting, and drilling)

1962 (Continued)

- ( 99) through to the firefront), as well as methods of analysis, and some  
(cont'd) elements of an optimum operating cycle for the exploitation of  
gas removing boreholes. (RZ)
- (100) Leshchiner, R.E.  
ECONOMICS OF TRANSPORTING UNDERGROUND-GASIFICATION  
GAS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 6, 125-30 (1962)
- (101) Leshchiner, R.E.  
DETERMINATION OF THE INFLUENCE OF VARIOUS TECHNOLOG-  
ICAL (PRODUCTION) LOSSES DURING UNDERGROUND GASIFICA-  
TION OF COAL ON THE COST OF THE GAS PRODUCED  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 108-14 (1962)
- (102) Nusinov, G.O. and G.P. Zybalova  
PRELIMINARY DATA ON UNDERGROUND GASIFICATION AT THE  
EXPERIMENTAL GASIFIER OF THE ANGREN STATION OF POD-  
ZEMGAZ  
Tr. Vses. Nauch. Issled: Inst. Podzemn. Gazif. Uglei No. 6, 3-10 (1962)
- (103) Nusinov, G.O., N.Z. Brushstein, and S.D. Kazachkova  
UNIFICATION (STANDARDIZATION) BY CALCULATION OF THE  
MAIN INDICES OF CROSSCUTTING BOREHOLES AND GASIFYING  
COAL AT PODZEMGAZ STATIONS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7,33-40 (1962)
- (104) Obert, Leonard  
EFFECTS OF STRESS RELIEF AND OTHER CHANGES IN STRESS  
ON THE PHYSICAL PROPERTIES OF ROCK  
Bur. Mines Rep. Invest. 6053 (1962)
- When rock is stress-relieved during the course of mining or in  
drilling a core, it may be altered or damaged to the extent that the  
physical properties of the relieved specimen are not the same as  
those of the *in situ* rock. (CA)
- (105) Perry, H., M.A. Elliott, and M.R. Linden  
CURRENT DEVELOPMENTS IN THE CONVERSION OF COAL TO  
FLUID FUEL IN THE UNITED STATES  
pp. 2497-2514 in Trans., 6th World Power Conf., Melbourne, Australia,  
20-7 October 1962.

1962 (Continued)

- (105) Summarizes the results of research, in the United States, on converting coal to fluid fuels and reviews the pertinent factors relating to the need for supplemental liquid and gaseous fuels produced from coal to meet the increasing demands for fluid fossil fuels. (BuM)
- (106) Rauk, Jerzy  
RELATIONSHIP BETWEEN THE COMPOSITION, CALORIFIC POWER, AND MOISTURE CONTENT OF GAS PRODUCED BY UNDERGROUND GASIFICATION OF (STONE) COAL  
Pr. Gl. Inst. Gorn. Series A, No. 303 (1962) 24 pp (In Polish)
- (107) Rauk, Jerzy and Jozef Bujok  
EFFECT OF GAMMA RAYS ON THE UNDERGROUND GASIFICATION OF COAL  
Przevl. Gorn. 18 (11), 647-50 (1962) (In Polish)

Results of laboratory experiments on the intensification of the *underground* gasification of coal by means of gamma rays are reported. The model of the coal seam was 2.5 x 1.1 x 0.6 meters and contained 0.6 cubic meters of coal; the experiments were conducted with coal and heated air blasts; the intensity of radiation was 50,000 roentgens/hour. During the irradiation, a combustion heat of the gas that was being produced increased by 83-100 kcal/nm<sup>3</sup>, and this increase in the intensity of the process was not a function of the temperature of the supplied air, but decrease with a temperature increase in the gasifier layer. It is noted that further study of the process is necessary, taking into account the possible practical importance of using radiation for intensifying the *underground* gasification of fuels. (RZ)

- (108) Semenenko, D.K.  
A FLOW OF GAS IN A GASIFICATION CHANNEL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 6, 20-7 (1962)
- (109) Semenenko, D.K.  
INVESTIGATION OF THE FLOW GAS IN A COAL BED  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 6, 28-42 (1962)

Observations were made at boreholes of the Shatskaya *underground* gasification station. The observation disproved the opinion that the flow of gas is necessarily subject to the linear law of

1962 (Continued)

(109) filtration both near the borehole and at a distance from it. One  
(cont'd) may neglect the non-linear part of filtration resistance only after  
prolonged blasting of the entire massif with gas. (RZ)

(110) Semenenko, D.K.  
SELECTION OF BLAST-GAS CONDITIONS FOR UNDERGROUND  
GASIFICATION BASED ON COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 21-7 (1962)

In the operating characteristic of an *underground* gasifier that expresses the real relationship between pressure in the gasified space and the volume of gas that is lost, this relationship is expressed by the equation  $p^2 = aV_y + bV_y^2 + c$ , where  $V_y$  is the gas loss reduced to atmospheric pressure and coal bed temperature; a, b, and c are the constants that can be determined empirically for the operational period that is to be investigated. Nomograms are given for choosing blast conditions and the methodology is given for resting gasifiers when recording the operating characteristic of the gasifier. (RZ)

(111) Simonovic, M.  
UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 1, 56-63 (1962)\*

(112) Sittig, M.  
COMBINE OXYGEN AND HYDROCARBONS FOR PROFIT. PART 11.  
OXYGEN AND OXIDATION OF COAL AND COKE  
Petrol. Refiner 41 (9), 245-50 (1962)

Data are presented on *underground* gasification and on many of the commercial types of generators. In his very brief discussion of *underground* gasification of coal, the author mentions that the subject "has been discussed by Clendenin, J.D. [Chem. Eng. Prog. 43 (11), 581 (1947)]. He quotes Nusinov, G.D. [Can. Chem. Process Inds. 30 (6), 29-32 (1946)] to the effect that 'one of the greatest existing difficulties is the problem of oxygen supply. The recovery of various types of gases used in organic synthesis, as well as that of a gas of high calorific value can only be accomplished by using oxygen, or air enriched with oxygen in *subterranean* gasification.' Nusinov goes on to point out, however, that very low-cost oxygen is critical to the economic success of such an operation."

1962 (Continued)

- (113) Warner, F.E., J. Szekely, and R.S.H. Mah  
UNDERGROUND GASIFICATION OF COAL  
Chem. Eng. No. 163, A68-78, (October 1962)

Some problems are discussed, for example control of burning, air supply, removal of the gas, drilling technology, etc. which have been used in England for *underground* gasification of coal. Qualitative explanations are given for the advancement of the burning zone, the influence of the thickness of the coal seam, the properties of the enclosing rocks, and the rate of air supply on the quality of the gas produced. The mechanism of CO formation is discussed. On the basis of kinetic considerations, it is concluded that wider spacing of boreholes is possible when a higher air supply rate is employed, the air is enriched with oxygen and thicker coal seams are worked, while otherwise factors that increase heat losses, for example inflowing water, require a closer spacing of boreholes. (C)

- (114) Yurchenko, V.P.  
NEW PROPOSALS FOR UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 8, 115-7 (1962)

The results of a competition for a new proposal for developing the technology of *underground* gasification of coal are reported. Prizes were awarded for the proposals for controlled directional cross-cutting of boreholes and for a new design for a highly productive *underground* gasifier. (RZ)

- (115) Zvyagintsev, K.N.  
INVESTIGATION OF THE EFFECT OF THE MOISTURE CONTENT OF DNEPR BROWN COAL ON ITS GASIFICATION BY OXYGEN BLAST  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 7, 41-7 (1962)

The gasification was conducted with a laboratory model employing oxygen blast. The characteristics of the initial coal (in % by volume) were:  $A^c$ , 10.0%;  $V^2$ , 56.0%. The influence of  $W^p$ , within the limits 2.5-58%, on the composition of the gas, its calorific power (Q), the temperature in the gasification zone, and the degree of dissociation of the steam was studied. When  $W^p$  was reduced from 47% to 35%, Q increased from 700 to 1500 kcal/nm<sup>3</sup> and to 2200°C with  $W^p$  increased to 57%. The high moisture content of the coal has a harmful effect on its gasification. (RZ)

- (116) Al'tshuler, V.S. et al  
**PROBLEM OF UNDERGROUND GASIFICATION OF COALS AT HIGH PRESSURE**  
 pp. 67-76 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
 (Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop. 13, (1963))

Experiments on thermal decomposition (semicoking and coking) of Lisichansk coal at h-p, and gasification of coke produced at same pressure; experiments were carried out on coal at pressures of 1, 20, and 100 atm at temperature of up to 600 C, and at 1, 20, and 50 atm at temperature of 1000 C; coking residues were analyzed at pressures of 1, 20 and 50 atm. (EI)

- (117) Anon  
**BITUMINOUS COAL RESEARCH. U.S. BUREAU OF MINES' PROGRAM IN COAL UTILIZATION**  
 Coal Age 68, 124-9, 132, 134 (March 1963)

An account of U.S. Bureau of Mines' Coal Research. Heat and power generation studies include an examination of magneto-hydrodynamic methods which hold considerable promise. Carbonization studies include improvement of coke quality, determination of the mechanism and kinetics of coal carbonization in fixed beds, the thermal-decomposition characteristics of tars from fluidized bed L.T. carbonization and investigations of production of chemical-grade coke. Gasification work includes an examination of the effects of gamma irradiation on the coal/stream reaction, the development of means for pretreating coals to avoid agglomeration in gasifiers, a coal gasification process using nuclear heat and a study of a slagging fixed-bed gasifier for lignite at the Grand Forks Laboratory. Conversion of coal to special products includes methods for making high B.t.u. gas from coal, high energy jet fuels from L.T. tar, by-product coronene production as a means for making coal hydrogenation to gaseous and liquid fuels more economical, coal-asphalt mixers as road binders, reaction of coal in

1963 (Continued)

- (117) a plasma jet to produce HCN, C<sub>2</sub>H<sub>2</sub> and other chemicals, and the  
(cont'd) evaluation of L.T. tar and pitch. Fundamental research studies  
include work on coal structure and the effect of radiation on  
coal. (FA)

- (118) Balfour, A.E.  
UNDERGROUND GASIFICATION OF COAL  
Colliery Guardian 206 (5311), 143-4, 146, 148, 150 (31 January 1963)

Report of conference held at Katowice, in Poland, during October 1962; results of work on *underground* gasification of bituminous and brown coals using oxygen and preheated air; recovery by *underground* gasification of coal left *underground* after conventional mining operations; preparing gasification channels in coal by passing current between 2 electrodes buried in seam; technique for making boreholes in coal seam by combustion process; influence of  $\gamma$ -rays on course of gasification of coal. (EI)

- (119) Baxter, J.S.  
UNDERGROUND GASIFICATION TRIALS - 2  
Colliery Eng. 40 (467), 13-8 (January 1963)

Features necessary for successful *underground* gasification of coal seams at Newman Spinney near Chesterfield, Derbyshire; dimensions and design of stopping, pumping, ignition and gasification of system, entrainment of solids in gas stream, control of gas quality and volume, results of 7 weeks gasification operation. (EI)

- (120) Biryukov, V.F., O. Kruglov, and I.D. Yudin  
EXPERIMENT IN THE OPERATION OF LISICHANSK STATION OF  
PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 11, 86-102  
(1963)

Between 1948 and 1961, the Lisichansk station produced 1,608,000,000 m<sup>3</sup> of gas. The mean annual production during that period was from 96,500,000 m<sup>3</sup> to 203,500,000 m<sup>3</sup> and the calorific power from 572 to 801 kcal/m<sup>3</sup>. The success of the station was due in large measure to the adoption of the method of hydraulic fracturing of the seam to create horizontal channels between the boreholes at depths of 30-35m, not exceeding 250m. When the gas permeability of the enclosing rock was several times

### 1963 (Continued)

(120) less than that of the coal seam, compressed-air crosscutting could  
(cont'd) be employed, which, in case of need, could be supplemented with hydraulic fracturing of the seam. In 1959 the station converted completely to shaftless preparation of gasifiers. At present extensive testing of hydraulic fracturing is being conducted at depths of 300-350 m. The problem of draining a coal pillar to be gasified by the shaftless method of preparing gasifiers was solved by using SKN-7 and SKN-5 rigs (pumping jacks). The use of immersion pumps for this purpose yielded less satisfactory results. After hydraulic fracturing, the cross-cut channels are rinsed with water until clear water comes out of the borehole (gas-removal) and then the channels are blown out with air at the rate of 1000-1500 m<sup>3</sup>/hr until water ceases to flow from the borehole. The channel is ignited under pressure using a sluice (air-lock) device. To reduce the resistance of the channel that forms, the channel is worked with hot-gas high-pressure blast at a rate of 2000-2500 m<sup>3</sup>/hr. At the same time the channel of the inclined borehole is fired. The working/firing/is considered finished when 2000-3000 or more m<sup>3</sup>/hr of low-pressure blast can be fed into 2-3 vertical boreholes connected with one inclined borehole. On the basis of the extensive experimental material accumulated at the station, recommendations are made for improving the activation and exploitation of inclined and vertical boreholes, for improving the technological process of gasification in proceeding to deeper levels, 400-500 m. (RZ)

(121) Borovicka, M.  
UNDERGROUND GASIFICATION OF SLOVAK COALS (LIGNITES)  
Pr. Ustava Vyzk. Paliv No. 6, 107-15 (1963)

Experimental work carried out in the Eastern part of the Southern Moravian coal basin. To prevent inflow of water, gasification with air was carried out at 6-7 atm. The maximum c.v. reached was 750 kcal/m<sup>3</sup>. (FA)

(122) Capp, John P., Robert W. Lowe, and Dorothy W. Simon  
UNDERGROUND GASIFICATION OF COAL, 1945-60: A BIBLIOGRAPH  
Bur. Mines Inform. Cir. 8193 (1963)

Provides a comprehensive list of more than 800 references on the *underground* gasification of coal from 1945 to 1960, including patents. (BuM)

1963 (Continued)

- (123) Chernyak, E. Yu.  
THE PROSPECTS FOR DEVELOPMENT OF UNDERGROUND GASIFICATION OF COAL IN THE TURGAY BASIN  
pp. 129-31 in Sb. Razvitiye proizvoditel'nykh sil Bol'shogo Turgaya, Moscow, Publishing House of the Soviet Academy of Sciences (1963)\*

Results are given of technical-economic calculations of the capital investments, productivity of labor, and costs of producing gas by *underground* gasification of coal in the Kushmurun and Ekibastuz deposits. (RZ)

- (124) Derman, B.M.  
STOICHIOMETRIC ANALYSIS OF THREE SIMULTANEOUS CONSTITUENTS OF REACTION OF OXYGEN WITH CARBON  
pp. 16-23 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop 13, 1963)

By comparing change in values of concentration parameters found experimentally with theoretical values, it is possible to select set of reactions which gives identical experimental and theoretical variations of these values; actual macromechanism of reaction between oxygen and carbon can only be obtained from results of experiment carried out in widest possible range of temperatures, concentrations, etc. (EI)

- (125) Derman, B.M.  
LAWS GOVERNING REACTION BETWEEN CARBON AND STEAM  
pp. 24-9 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop. 13, 1963)

Review of theoretical relationships of stoichiometric coefficients in reaction between carbon and steam; comparison of experimentally determined values with theoretical enables that combination of reactions to be chosen for which laws governing variations in experimental and in theoretical quantities are identical. (EI)

1963 (Continued)

- (126) Derman, B.M., M.I. Rogailin, and I.L. Farberov  
INFLUENCE OF CONCENTRATION OF STEAM ON RATE OF REACTION BETWEEN STEAM AND CARBON  
pp. 30-4 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop. 13, 1963)

Relationships between specific rate of decomposition of steam and its initial concentration in reaction mixture are different at temperatures of 1055 and 1100 C; at 1100 C specific rate increased with increase in concentration of steam; at 1055 C it increases only up to concentration of steam equal to 35% (by volume) and then remains steady; reaction changes from 1st to zero order. (EI)

- (127) Derman, B.M. et al  
STUDY OF CHANNEL GASIFICATION OF SEMICOKE FROM MOSCOW COAL WITH STEAM-OXYGEN BLAST  
pp. 35-9 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop. 13, 1963)

Study of channel gasification in steam-oxygen blast of various compositions and velocities shows that positions of  $CO_{2\max}$  and  $t_{\max}$  in oxygen zone, and hence beginning of apparent decomposition of steam, depend on duration of gasification; increase in extent of gasification of block leads to longitudinal extension of zones and to decrease in Co and  $H_2$  and increase in  $CO_2$  content; optimum value of steam is 10-20%. (EI)

- (128) Derman, B.M. and V.A. Nikolaeva  
THE INFLUENCE OF PRELIMINARY THERMAL TREATMENT ON THE COMPOSITION OF THE GAS IN THE GASIFICATION OF COAL FROM THE MOSCOW AREA IN A FILTRATION CHANNEL  
pp. 40-3 of TT-63-11063, "Underground Processing Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop. 13, 1963)

1963 (Continued)

(129) Elder, James L.

**THE UNDERGROUND GASIFICATION OF COAL**

pp. 1023-40 (Chap. 21) in *Chemistry of Coal Utilization, Supplementary Volume*, John Wiley and Sons, Inc., New York, N.Y. 1963

Reviews briefly the early history, starting in 1868, of the *underground* gasification of coal; discusses various methods, including the chamber or warehouse method, the borehold-producer method, the stream method, and the percolation or filtration method; summarizes experiments, starting in 1944, in countries other than Russia; details *underground* gasification processes since 1951; and reviews the commercial application of *underground* gasification of coal.

(130) Elder, James L. and Wayne R. Kube

**TECHNOLOGY AND USE OF LIGNITE PROCEEDINGS: BUREAU OF MINES-UNIVERSITY OF NORTH DAKOTA SYMPOSIUM, GRAND FORKS, N. DAK., April 1961**

Bur. Mines Inform. Cir. 8164 (1963)

Gives the text of papers presented at the 1961 Lignite Symposium. Technical developments in lignite research were presented, and lignite resources and market trends were evaluated by representatives of government and private industry from the United States and Canada. (BuM)

(131) Fedorov, N.A.

**GAS PERMEABILITY OF COAL BEDS AND SELECTION OF A METHOD FOR CREATING GAS PERMEABLE CHANNELS**

Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 10, 39-42 (1963)

In selecting a method for joining (crosscutting) boreholes during the *underground* gasification of coal, it is recommended that coal beds or seams be divided into three groups on the basis of their natural gas permeability: those with a gas permeability from 0.5 darcy, those from 500 to 50 m darcy, and those with less than 50 m darcy. For crosscutting coal seams of the first group it is recommended that high infiltration crosscutting and hydraulic fracturing be used; for those of the second group – air under pressure and hydraulic fracturing, for those of the third group – controlled directional drilling and hydraulic fracture. (RZ)

1963 (Continued)

- (132) Golger, S.P. et al  
PRODUCTION OF TECHNOLOGICAL GAS IN UNDERGROUND GAS-  
IFICATION OF LISICHANSK COALS  
pp. 77-80 of TT-63-11063, "Underground Processing of Fuels," Published  
for NSF and Dept. of the Interior by the Israel Program for Scientific  
Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, 1963)

Experiments were carried out at individual wells, in experimental  
gas generators, and in industrial *underground* gas generator; aver-  
age thickness of coal layer was 1.2m; experiments were carried out  
**with steam-air** blast enriched with oxygen; value of ratio  $CO + H_2 :$   
 $N_2$  between 2-2.5 was favorable for synthesis of ammonia. (EI)

- (133) Heide, Karl and Willy Eilhauer  
UNDERGROUND GASIFICATION OF COAL IN THE SOVIET UNION  
AND CZECHOSLOVAKIA  
Freiberg. Forshungsh. [Series] A, No. 256, 45-67 (1963) (In German)

A detailed discussion of *underground* gasification operations con-  
ducted in the Soviet Union and in Czechoslovakia. (RZ)

- (134) Kalashnikov, P.I.  
THE INFLUENCE OF MOISTURE ON THE GASIFICATION PROCESS  
AT THE ANGREN STATION OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 11, 22-34 (1963)

The author presents the following method for studying the influ-  
ence of moisture on the heat of combustion of the gas produced  
by *underground* gasification of coal. In practice one may conduct  
a gasification process which at first approximation is quasistation-  
ary. In this process, the heat of combustion of the gas  $Q$  will be a  
function fundamentally of the moisture which participates in the  
formation of the gas ( $W_{\phi}$ );  $Q = f(W_{\phi})$ . If during the gasification  
process the heat of combustion increases, this answers to the  
condition where the total influx of moisture into the gas  $W$   
decreases. When the process worsens, the condition that  $W$  in-  
crease is sufficient but not obligatory, since this worsening may be  
caused by some other factor that influences the gasification pro-  
cess. An increase in  $W$  in this case takes place only due to the

### 1963 (Continued)

(134) (cont'd) influx of water into the zone of transition of the gas. We group into Group 1 indices corresponding to an increase of  $W$ , and in Group 2 we group indices corresponding to a decrease in  $W$ , we plot these on a graph of the relationship between  $Q$  and  $f(W\phi)$ . The points of Group 1 lie in the lower part of the graph, the points of Group 2 in the upper of the graph, forming a region of coexistence in which lies the curve of the relationship  $Q = f(W\phi)$ . A relationship found allows us to integrate the relation of the moisture (water) of the enclosing rock on the gasification of *underground* coal of various thicknesses. (RZ)

(135) Katell, S.  
PROCESS EVALUATION IN A RESEARCH PROGRAM  
Cost Eng. 8 (2), 4-13 (1963)

An economic evaluation was made of the processes of electro-linking and hydraulic fracturing employed in *underground* gasification studies. A flow sheet was prepared which could be used as a basis for economic study of the potential application of nuclear energy to the production of synthetic pipeline gas, using coal as the basic raw material. (FA)

(136) Kirichenko, L.P.  
CERTAIN CONTROL PROBLEMS IN UNDERGROUND GASIFICATION OF COAL  
pp. 148-152 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop 13, 1963)

*Underground* gasification of coal may shift, sag, or cave in. Consequently, practical difficulties due to rock pressure have required the establishment of methods and system for *underground* gasification under different mining geological conditions. Roof conditions must be considered; the same type of roof can be suitable or unsuitable for different techniques of the gasification process. To ensure that the behavior of the roof will not deter the process of *underground* gasification, it is necessary to create conditions in which the by-passing of blast and gas streams and the inflow of water from the overburden into the reaction space are made impossible, and that the supply of blast to the combustion

1963 (Continued)

- (136) zone is not impeded by any form of rock pressure. Discussed are  
(cont'd) various methods of supplying blast and methods of drilling bore-  
holes and wells.

- (137) Klimentov, P.P.  
EFFECT OF GROUND WATERS ON THE UNDERGROUND GASIFI-  
CATION OF COAL DEPOSITS  
Izv. Vyssh. Ucheb. Zaved. Geol. Razved. No. 4, 106-19 (1963)

A survey. (RZ) (Original article translated.)

- (138) Kreinin, E.V. and I.L. Farberov  
RATIONAL HYDRODYNAMIC CONDITIONS FOR PROCESS OF  
WELL CROSS-CUTTING BY FIRE-PERCOLATION METHOD  
pp. 119-24 of TT-63-11063, "Underground Processing of Fuels," Pub-  
lished for NSF and Dept. of the Interior by the Israel Program for  
Scientific Translations 1963

(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, 1963)

From point of view of hydrodynamics, process of cross-cutting  
toward gas offtake well is more promising than cross-cutting to  
blast well; however, when cross-cutting process can be carried out  
only to blast well, it is imperative to maintain minimum static  
pressure in gasification channel which has already been  
formed. (EI)

- (139) Kreinin, E.V. and M. Ya. Kogan  
SWELLING OF SOUTH ABINSK COAL IN A CHANNEL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 11, 38-42 (1963)

The swelling of South Abinsk coal in a channel when thermally  
processed during *underground* gasification was studied under labo-  
ratory conditions. (RZ)

- (140) Lisin, L.M. and K.A. Matasova  
DIFFUSION-KINETIC STUDY OF THE THERMAL DESTRUCTION OF  
COAL SUBSTANCE IN SITU. II.  
Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Khim. Nauk No. 1, 125-35 (1963)

The pyrolytic generation of gaseous products from coal is gener-  
ally subject to the Arrhenius temp.-reaction rate relation when  
provision is made for a suitable overall diffusion const. Exptl. data

1963 (Continued)

(140) for 2 varieties of coal obtained on pyrolysis at 300-700° are  
(cont'd) consistent with the equation derived. (CA) (Original article translated.)

(141) Petrenko, I.G.  
METHOD FOR STUDY OF REACTIONS BETWEEN CARBON OXIDES  
AND COAL WITH RADIOACTIVE ISOTOPE OF CARBON C<sup>14</sup>  
pp. 2-9 of TT-63-11063, "Underground Processing of Fuels," Published  
for NSF and Dept. of the Interior by the Israel Program for Scientific  
Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, (1963)

Study of exchange reaction between CO and CO<sub>2</sub>, exchange  
reaction between elemental carbon and its oxides, and mechanism  
of reaction between CO<sub>2</sub> and solid fuel at elevated temperatures  
with aid of radioactive isotope carbon C<sup>14</sup>; experimental methods  
for determination of activity of soft β-radiation of gas in course of  
experiment. (EI)

(142) Petrenko, I.G. and I.B. Krichko  
STUDY OF EXCHANGE REACTION BETWEEN CARBON MONOXIDE  
AND DIOXIDE UNDER HOMOGENEOUS CONDITIONS  
pp. 10-5 of TT-63-11063, "Underground Processing of Fuels," Published  
for NSF and Dept. of the Interior by the Israel Program for Scientific  
Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, (1963)

Experimental data on study exchange reaction between radio-  
active CO<sub>2</sub> and inactive CO under homogeneous conditions indi-  
cate that reaction proceeds at appreciable rate of temperature  
above 800 C; rate of exchange reaction under homogeneous con-  
ditions is somewhat lower than that of reaction of reduction of  
CO<sub>2</sub> by coal. (EI)

**1963 (Continued)**

- (143) Petrenko, I.G. and E.M. Belyanova  
STUDY OF FLOW IN UNDERGROUND GAS GENERATOR WITH AID  
OF RADIOACTIVE ISOTOPES  
pp. 139-47 of TT-63-11063, "Underground Processing of Fuels," Pub-  
lished for NSF and Dept. of the Interior by the Israel Program for  
Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, 1963)

Study of flow of gas streams was made by using radioactive gas  
xenon-133 as tracer and multicoil oscillograph as analyzer: use of  
oscillograms makes it possible to calculate paths, velocities and  
amounts of gas penetration into neighboring gas generators and  
degree of turbulence of gas and to note paths through which it can  
pass between various wells. (EI)

- (144) Pitin, R.N. and G.S. Golovina  
SOME RESULTS OF INVESTIGATION OF ELECTROOSMOSIS IN  
BROWN COAL FROM MOSCOW AREA  
pp. 48-55 of TT-63-11063, "Underground Processing of Fuels," Published  
for NSF and Dept. of the Interior by the Israel Program for Scientific  
Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, (1963)

Effect of d-c electrical drying on brown coals; electric current  
increases flow of water through coal and in absence of influx of  
fresh moisture, lowers its residual moisture; electroosmotic drying  
of brown coal from Moscow area depends on its initial humid-  
ity. (EI)

- (145) Pitin, R.N. and K.I. Cheredkova  
EFFECT OF OXYGEN CONCENTRATION IN BLAST ON VELOCITY  
OF MOVEMENT OF ZONES IN CROSS-CUTTING STAGE IN UNDER-  
GROUND GASIFICATION  
pp. 56-64 of TT-63-11063, "Underground Processing of Fuels," Published  
for NSF and Dept. of the Interior by the Israel Program for Scientific  
Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk. Tr. Inst. Goryuch.  
Iskop. 13, 1963)

1963 (Continued)

(145) When concentration of oxygen in blast is increased, velocity of movement of incipient gasification zones in channel increases for all fuels tested; there is certain minimum limit of concentration of oxygen in blast for every type of fuel; when its concentration is below that value, no movement of incipient gasification zones is observed. (EI)

(146) Pitin, R.N. and K.I. Cheredkova  
RATE OF ZONE MOVEMENT AND HUMIDITY OF FUEL IN CROSS-CUTTING STAGE IN UNDERGROUND GASIFICATION  
pp. 65-8 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop. 13, (1963)

Decrease in humidity of brown coal from Moscow area from 30 to 9% results in 5-fold increase in velocity of zone movement; when blasting with air no zone movement occurs if moisture content of fuel is above certain limiting value which is different for each fuel; to obtain greater efficiency of cross-cutting, it is necessary to develop predrying techniques for very humid coal layers. (EI)

(147) Pitin, R.N., N.S. Miringof, and V.S. Levanevskii  
INFLUENCE OF CERTAIN TECHNOLOGICAL PARAMETERS OF PROCESS OF UNDERGROUND GASIFICATION OF COALS ON MAGNITUDE OF GAS LOSSES  
pp. 97-108 of TT-63-11063, "Underground Processing of Fuels," Published for NSF and Dept. of the Interior by the Israel Program for Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch. Iskop. 13, (1963)

Total losses of blast and gas at station Podzemgaz near Moscow reach 30% or more; investigation showed that volume of gas losses increases when static pressure in *underground* gas generators is raised; relative value of gas losses decreased with increase in output; as burnt-out space increases, gas losses increase. (EI)

1963 (Continued)

- (148) Pitin, R.N.  
CERTAIN PROBLEMS INVOLVED IN THE REDUCTION OF LOSSES  
OF BLAST AND GAS IN UNDERGROUND GASIFICATION OF  
BROWN COAL FROM MOSCOW AREA  
pp. 109-18 of TT-63-11063, "Underground Processing of Fuels," Pub-  
lished for NSF and Dept. of the Interior by the Israel Program for  
Scientific Translations 1963  
(Translations of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, (1963))

*Underground* gasification of brown coal from Moscow area takes  
place in two stages; first stage is aimed at formation of permeable  
channels; second stage is gasification of coal bed with aid of blast;  
leakages of blast and gas take place in both stages; methods of  
reducing blast and gas losses were developed. (EI)

- (149) Pitin, R.N. Yu. A. Ponnik  
DISTRIBUTION OF BLAST IN CROSS-CUTTING PROCESS IN UN-  
DERGROUND GASIFICATION OF FUELS  
pp. 125-38 of TT-63-11063, "Underground Processing of Fuels," Pub-  
lished for NSF and Dept. of the Interior by the Israel Program for  
Scientific Translations 1963  
(Translation of Podzemn. Pererab. Top. Akad. Nauk Tr. Inst. Goryuch.  
Iskop. 13, (1963))

Electrohydrodynamic analogy method based on analogy between  
distribution of parameters of percolation flow and of electric  
current, and modeling method of gas movement in fuel layer being  
cross-cut were developed; this permitted experimental data to be  
obtained on effectiveness of distribution of blast in coal layer in  
process of cross-cutting chain of wells by fire face. (RI)

- (150) Rauk, Jerzy  
UNDERGROUND GASIFICATION OF COAL  
Chemik 16 (4), 120-4 (1963) (In Polish)

Results of investigations of *underground* gasification of stone and  
brown coals with air and oxygen and with steam added are  
described. These investigations were conducted in Poland in the  
Sersza mine with the assistance of the Institute of the Mining  
Industry (Instytut Gornictwa). The most economic boring method  
was the burning out of channels in the layer while air was being

1963 (Continued)

- (150) supplied to the combustion zone by an air blower. Electrocarboni-  
(cont'd) zation (a current-conducting coke channel is created between  
electrodes placed in the coal bed by supplying electric current to  
these electrodes); this method may be used also for the production  
of high calorie gas (heat of combustion 2400-3200 kcal/nm<sup>3</sup>).  
From a study of the influence of gamma rays on the gasification  
of coal it was found that when CO<sup>60</sup> is employed, the sensible  
heat increased 80-100 kcal/nm<sup>3</sup>. In this paper we characterized  
the prospects for the development of *underground* gasification of  
coal in Poland. (RZ)
- (151) Revva, M.K. and S.S. Linetskii  
ON THE EXPANSION OF THE SOUTHERN-ABINSK STATION  
PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 11, 102-11  
(1963)
- (152) Semenenko, D.K.  
A METHOD OF CALCULATING GAS LOSSES IN UNDERGROUND  
GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 10, 10-7 (1963)
- (153) Shotts, R.Q. and J.B. Gayle  
RESEARCH AND TECHNOLOGIC WORK ON ALABAMA COALS: AN  
ANNOTATED BIBLIOGRAPHY  
Bur. Mines Inform. Cir. 8186 (1963)

References are arranged in order of subject matter. Geology,  
preparation, and carbonization of coal are emphasized. This bibli-  
ography is especially of interest to those in areas where thinner  
and less regular coalbeds must be exploited. This report, which  
includes author and areal indexes, was prepared in cooperation  
with the University of Alabama. (BuM)

- (154) Skafa, P.V.  
COSTS FOR BLASTING IN UNDERGROUND GASIFICATION OF  
COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 10, 104-18  
(1963)

**1963 (Continued)**

- (155) Willmott, L.F., W.R. Huff, and W.E. Crockett  
**AQUEOUS SLURRIES OF COAL AND GRANULAR MATERIALS: A  
BIBLIOGRAPHY**

Bur. Mines Inform. Cir. 8165 (1963)

Presents a compilation of material collected from an extensive literature search into the technology of aqueous slurries in order to establish design criteria for a pilot-plant-scale continuous integrated coal-water slurry system for feeding coal to a pressure gasifier, and to correlate various phases of the work with that of other investigators. Aqueous slurries of granular materials cover a broad spectrum of industrial materials, including hydraulic cements and mortars, drilling muds, clay slips for ceramics, etc. (BuM)

- (156) Anon  
 COAL GASIFICATION IN NEW SOUTH WALES  
 Colliery Guardian 209 427 (25 September 1964)

*Underground* gasification recommended after 2 year study. (FA)

- (157) Belova, I.F.  
 DEVELOPMENT OF AN EXPERIMENTAL BATTERY GENERATOR  
 OF UNDERGROUND GASIFICATION OF COAL BY THE HYDRAU-  
 LIC FRACTURING OF THE COAL SEAM  
 Tr. Tatar, Neft. Nauch. Issled. Inst. No. 5, 146-52 (1964)\*

As the result of an experimental-industrial experiment, the possibility is shown for developing an *underground* gasifier by hydraulic fracturing of the coal seam and production of plane horizontally oriented cracks of large radius. (RZ)

- (158) Biryukov, V.F., O. Kruglov, and I.D. Yudin  
 EXPERIMENT AND OPERATION OF THE LISICHANSK STATION OF  
 PODZEMGAZ  
 Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 12, 161-3 (1964)

- (159) Dryden, I.G.C.  
 COAL  
 Kirk-Othmer Encyclopedia of Chemical Technology 5 606-78 (1964)

In discussing briefly the topic of *underground* gasification (pp. 671-2) the author states that, "The *underground* gasification of coal envisages the total gasification of a seam of coal *in situ*, resulting in the conversion of the coal substance into gas and leaving the unwanted mineral matter *underground*. This method requires access to the coal seam by shafts and galleries and/or boreholes to allow the circulation of the air or oxygen essential to the gasification process. The low-grade gas produced could be used in gas turbines for electricity generation, or possibly as a substitute for producer gas. Many countries, including Great Britain, the U.S., Italy, and Belgium, have now concluded that the process is uneconomic, and experimental work in these countries has ceased. Where brown coal deposits exist in thick seams, results have been somewhat more promising and Russia is operating several power stations based on *underground* gasification. It is doubtful if the system will come to occupy any significant place in the Russian economy."

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\*Original article not available

1964 (Continued)

- (160) Gibb, A. et al  
UNDERGROUND GASIFICATION OF COAL  
Pitman and Sons, Ltd., London, 1964, 205 pp.

This is a report prepared for the NCB by Sir Alexander Gibb and partners. In 1949 the Ministry of Fuel and Power initiated experimental work on *underground* gasification of coal. The work was completed in 1959 under the NCB. The report contains detailed accounts of the operation and results of methods developed throughout a number of trials, a description of the setting up and operation of a pilot generating station by the CEGB and an estimation of the costs of a commercial project. Special reference is made to the work done in the USSR up to 1958. (FA)

- (161) Golger, S.P.  
FIRST EXPERIMENTS ON THE UNDERGROUND GASIFICATION OF  
LEAN DONETS COAL AT THE KAMENSKAYA STATION OF  
PODZEMGAZ 1961-1962  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 12, 13-9 (1964)

- (162) Hokao, Zenjiro  
TEMPERATURE DISTRIBUTION ON THE SURFACE OF BOREHOLES  
AND ON THE COAL SEAMS DURING UNDERGROUND GASIFICA-  
TION  
Nippon Kogyo Kaishi 80 876-80 (1964) (In Japanese)

When coal is gasified by the *underground* method, it is very important to know the temperature distribution on the surfaces of the gasified area and on the surface of the borehole. The temperature is a function of many factors in this case, for example the concentration of the oxygen in the blast, the amount of oxygen, and others. The paper gives a theoretical derivation and describes equations by which one can calculate the temperature and the factors that influence the temperature. The result of this investigation can be applied in practice. (CZ)

- (163) Hokao, Zenjiro  
ON MOVEMENT VELOCITY OF BOREHOLE FIRE FRONT IN UN-  
DERGROUND GASIFICATION, AND INFLUENCE OF HUMIDITY OF  
COAL SEAM ON GASIFICATION  
Nippon Kogyo Kaishi 80 (918), 1041-5 (1964)

**1964 (Continued)**

- (163) (cont'd) Suitable concentration of oxygen in blast and required magnitude of blast required to create fire front in case of *underground* gasification of coal in Japan were calculated; relationships between humidity of coal seam and maximum temperature of borehole were investigated. (EI)
- (164) Kashkin, A.A., S.S. Linetskiy, and N.S. Ol'shanskaya  
TECHNOLOGICAL ANALYSIS OF THE OPERATION OF THE SOUTH ABINSK STATION OF PODZEMGAZ FOR THE FIRST QUARTER OF 1963  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 12, 35-45 (1964)
- (165) **Katell, Sidney**  
**R&D AIMS AT FUTURE GASES**  
Am. Gas J. 191 (11), 41-2 (Sept. 1964)  
  
Summarizes the status of research and development, in both Government and private industry, on synthetic gaseous fuels. (BuM)
- (166) **Katell, Sidney and John H. Faber**  
**WHAT HYDROGEN FROM COAL COSTS**  
Hydrocarbon Process. Petrol Refiner 43 (3), 143-6 (1964)  
  
Presents the economics of several processes for producing hydrogen from coal. (BuM)
- (167) **Klimentov, P.P.**  
**HYDRAULIC FRACTURE FOR UNDERGROUND GASIFICATION OF COAL BEDS**  
Izv. Vyssh. Ucheb. Zaved. Geol. Razved. No. 10, 97-105 (1964)  
  
Hydraulic fracturing for *underground* gasification of coal deposits; hydraulic fracturing consists in injecting water with screened sand into coal bed through boreholes; water fractures coal creating highly permeable fractures which are prevented from closing by sand; however, better results were obtained when no sand was added to water; in this case circulation of water between two boreholes produced channels which served purpose of ignition and *underground* gasification of coal. (EI) (Original article translated)

1964 (Continued)

- (168) Kononov, V.I.  
EFFECT OF ARTIFICIAL HEAT SOURCE (SUBSURFACE GASIFICATION) ON FORMATION AND COMPOSITION OF SUBSURFACE WATERS  
Gidrogeoterm. Usloviya Verkh. Chastei Zemnoi Kory pp. 35-51 (1964)

Three zones, having different hydrogeothermal conditions were separated in geol. sections of coal gasification area in Moscow and Lisichansk (northern part of the Donets Basin): (1) the zone of circulation of steam-water mixture; (2) the zone of anomalously heated waters; and (3) the zone of *subsurface* waters with temperature usual for the depth but having an anomalous gasochem. composition. In 1st zone the temperature of water is higher than the b.p. of water at given pressure. The *subsurface* waters, free and bound, are transformed there in the gaseous state. The phys. properties of such waters (d., viscosity, etc.) change considerably and the degree of dissocn. changed from  $1.4 \times 10^8$  at  $100^\circ$  to  $2.52 \times 10^{-7}$  at  $1000^\circ$ . Therefore, the part of the steam present in the 1st zone is dissocd. into  $H^+$  and  $OH^-$ . The steam-water mixture in addition is intensively saturated with acid components ( $CO_2$ ,  $SO_2$ , and other). In most coal basins the 1st zone, having a temperature  $\geq 1200^\circ$  is distributed around the gasification center to the distance of 6 m. in the roof and 1 m. in the underlying stratum. In the Lisichansk Basin the temperature of water in the 1st zone varies from  $1300$  to  $120^\circ$  and the zone is distributed to a distance of 3 m. both in the roof and in the underlying rocks. The difference in composition of country rocks of the Moscow and Lisichansk Basin is reflected in amount of the elements leached from country rocks by the steam-water current. The spectral analysis showed that Mn, Pb, and Cu are removed from the arenaceous and argillaceous rocks and coals of the Moscow Basin, while in addition to these elements also As, Sb, Te, Ga, Bi and Zn are removed from the arenaceous-argillaceous shales and coals of the Lisichansk Basin. It is interesting that steam-water mixtures in the 2nd zone contain no Ni, Sr, and Ba present in rocks and waters of 1st and 3rd zone. The 2nd zone is also subjected to the heat effect of the center of *subsurface* gasification. But the temperature in it is below the critical temperature ( $140^\circ$  for the Moscow and  $120^\circ$  for the Lisichansk Basin). The *subsurface* waters in 2nd zone are rich in Mn, Pb, Cu, Ni, Ti, and others. Only small increases were observed in mineral concentration, gas saturation, and phenols for water in the 3rd zone. The

1964 (Continued)

(168) waters of the 3rd zone in addition to Cu, Pb, and Mn (present in  
(cont'd) waters of the 1st 2 zones) also contain Mo and Ga. The composition of *subsurface* waters rapidly returns to the normal as soon as *subsurface* gasification of coals ceases to exist. (CA) Original article translated)

(169) Kreinin, E.V.  
THE INFLUENCE OF VARIOUS FACTORS ON THE HEAT OF COMBUSTION OF GAS PRODUCED BY UNDERGROUND GASIFICATION OF COAL (TAKING AS AN EXAMPLE THE SOUTH ABINSK STATION OF PODZEMGAZ)  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 12, 3-12 (1964)

By generalizing the available exploitational data we were able to determine the influence of certain factors on the heat of combustion of the gas obtained and in this paper we discussed the role and significance of the following factors: the design and construction of *underground* gasifier; the methods for crosscutting boreholes; the influence of the intensity of the process on the quality of the gas; the change in the heat of combustion of the gas as a function of the thickness of the coal bed to be gasified; the role of irrigation (flooding) of the area being gasified and the role of the moisture content of the gas; the influence of the aerodynamic parameters of the process of *underground* gasification on the heat of combustion of the gas produced. (RZ)

(170) Kreinin, E.V. and I. L. Farberov  
EXPERIMENTAL INVESTIGATION OF THE GAS PERMEABILITY OF VIRGIN COAL SEAMS OF THE KISELEV-PROKOP'YEV REGION OF THE KUZNETSK BASIN  
Gazif. i piroliz topl. pp.184-7 (1964)

(171) Kube, Wayne and James L. Elder  
TECHNOLOGY AND USE OF LIGNITE  
Bur. Mines Inform. Cir. 8234 (1964)

Gives the texts of the papers presented at the 1964 Lignite Symposium. Technical developments in lignite research were presented, and lignite resources and market trends were evaluated by representatives of Government and Industry. (BuM)

1964 (Continued)

- (172) Leonovich, K.M. and E.A. Sidorov  
MEANS OF IGNITING UNDERGROUND GASIFIERS IN SEAMS WITH  
LEAN COAL  
Tr. Vses.Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 12, 27-32 (1964)
- (173) Lewis, Paul S., Henry H. Ginsberg, and Raymond W. Hiteshue  
GASIFICATION OF COAL IN THE PRESENCE OF GAMMA RAYS  
Bur. Mines Rep. Invest. 6363 (1964)

Shows that irradiation with 3.57 million roentgens has no gross effect on the gasification rate or on the yield and distribution of methane and hydrogen. Concludes that gamma-ray irradiation produces no improvement in the technology or economics of coal gasification. (BuM)

- (174) Morrison, Warren E.  
SUMMARY ENERGY BALANCES FOR THE UNITED STATES:  
SELECTED YEARS 1947-62  
Bur. Mines Inform. Cir. 8242 (1964)

Presents annual energy balances prepared for 8 selected years between 1947 and 1962, using official data available from the Bureau of Mines and other official sources. These balances, covering a recent historical period, should be useful for general analysis of the energy economy and for projecting or forecasting the country's future energy position. (BuM)

- (175) Petras, J.  
THE USE OF TERRESTRIAL PHOTOGRAMMETRY IN CONNECTION  
WITH SUBSIDENCE DUE TO UNDERGROUND GASIFICATION  
Freiberg. Forschungsh. A330, 111-4 (August 1964)

- (176) Pitin, R.N. and Y. A. Ponnik  
AERODYNAMIC EFFECTIVENESS OF THE CROSSCUTTING PRO-  
CESS IN UNDERGROUND GASIFICATION OF COAL  
Gazif. i piroliz topl, pp. 165-78 (1964)\*

- (177) Rauk, Jerzy  
ANALYSIS OF THE TEMPERATURE AND DEGREE OF GASIFICA-  
TION OF A COAL MASS (IF) DURING UNDERGROUND GASIFICA-  
TION OF COAL  
Pr. Gl. Inst. Gorn. No. 336 (1964)\* (In Polish) 20pp

1964 (Continued)

(177)  
(cont'd)

Employing a laboratory model consisting of a block of coal secured with cement, a study was made of the influence of temperature in the the oxidation zone on the extent and degree of sublimation of the volatile substances from the coal mass in the sectors which remained beyond the *underground* gasifier after the coal had been gasified by air or oxygen. The method of investigation consisted in determining a yield of volatile substances and in measuring the distribution of temperature in the coal block at different distances from the gasifying borehole. From the investigations, it was concluded that the extent in degree of gasification of a coal mass varies as a function of the oxidation methods employed. Gasification takes place to its greatest extent (depth) in the oxidation zone in the initial part of the gasifier, and also in the roof and in the middle of the seam. The extent and depth in gasification of a coal mass in the oxidation zone reaches 60 centimeters when gasified with air and 100 centimeters when gasified with oxygen. These values may be used to determine the distance between generator boreholes. Intensive gasification in the oxidizing zone with the yield of volatile substances up to 10-13% takes place at a depth of 0-30 centimeters when gasification is by air and 0-50 centimeters when gasification is by oxygen. The change in temperature at these depths is greater than 1000 to 500°C. The depth of gasification in the zone of a gasifying borehole does not exceed 10 to 20 centimeters. The depth and degree of gasification of a coal mass decreases as the voids fill with slag. Preliminary drying of the coal mass has a positive effect on increasing the depth and degree of gasification. An empirical formula is proposed for determining the depth gasification of the [fire] front under natural bedding conditions. (RZ)

(178) Rewa, M.K., D. K. Semenenko, and V. G. Smirnov  
INVESTIGATION OF THE PROCESS OF UNDERGROUND GASIFICATION OF COAL IN POLAND  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 12. 161-3 (1964)

This is a survey of the reports made at the AP All-Poland Conference in *underground* Gasification of Coal which took place from 22-25 October 1962 in Katowice. At the conference it was pointed out that in this area certain success has been achieved, with stress on shaft methods of preparing the coal for gasification and on the use of oxygen. (RZ)

**1964 (Continued)**

- (179) Yudin, I.D., O.V.Kruglov, M.I. Makerova, and V.F. Biryukov  
RELATIONSHIP OF THE HEAT OF COMBUSTION OF GAS TO THE  
FLOW RATE IN A GASIFICATION CHANNEL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 12, 19-27 (1964)

- (180) Al'tshuler, M.M.  
EFFECT OF THE PRODUCTION CAPACITY OF PODZEMGAZ STATIONS ON ECONOMIC INDICES  
Tr. Vses. n.-i. in-ta ispol'z. gaza v nar. kh-ve i podzemn. khraneniya nefi, nefte produktov i szhizh gazov No. 1, 168-80 (1965)\*
- (181) Al'tshuler, M.M. et al  
TECHNICAL-ECONOMIC ANALYSIS OF THE PERFORMANCE OF THE ANGRESKI SOUTHERN-ABINSK AND LISICHANSK STATION PODZEMGAZ IN 1963  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 107-16 (1965)
- (182) Belova, I.F.  
HYDRAULIC FRACTURING OF COAL BED RESULTING IN FORMATION OF FRACTURES ALONG 100 M RADII  
Ugol No. 2, 59-60 (1965)
- Hydraulic fracturing of coal bed resulting in formation of fractures along 100 m radii; study is concerned with improvement of *underground* gasification of coal; permeability of coal bed can be increased by means of hydraulic fracturing and injection of sand.  
(EI)
- (183) Belyanova, E.M. and Yu. B. Golubev  
EXPERIENCE IN THE USE OF PROTECTIVE DEVICES FOR MANOMETERS UNDER CONDITIONS OF UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. n.-i. in-ta ispol'z. gaza v nar. kh-ve i podzemn. khraneniya nefi, nefte produktov i szhizh gazov No. 1, 163-7 (1965)\*
- (184) Biryukov, V.F., I.D. Yudin, and M.I. Makerova  
METHOD OF ANALYZING THE TECHNOLOGICAL INDICES OF THE LISICHANSK STATION OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 6-10 (1965)
- (185) Bogdanov, I.F. et al  
CHEMICAL CONVERSION OF THE GAS FORMED IN THE UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 26-31 (1965)

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\*Original article not available

1965 (Continued)

- (185) (cont'd) A review of the uses of the gas from *underground* gasification of coal covers conversion to synthesis gas, use in the synthesis of MeOH, in the synthesis of hydrocarbons (both by the Fischer-Tropsch and Kaelbel processes), and in the synthesis of NH<sub>3</sub> and urea. (CA)
- (186) Dimitriev, A.V., and V.L. Lebedev  
BENCH TRIALS OF AN ABRASIVE PERFORATOR FOR HYDRO-FRACTURING OF A COAL SEAM  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 61-5 (1965)
- (187) Golubev, Yu. B., G.P. Zybalova, N.N. Petukhova, and A.M. Shchad'ko  
DYNAMICS OF GAS FORMATION DURING THE GASIFICATION OF A BROWN COAL SEAM AT THE EXPERIMENTAL GASIFIER OF THE ANGREN STATION OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 11-7 (1965)
- (188) Gushchina, T.M.  
PHYSICAL-CHEMICAL PROPERTIES OF LEAN COALS IN A SECTION OF THE KAMENKA (KAMENSKAYA) STATION OF PODZEMGAZ  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 21-5 (1965)

Physico-chemical properties of lean coal (stone coal) were studied in connection with the *underground* gasification. It was established that Class 13-6 mm undergoes only negligible destruction by heat, while Class 50-25 mm is thermally unstable. The coal has low combustibility,  $V^{\text{comb}}$  10.63%. To increase the intensity of the release of heat during the gasification of such coal, one must insure that a large amount of coke residue burns per unit time. For this purpose it is expedient to employ the gasification method in which blast is supplied to the reaction surface of the coal with increased wall velocities. (RZ)

- (189) Hokao, Zenjiro  
RATE OF COMBUSTION ZONE MOVEMENT IN UNDERGROUND GASIFICATION AND ONE PROPOSAL OF UNDERGROUND GASIFICATION SYSTEM IN JAPAN  
Nippon Kogyo Kaishi 81 (920), 19-24 (January 1965) (In Japanese)

Method proposed is suitable in Japan; rate of combustion zone movement and distance from center of borehole are studied with view to enlarge combustion zone. (EI)

1965 (Continued)

- (190) Ishikura, Toshiaki and Fujihiko Ebuchi  
MODELING OF DIRECT-FLOW AND COUNTER-FLOW  
Kyushu Daigaku Seisankagaku Kenkyusho Hokoku No. 39, 8-19 (1965)

In *underground* gasification of coal, the combustion process may be organized in two ways. In one system, the combustion zone moves with the direction of flow of the blast stream, in the other system it moves counter to it. Employing a model to study the characteristics of these processes, the authors concluded that stone coal can burn even in channels of small cross section in the counter-flow system, channels in which it would be practically impossible for the coal to burn continuously in the direct-flow system. On the basis of the results, it is proposed that the combustion process employing counter-flow is not applicable in practice for *underground* gasification of coal under natural conditions of bedding, since the gas produced in this way has too low calorific power. In this connection, it is recommended that the counter-flow process be used to prepare the coal seams for gasification.  
(RZ)

- (191) Kazak, V.N.  
THE MECHANISM OF BEHAVIOR OF ROCK DURING UNDERGROUND GASIFICATION OF THIN GENTLY SLOPING AND INCLINED COAL SEAMS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 42-52 (1965)

- (192) Kazak, V.N., and K.P. Molchanova  
THE PARTICIPATION OF THE ROCKS ON THE ROOF OF A COAL SEAM IN THE PROCESS OF UNDERGROUND GASIFICATION  
Tr. Vses. n.-i. in-ta ispol'z, gaza v nar. kh-ve i podzemn. khraneniya nefi, nefte produktov i szhizh gazov No. 1, 135-40 (1965)

- (193) Kazak, V.N.  
EFFECT OF THE ANGLE OF DIP AND THE BEARING PRESSURE OF THE ROCK ON THE DEPTH OF HEATING OF THE COAL SEAM IN ADVANCE OF THE FIRE FRONT (ALONG THE UP-DIP OF THE SEAM) DURING GASIFICATION OF THIN STONE COAL SEAMS

Tr. Vses. n.-i. in-ta ispol'z, gaza v nar. kh-ve i podzemn. khraneniya nefi, nefte produktov i szhizh gazov No. 1, 140-3 (1965)\*

1965 (Continued)

- (194) Kiyani, A.F.  
THE MATERIAL AND THERMAL BALANCE OF THE UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. n.-i. in-ta ispol'z. gaza v narodny khozyaystvd i podzemn. khraneniya nefi, nefte produktov i szhizh gazov No. 1, 12-135 (1965)\*
- (195) Kreinin, G.F. and N.S. Miringof  
COMBINED METHOD OF CROSSCUTTING BOREHOLES AT THE SHATSKAYA STATION OF PODZEMGAZ  
Tr. Vses. n.-i. in-ta ispol'z, gaza v nar. kh-ve i podzemn. khraneniya nefi, nefte produktov i szhizh gazov No. 1, 125-32 (1965)\*
- (196) Lushnikov, S.A. and N.S. Danilin  
SURVEY OF FOREIGN PATENT LITERATURE IN THE AREA OF UNDERGROUND GASIFICATION OF COAL, PETROLEUM AND COMBUSTIBLE SHALE  
Tr. Vses. Nauch. Issled. Podzemn. Gazif. Uglei No. 13, 117-22 (1965)
- (197) Nakamura, Hazime and Shin Irie  
UNDERGROUND GASIFICATION OF COAL  
Nenryo Kyokai-shi 44, 684-96 (1965) (In Japanese)  
A project for *underground* gasification of coal is discussed. The procedure is described. (CZ)
- (198) Nusinov, G.O. and S.Ts. Kazachkova  
SOME GENERALIZATIONS OF PRACTICAL EXPERIENCE IN UNDERGROUND GASIFICATION IN THE PODMOSKOVNAYA BASIN  
Tr. Vses. n.-i. in-ta ispol'z. gaza v nar. kh-ve i podzemn. khraneniya nefi, nefte produktov i szhizh gazov No. 1, 89-109 (1965)\*
- (199) Nusinov, G.O.  
RELATIVE INFLUENCE AND SEVERAL TECHNOLOGICAL FACTORS ON THE ECONOMY OF THE PROCESS OF UNDERGROUND GASIFICATION OF COAL  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 97-107 (1965)
- (200) Semenenko, D.K., S.A. Khenkina, and Ya. V. Shubin  
CALCULATION OF GAS LOSSES DURING THE JOINT OPERATION OF SEVERAL UNDERGROUND GASIFIERS  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 17-21 (1965)

1965 (Continued)

- (201) Semenenko, D.K.  
THE DISINTEGRATION OF ROCKS DURING THE UNDERGROUND  
GASIFICATION OF COAL IN THE PODMOSKOVNY BASIN  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 32-5 (1965)
- (202) Sinel'nikova, O.L.  
ESTIMATE OF THE INFLUENCE OF THE BLAST PRESSURE ON THE  
CHANGE IN THE WATER LEVEL OF THE UPA  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 85-8 (1965)
- (203) Warner, F.E. and J. Szekely  
UNDERGROUND GASIFICATION OF COAL II.  
Proc. A.I.Ch.E., Joint Meet., London No. 2, 49-55 (1965)
- Experimental results from the large-scale trials in Great Britain of *underground* gasification include data, after excavation, on temperature levels and the state of adjoining coal seams and strata. A model of the gasification process is proposed. In this, the width of the combustion zone is directly proportional to the seam thickness, the calorific value of the coal, and the sq. root of initial speed of the combustion front. Results can be predicted from these calculations which are consistent with earlier experimental data and those revealed by excavation. (CA)
- (204) Yefremochkin, N. V.  
THE INFLUENCE OF BLAST AND GAS PRESSURE ON THE OPERATION OF VERTICAL DRAINAGE BOREHOLES  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 81-5 (1965)
- (205) Yudin, I.D., V.F. Biryukov, and M.I. Makerova  
ANALYSIS OF THE EXPLOITATION OF HORIZONTAL-INCLINED BOREHOLES AT THE LISICHANSK STATION OF PODZEMGAZ  
Tr. Vses. n.-i. in-ta ispol'z. gaza v nar. kh-ve i podzemn. khraneniya nefiti, nefte produktov i szhizh gazov No. 1, 119-25 (1965)\*
- (206) Zhukov, V.V.  
NATURE OF THE GASIFICATION OF A PIT COAL BED IN THE ANGREN DEPOSIT AND DISINTEGRATION OF THE ROCK BLAST (ACCORDING TO THE RESULTS OF SHIFTING OF DEEP BENCH MARKS)  
Tr. Vses. Nauch. Issled. Inst. Podzemn. Gazif. Uglei No. 13, 35-42 (1965)

1965 (Continued)

- (207) Zimakov, B.M.  
STUDY OF THE GAS CONTENT OF COAL DEPOSITS  
Mater. Geol. Polez. Iskop. Sev.-Vostoka Evr.-Chasti SSR, Sb. Statei No. 4,  
101-9 (1965)\*
- (208) Zvyagintsev, K.N. and P.F. Krakhmalyuk  
THE HEATING UP OF THE GASIFIER AND THE CROSSCUTTING OF  
BOREHOLES AT AN EXPERIMENTAL SECTION IN THE DNEPR  
BASIN  
Tr. Vses. Nauch Issled. Inst. Podzemn. Gazif. Uglei No. 13, 74-8 (1965)
- (209) Zybalova, G.P., B. Yu. Golubev, and A.E. Zhirnye  
FIRST RESULTS OF THE EXPLOITATION OF THE ANGREN STA-  
TION OF PODZEMGAZ AND THE METHOD FOR ANALYZING THE  
OPERATION OF THE INDUSTRIAL GASIFIERS  
Tr. Vses. n.-i. in-ta ispol'z, gaza v nar. kh-ve i podzemn. khraneniya nefi,  
nefte produktov i szhizh gazov No. 1, 109-19 (1965)\*

- (210) DeCarlo, Joseph A., Eugene T. Sheridan, and Zane E. Murphy  
SULFUR CONTENT OF UNITED STATES COALS  
Bur. Mines. Inform. Cir. 8312 (1966)

The coals are separated into 3 classes: low-S,  $\leq 1\%$ ; medium-S, 1.1-3%; and high-S,  $\geq 3.1\%$ . Illinois has the largest bituminous reserve, with 80% containing  $>3\%$  S. West Virginia ranks 2nd, with 46% being low-S and 45% medium-S types. Deposits of anthracite and semianthracite occur in 7 States, but  $>80\%$  of the reserve is in Pennsylvania and contains  $<1\%$  S. The amounts of coal produced in 1964 are tabulated according to rank and S. content, showing that 96% was bituminous and subbituminous coal, 3% was anthracite, and  $<1\%$  was lignite. The S content of exported coals is low, since the bulk are metallurgical or special-purpose coals. Approximately 47% of the bituminous-coal output is burned by elec. utilities. (CA)

- (211) El'bert, E.I., I. Panfilov, M. Revva, and L. Soboleva  
CHEMICAL COMPOSITION OF GAS FROM THE SOUTHERN ABA  
STATION PODZEMGAZ  
Podzemn. Gazif. Uglei v Kuzbasse, Kemerovo, No. 1, 80-7 (1966)\*
- (212) Gershevich, E. et al  
EFFICIENCY OF THE OPERATION OF THE SOUTHERN ABINSK  
STATION PODZEMGAZ  
Podzemn. Gazif. Uglei v Kuzbasse, Kemerovo, No. 1, 15-21 (1966)
- (213) Kreinin, E. and M. Revva  
UNDERGROUND GASIFICATION OF COAL  
Kemer. Knizh. Izd. 1966. 86pp

On the basis of the experience of the South Abinsk station Podzemgaz, the brochure describes the technology of *underground* gasification of coal. Presented are technical-economic characteristics of the method of exploitation of coal deposits in Kuzbasse. The brochure is designed for workers in the coal and gas industry.

- (214) Lavrov, N.V. et al  
INFLUENCE OF THE THICKNESS OF THE COAL LAYER ON THE  
HEAT OF COMBUSTION DURING UNDERGROUND GASIFICATION  
OF COAL  
Dokl. Akad. Nauk SSSR 171 (3), 656-8 (Nov. 1966)

\*Original article not available.

NOT REPRODUCIBLE

### 1966 (Continued)

- (214)  
(cont'd) An exptl. and math. study of *underground* coal gasification is presented. The dependence of the heat of combustion of the gas on the water content and the sp. water flow in the gas were detd. and expressed by empirical formulas. Curves giving the heat of combustion as a function of the coal-layer thickness were plotted at const. water content and sp. water flow in the gas, and an equation expressing this dependence was found. A heat of combustion of 1000 kcal./m.<sup>3</sup> was obtained from coal layers 1 m., 2m., and 8.5 m. thick at 120, 200, and 250 g./m.<sup>3</sup> water content, resp., and 600, 1200, and 1600 kg./ton water flow. The efficiency of the *underground* gasification was 60-5% in coal layers 2 m. thick after intensive drying of the coal. The efficiency of the gasification was low for coal layers with thickness <1 m. (CA)

- (215) Littlewood, K.  
FUEL AND POWER  
Rep. Progr. Appl. Chem. 51, 223-5 (1966)

A review of coal, as related to the economy of the United Kingdom, including production and consumption, carbonization, *underground* gasification, chem. raw material, phys. and chem. structure, generation and distribution of electricity, comparison with nuclear power, and techniques for direct conversion (CA)

- (216) Mahajan, H.L.  
BEHAVIOUR OF ROCK STRATA DURING UNDERGROUND GASIFICATION OF COAL  
J. Mines Metals Fuels 14 (9), 273-5 (1966)

It is necessary to know behaviour of strata in vicinity of and in contact with coal gasified *underground*. Although roof is subjected to thermal and mechanical changes, floor is subjected only to thermal changes. Changes in temperature only extend a few metres into adjacent strata. When air is used as gasifying medium coal ash remains porous at temperature usually reached during *underground* gasification. Strata thus assist stability of gasification process, requiring no artificial support of gasification channel. (FA)

1966 (Continued)

- (217) Oppelt, W.H., H. Perry, J.L. MacPherson, and E.J. Vitt  
LURGI-GASIFIER TESTS OF PITTSBURGH-BED COAL  
Bur. Mines Rep. Invest. 6721 (1966)

Two exploratory gasification tests of limited duration were made at Dorsten, Germany, with strongly coking Pittsburgh-bed coal in a fixed-bed pressure gasifier. To reduce the coking potential of the Arkwright coal, ash refuse from the gasification of Dorsten (Leopold) coal was added to prepare coal-ash mixtures which contained nominal 20 and 30 percent ash. Major adjustments in principal process variables at the beginning of the tests resulted in wide fluctuations in the rate of gas production, gas offtake temperature, and carbon dioxide concentration in the gas. Because a higher steam-to-oxygen ratio was used in the tests than was customarily employed for routine operation, gas production was lower, and steam and oxygen consumption was higher. After operating conditions had been improved, the results of a 12 1/2-hour-long test with addition of sufficient ash refuse to obtain a nominal 30-percent ash concentration indicated that operation is feasible with this coal mixture using a fixed-bed pressure gasifier equipped with a rotating coal distributor and stirrer. Work done in cooperation with the Blaw-Knox Co. (BuM)

- (218) Rauk, J.  
UNDERGROUND GASIFICATION OF COAL IN CZECHOSLOVAKIA  
Przegl. Gorn. 22 (5), 216-20 (1966)

Results of experiments with shaftless gasification of brown coal in Bozislava and Brezena and of lignite in Laksarska Nova Vese are described. Air is supplied and gas is removed through boreholes spaced 25 to 50 meters apart. The boreholes were crosscut by the filtration method. As the result of gasification of the seams of brown coal with a total thickness of 4.8 meters and an ash content of 45%, lying in a depth of 36 to 50 meters,  $36 \times 10^6$  NM<sup>3</sup> of gas was obtained with a calorific power of 900 kcal/NM<sup>3</sup>. The average productivity of the apparatus was 3300 NM<sup>3</sup> per hour, thermal efficiency 75%, consumption of energy per 1000 NM<sup>3</sup> of gas - 100 kwh. The influx of water up to 10 liters per minute did not interrupt the operation of the generator. (RZ)

1966 (Continued)

- (219) Revva, M. and L.V. Mustafina  
TECHNICAL-ECONOMIC ANALYSIS OF THE SOUTHERN ABINSK  
STATION OPERATION FOR THE FIRST HALF OF THE YEAR 1965  
Podzemn. Gazif. Uglei v Kuzbasse, Kemerovo, No. 1 69-74 (1966)
- (220) Sharkey, A.G., J.L. Shultz, and R.A. Friedel  
GASES FROM FLASH AND LASER IRRADIATION OF COAL  
pp. 643-9 in Coal Science, Advances in Chemistry Series 55, American  
Chemical Society, Wash., D.C., 1966

Gases from the flash and laser irradiation of Pittsburgh seam (hvab) coal were investigated to determine the action of high temperatures on coal. Temperatures in excess of 1,000° C were reached with both types of irradiation. Craters about 300 microns in diameter were produced in the coal with millisecond pulses from the laser unit rated at 1.7 joules output. Gaseous products from the laser and flash irradiations showed 21 and 8 percent acetylene, respectively. Diacetylene, vinylacetylene, and other products to molecular weight 130 were indicated in the mass spectrum of the gas from the laser study. The results indicated that the distributions of products obtained from the flash and laser irradiation of coal were different from that produced in high-temperature carbonization. (BuM)

- (221) Sharkey, A.G., J.L. Shultz, and R.A. Friedel  
COMPARISON OF PRODUCTS FROM HIGH-TEMPERATURE IRRADIATION AND CARBONIZATION OF COAL  
Bur. Mines Rep. Invest. 6868 (1966)

Gases produced by the flash and laser irradiation of Pittsburgh seam, high-volatile A bituminous coal were examined as a part of a study of techniques for the rapid heating and cooling of coal. Thin sections or 150-mg. samples of 200-mesh coal were put in 0.5-in.-diam. tubes and laser irradiated with outputs of 1.7, 2, and 10 j. at 6943 amp. For the flash irradiations the ruby rod and lens were removed, and the sample tube was placed in the rod's position. Energy from a 4000-j supply was discharged through a Xe lamp for a 1-millisecond flash. The gases were analyzed by mass spectrometry after fractionation with liquid N, dry ice, ice water, 25° H<sub>2</sub>O, and 60° H<sub>2</sub>O as baths. Craters 300μ in diam. were produced by using focused laser energy from the 1.7-j. source. A comparison of gases from the flash irradiation and the 900°

1966 (Continued)

- (221) carbonization of coal confirmed that the former produces gas richer in  $C_2H_2$ , CO, and H, and poorer in  $CH_4$  and  $C_2$  hydrocarbons other than  $C_2H_2$ . Based on an estimate of 11 mg. of powd. coal being flash irradiated, the gaseous product (exclusive of  $H_2O$ ) was 18% of the coal irradiated. Gas from the laser irradiation showed higher percentages of  $C_2H_2$ ,  $C_2H_4$ , and  $C_3$  and higher hydrocarbons than gas from the  $900^\circ$  carbonization or from the flash irradiation. About the same percentages of  $CH_4$  and CO were produced in the flash and laser irradiations. Diacetylene, vinyl-acetylene, and other products with mol. wts. up to 130 were indicated in the mass spectrum of the gas from the laser study. (CA)

- (222) Sohns, H.W., and H.C. Carpenter  
SHALE OIL DEVELOPMENTS: IN SITU OIL SHALE RETORTING  
Chem. Eng. Progr. 62 (8), 75-8 (1966)

*In situ* techniques that have been successfully employed in petroleum recovery can probably be used for recovery of oil from shale. Field tests should provide solutions to most of the problems.

- (223) Szekely, J. and N.G. Maroudas  
A NOTE ON THE REACTION MECHANISM IN THE UNDERGROUND GASIFICATION OF COAL  
Trans. Inst. Chem. Eng. 44 (1), 3-6 (1966)

Two contradictory hypotheses have been expressed with regard to the mechanism of CO formation during *underground* gasification of coal: (a)  $O_2$  and C react with the formation of CO as a primary product, the CO immediately oxidizes in the gaseous phase into  $CO_2$ , subsequent reduction of  $CO_2$  yields the CO of the final gas; (b) the oxidation of CO does not take place in full, the remaining CO is present in the final gas. The authors found by means of constructing a mathematical model and testing it on a computer, that mechanism (a) dominates during *underground* gasification. (RZ)

- (224) Wasilewski, Jozef  
RELATION OF THE PROCESS OF UNDERGROUND GASIFICATION OF COAL TO THE TYPE AND RATE OF FLOW OF THE GASIFYING AGENT

## 1966 (Continued)

(224) Pr. Gl. Inst. Gorn. Komun. No. 400 (1966)\* 16pp (In Polish)  
(cont'd)

A discussion of the influence of reactivity of coal and gasifying agents, temperature, blast velocity, water vapor, and diffusion of O upon *underground* gasification of coal is presented. The gasification zones of the gas-producer channel were studied and analyzed, i.e., the preheating of reagents, reaction, and oxygen-free zone. The studies were graphically illustrated with cross-sectional views, and the physicochem. changes occurring here are discussed. There is a tendency of the channel of the producer to be displaced toward the roof of rock with high temperature and high angle of dip of the gasified seams. The fire advance in the channel of the producer may proceed against the blast stream, with the stream, or radially; they are inter-related, and the fire advance direction depends on speed of the blast stream. Gasification in level or seams with angles of dip up to  $25^{\circ}$  produces gas of high calorific content (2000 kcal/m<sup>2</sup> or higher), but does not favor regular burning of the seam. By using an unheated air blast, a temperature of 1000-1300° was obtained, producing a gas of 800 kcal/m<sup>2</sup>. The reverse advance of fire increases with increase of blast speed until the crit. point is reached; continuing beyond this point, the reverse flow decreases and then advances with blast flow (greater than 1 m/sec). With a decrease of blast velocity, the radial fire advance increases with a corresponding decrease of reverse flow. To obtain a large gasification area in the seam, the speed of the blast stream should be 1.5-2.0 m/sec; optimum gasification factors are obtained with approximately speeds of 2 m/sec. Complete gasification of coal in a seam depends on angle of dip, temperature of reaction zone, and length of producer hole. Tables, formulas, and equations are included. (CA)

- (225) Antonova, R.I. et al  
 STUDY OF SOME REGULAR PARAMETERS OF UNDERGROUND  
 COAL GASIFICATION  
 Khim. Tverd. Topl. No. 1, 86-96 (1967)

The experimental and operational data obtained during 1955-1966 on the *underground* gasification of Kuzbasse hard coal at South Abinsk was generalized with the object of explaining the basic regularities of the process, which det. the method of working and controlling the process in different mining and hydrogeol. conditions. The basic parameters of the process, e.g. heat of combustion of the gas, its chemical compound and moisture content, the intensity of gasification, seam width, and the degree of separation of gas, were interdependent, and empirical equations were developed expressing the relations between them. These empirical equations were used for control and management of the process. One of the most important parameters was the influx of water to the zone of gasification, and regulation of this influx was one of the basic methods of control of the process. (CA)

(Original article translated)

- (226) Boley, Charles C. and Wayne R. Kube  
 WESTERN COALS: SOME TRENDS IN UTILIZATION AND RE-  
 SEARCH  
 pp. 195-221 in "Natural Gas, Coal, Ground Water: Exploring New Meth-  
 ods and Techniques in Resources Research." 8th Western Resources Con-  
 ference, University of Colorado Press, 1967

A review of past and future utilization trends. Trends in coal research are reviewed in terms of gasification, liquefaction, and carbonization. BuMines research program on western coals is described.

- (227) Cervik, Joseph  
 AN INVESTIGATION OF THE BEHAVIOR AND CONTROL OF METH-  
 ANE GAS  
 Min. Cong. J. 53 (7), 52-7 (1967)

The flow of gas in U.S. coalbeds is governed predominantly by Darcy's law. Therefore, control measures and degasification techniques will be aimed primarily at reducing pressure, reducing permeability, or filling of the pore volume with a more viscous liquid. (BuM)

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\*Original article not available.

1967 (Continued)

- (228) Eckels, Robert E.  
NUCLEAR BREAKING OIL SHALES  
Western Oil Reporter 24 (7), 35-6 (1967)

Various authorities support the concept of *in situ* breaking and retorting of the Kerogen rich shales of Colorado and other states; others contend that a workable *in situ* method cannot be developed. Among the more promising methods being considered for the breaking of rock and oil shale *underground* is the likely use of nuclear explosive devices.

- (229) Fedorov, N.A. et al  
CONTROL OF THE MOVEMENT OF THE COMBUSTION CENTER IN  
THE COAL CHANNELS OF GAS REMOVAL BOREHOLES  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 27-30 (1967)\*

The channels of gas removal boreholes drilled in a coal seam, after being connected with the gasified space, are worked either by removing fuel gas from the boreholes or by drawing the combustion center upwards along the channel while supplying air blast into the borehole. From the point of view of the quality of working a channel (making a channel), the second method is more effective but requires strict control of the position of the combustion center along the borehole. A method is proposed for determining the position of the combustion center, based on the change in the electrical resistance of a wire inserted into the channel, change caused by the reduction of its length as the combustion center works upward. (RZ)

- (230) Hokao, Zenjiro  
DEVELOPMENT OF UNDERGROUND GASIFICATION OF COAL IN  
JAPAN  
Nenryo Kyokai-shi 46, 445-55 (June 1967)

The possible application of *underground* gasification in Japan and some problems connected with it are now being discussed by (our) investigation committee of *underground* gasification. As is well known, these *underground* gasification techniques were mainly developed in Russia and now the Russians produce about 2500 million cubic meters per year of gasified gas. They gasify the coal seam by boring from the surface and their first aim is to eliminate *underground* heavy works in coal mines.

## 1967 (Continued)

(230)  
(cont'd)

Today many coal mines in Japan are scraped for economic reasons. We discuss and propose the *underground* gasification of coal in scraped mines. Many scraped mines contain sufficient coal seams in which we can carry out trials of gasification. The *underground* gasification of coal in scraped mines requires some *underground* works but also has many advantages. We may call this method "underground method" compared with "surface method" in Russia. The *underground* method, now being discussed in committee, has the following advantages:

- The boring from the surface to coal seam is not necessary and we can use the galleries and many roads in scraped mines.
- It is very easy to make a channel of gasification in the coal seam. We can bore from the gate road to the coal seam.
- It is easy to transport gasified gas to the surface. We can use the pipe lines in galleries.

We can use many technical data which obtained in Russia and we believe the *underground* gasification of coal in scraped mines in Japan will be successful. (Author's summary)

(231) Kalashnikov, P.I. and R.S. Khvoinskaya

### WATER BALANCES OF UNDERGROUND GASIFIERS

Tr. Vses. N.-i. in-ta ispol'z. gaza v nar. kh-ve i podzemn. Khraneniya nefiti, nefte produktov i szhizh gazov No. 2, 97-110 (1967)\*

The following forms of balances are proposed for analyzing the water regime of an *underground* gasifier. 1. The balance of moisture participating in the formation of the gas. The balance equation includes the moisture of the blast, the coal, the rocks of the floor in the roof, the inflowing water, and also the dissociated and undissociated moisture (water) in the zone of heterogeneous reactions. 2. The balance of moisture vaporized by the gas. 3. The water balance of the *underground* gasifier. A method is given for determining the items entering into the equations of all forms of the balance. Furthermore, a balance of gravitational water in the gasification area is proposed for analysis and evaluation of the effectiveness of the drainage operations. Examples are given of calculations of water balances. (RZ)

- (232) Karn, F.S., R.A. Friedel, and A.G. Sharkey  
DISTRIBUTION OF GASEOUS PRODUCTS FROM LASER PY-  
ROLYSIS OF COALS OF VARIOUS RANKS  
Carbon 5, 25-32 (1967)

The irradiation of coal by laser energy is one of the more promising new methods of pyrolyzing coal rapidly at high temperatures. Gaseous products from the laser irradiation of coals of various ranks were analyzed by mass spectrometry. The total gas yield varied inversely with coal rank, showing a fourfold increase between anthracite and lignite. The atomic C-H ratio for the gases was lower than for the corresponding coal. Yields of acetylene, hydrogen, carbon monoxide, and carbon dioxide generally increased between anthracite and lignite. Changes were most pronounced between anthracite and low-volatile bituminous coal. Liquid products were not detected. The infrared spectrum of the solid residue showed few of the characteristic coal bands. (BuM)

- (233) Lavrov, N.V. and I.D. Yudin  
INCREASE IN THE HEAT OF COMBUSTION OF GAS IN UNDER-  
GROUND GASIFICATION OF COALS  
Khim. Tverd. Topl. No. 4, 93-6 (1967)

A scheme and description of an *underground* gas generator are given. Results of different types of experiments are tabulated. A series of experiments was carried out with the coal layer burning under the action of a dry blast containing 150 g. steam/m.<sup>3</sup> The air and steam blowing was periodically replaced by air blowing. Addition of steam to air resulted in an increase in the H content of the gas by 8% after the 1st steam blowing and by 7% after repeated steam blowing. Each pause in the air and steam blast, i.e., each air-blowing period, resulted in a decrease in the heat of combustion of the gas by 300-400 kcal./m.<sup>3</sup> In a gas generator constructed by drilling holes in a coal layer at a 350-m. depth, a series of experiments was carried out with O blowing, i.e., with an air-O mixture containing 65-8% O. Gas with a heat of combustion of 1380-1630 kcal./m.<sup>3</sup> was obtained. Blowing with a mixture of air, O, and steam containing 59.5-68.0% O and 130-250 g. steam/m.<sup>3</sup> resulted in an increase in the heat of combustion heat of the gas by 400-600 kcal./m.<sup>3</sup> (CA) (Original article translated)

1967 (Continued)

- (234) Lekas, Mitchell A., et al  
THE BRONCO OIL SHALE STUDY. PART I. THE FEASIBILITY OF USING NUCLEAR EXPLOSIVES IN THE PRODUCTION OF SHALE OIL. PART II. A DESIGN FOR PROJECT BRONCO, AND EXPERIMENT FOR NUCLEAR FRACTURING AND IN SITU RETORTING OF OIL SHALE  
PNE-1400 (13 Oct. 1967) 64 pp. (Available from Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Dept. of Commerce)

A study of the feasibility of fracturing oil shale with nuclear explosions, the extraction of oil by *in situ* retorting, and the design of an experiment to test this concept. Prepared by the United States Atomic Energy Commission, the United States Dept. of the Interior, CER Geonuclear Corporation, and the Lawrence Radiation Laboratory.

- (235) Lombard, D.B., and H.C. Carpenter  
RECOVERING OIL BY RETORTING A NUCLEAR CHIMNEY IN OIL SHALE  
J. Petrol. Technol. pp. 727-33 (June 1967)

A method is proposed for recovering oil by retorting oil shale shattered by deep *underground* nuclear explosions. Because most of the oil will be obtained from chunks of oil shale with maximum dimensions exceeding 1 ft, retorting times of up to several weeks are needed for complete recovery. A study of the heat economy of the retorting process in an underground nuclear chimney suggests that the nuclear detonation itself and the subsequent controlled combustion of residual carbon in retorted oil shale will provide ample energy. The proposed method is shown to be thermally efficient.

- (236) Mahajan, H.L.  
UNDERGROUND GASIFICATION TECHNIQUES  
J. Mines Metals Fuels 15 (4), 103-10 (1967)

Systems described include the blind borehole system, the stream method, the gallery to gallery system, electro-linking and pneumatic and hydraulic fracturing. (FA)

1967 (Continued)

- (237) Panfilov, I.A., E.I. El'bert, and M.K. Revva  
RECOVERY OF CHEMICALS FROM UNDERGROUND COAL GASIFICATION GAS IN A LARGE-SCALE LABORATORY APPARATUS  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 91-5 (1967)\*

A pilot-scale laboratory apparatus for recovery of  $\text{NH}_4$ , tar, and pyridine bases from *underground* coal-gasification of gas was tested. Gas ( $2256 \text{ m}^3$ ) was passed through the saturator of the apparatus from the take-off of the gas generator at an average rate of  $10 \text{ m}^3/\text{hr}$ . Results of analysis of the gas condensate and circulating water are presented. (CA)

- (238) Revva, M.K.  
EXPERIMENTAL INVESTIGATIONS OF THE CONSUMPTION OF COAL SUPPLIED BY AN UNDERGROUND GASIFIER  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 68-83 (1967)\*

The data on the *underground* gasification of steeply dipping coal beds in the Kuznetsk basin are analyzed. These experiments were carried out in an experimental-industrial gasifier at a depth of 52-206 meters. It was established that the degree of utilization of coal prepared for gasification may be raised to 95-98% by improving the design of the gasifier and by improving the technology of the process, also by preventing leakages of gas and blast. (RZ)

- (239) Revva, M.K. et al  
THE CONSTRUCTION OF UNDERGROUND GASIFIERS IN THE (MOSACHNY) (THICK) COAL BED  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 84-90 (1967)\*

A number of recommendations are made for better construction of *underground* gasifiers in a steeply dipping bed 18-20 meters thick. (RZ)

- (240) Revva, M.K. et al  
INTENSIFICATION OF THE UNDERGROUND GASIFICATION OF THICK STONE COAL BEDS  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 106-15 (1967)\*

To produce gas with a calorific power of  $1250 \text{ kcal/m}^3$  with an influx of water of  $7-16 \text{ m}^3/\text{hr}$ , the rate of influx of blast must be three times higher than when the influx rate of water is  $2-4 \text{ m}^3/\text{hr}$ .

1967 (Continued)

(240) (cont'd) When the blast rate to the gas generator is 35 thousand  $m^3/hr$  one may obtain gas with a calorific power of 1000-1100 kcal/hr with an influx of water of 15  $m^3/hr$ . To insure a high blast rate, the diameter of the blast boreholes should be increased to 200 mm, the gas removal boreholes should be increased to a diameter of up to 350mm. (RZ)

(241) Revva, M. K. and E.V. Kreinin  
STUDY OF THE RELATIONSHIPS BETWEEN THE RATE OF MOVEMENT FOR THE COMBUSTION CENTER, THE VOLUMENTARY BLAST VELOCITY, AND THE SPECIFIC CONSUMPTION OF BLAST DURING THE CROSSCUTTING OF BOREHOLES  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 116-23 (1967)\*

The economic effectiveness of crosscutting is determined by the specific consumption of blast per unit length of channel produced. Theoretical and experimental data indicate a linear relationship between the crosscutting rate and the consumption of blast under the conditions of the South Abinsk station. Given the same consumption of blast, the rate of advance of the center of combustion in brown coal is smaller [than in stone coal] and the above relationship in the case of brown coal is curvi-linear. (RZ)

(242) Revva, M.K. and E.V. Kreinin  
EXPERIMENTAL INVESTIGATIONS OF SOME LAWS OF UNDERGROUND GASIFICATION OF INCLINED COAL SEAMS  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 143-53 (1967)\*

To produce gas with a calorific power of 1000 kcal/ $m^3$  in seams 12 and 8.5 meters thick, a specific influx of water should be less than 600, 1200, and 1600 kg/ton respectively. Under natural conditions, the specific water influx in seams one meter and two meters thick is 1500-2500 kg/ton and the moisture content of the gas is 250-400 g/ $m^3$ . In view of the above, the efficiency of gasification of these seams is 45-55%. For thinner seams to be gasified, the specific participation of inflowing ground water must be reduced during the gasification process; this may be obtained by dragging the coal seam or by intensifying the gasification process. (RZ)

1967 (Continued)

- (243) Revva, M.K.  
OPTIMUM PARAMETERS OF THE BASIC ELEMENTS OF AN UNDERGROUND GASIFIER FOR THICK (STONE) COAL SEAMS WITH A STEEP DEPTH  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 169-82 (1967)\*
- (244) Salcewicz, Josef and Alina Kijewska  
DISCHARGE OF VOLATILES AND CHANGES IN ELEMENTARY COMPOSITION OF COALS DURING DEGASIFICATION  
Koks, Smola, Gaz 12, (6), 141-5 (1967)

Dynamics of degasification and changes in elementary composition were investigated for various types of coal. Four stages of degasification are considered. The temperature regions were established as 300°, 300-500°, 500-700°, and 700-1000°. The initial period (up to 300°) is distinguished by loss of H<sub>2</sub>O and by a certain release in the coal structure (the heat consumption is considerably higher than the evaporation heat of H<sub>2</sub>O); the index of coalification does not rise. In the range 350-500°, phys.-chem. changes and chemical reactions take place, characteristic of the plasticizing process. Heavy hydrocarbons volatilize; however, the coal matter loses more H and O than C (by wt.). Polymerization and condensation of the coal matter take place at 500-700°. The volatiles contain H, O, CO<sub>2</sub>, and light hydrocarbons; the index *N* increases steeply. Then, aromatization occurs to a noticeable extent and the semi-coke structure is formed. The last stage is →700° when the amount of volatiles separated is reduced (H and CH<sub>4</sub> prevail) and the *N* approaches asymptotically an infinite value. (CA)

- (245) Skafa, P.V., M.K. Revva, and V.N. Margushin  
PRESENT STATUS OF UNDERGROUND GASIFICATION OF COAL IN THE USSR  
Probl. Podzemn. Gazif. v Kuzbasse, Kemerovo, No. 2, 183-97 (1967)\*

The production of gas produced by *underground* gasification of coal in 1958 was approximately 680 million cubic meters; in 1965 it was approximately 2 billion 500 million cubic meters. According to the data of the Central Scientific Research and Planning and Design Boiler Turbine Institute named for I.I. Bolzunov, the gas produced by *underground* gasification of coal may service fuel for central heating and power plants using a steam-gas power cycle

1967 (Continued)

- (245) (cont'd) (coal is not applicable for these purposes). In this case, a central heating and power plant operating on steam and gas uses 8% less fuel than does a steam central heating and power plant of the same parameters. The production of the gas of *underground* gasification also yields the by-products: phenols, benzene, pyridine, NH<sub>3</sub>, fatty acids, sulphur, and other products. Calculations of the economics of producing gas by *underground* gasification of coal are given for individual stations of Podzemgaz. (RZ)

- (246) Smith, Sam and C.H. Atkinson  
PROJECT GASBUGGY  
Midwest Eng. 19 (8), 9-11 (April 1967)

Gives a brief history and review of the technical aspects of a project involving the firing of a 20-kiloton nuclear explosive *underground* to shatter natural gas-bearing rock to increase recovery. (BuM)

- (247) Watkins, J. Wade  
OIL SHALE UTILIZATION – WHEN AND HOW?  
Western Oil Reporter 24 (7), 18-22 (1967)

Technology is available to produce shale oil from Green River oil shale by conventional mining, crushing, and retorting methods. The economics of shale oil production, however, have not been demonstrated to be favorable. Research on *in situ* retorting is yielding promising results but this method has not been demonstrated to be technically feasible on a large scale. The present level of effort by both Government and industry, the five-point oil-shale development program of the Department of the Interior, and other considerations lead to the conclusion that there will be some commercial production of shale oil by 1980 and that production may be appreciable by the end of the century.

- (248) Wold, J.S. et al  
PROJECT THUNDERBIRD  
Coal Age 72 (9), 64-5, 68 (1967)

A 100 sq. mile block of Wyoming lands, underlain by 20,000+ million tons of coal, is the site for a new *in situ* coal-energy experimental program called "Project Thunderbird." One of the proposed experiments involves a nuclear chimney to form an immense *underground* coke oven. The products from controlled

1967 (Continued)

(248) combustion in the oven, such as low BTU gas, will be drawn off  
(cont'd) and upgraded at the surface. (FA)

(249) Yanagimoto, Takeichi, Masaki Komatu, and Arata Tomisaki  
STUDIES ON SPONTANEOUS COMBUSTION AND UNDERGROUND  
GASIFICATION OF COAL. I. THE COAL COMBUSTION GAS  
Kyushu Kosan Gakkai-Shi 35 (11), 421-9 (1967)

An apparatus was constructed in order to study the temperature dependence of the composition of gas produced by oxidative decomposition of coal. In this apparatus, the flow rate of air and other gases, air humidity, composition of the blown gas, and reaction temperature can be varied. The product gas is analyzed by 2 chromatographic gas analyzers. (CA)

(250) Yudin, I.D. and M.K. Revva  
EXPERIMENT IN OPERATING AN UNDERGROUND GASIFIER  
USING STEAM-AIR BLAST  
Probl. Podzemn. Gazif. v Kubasse, Kemerovo, No. 2, 103-5 (1967)

Experiments in the use of steam at gasifier No. 1 of the South Abinsk sector showed the possibility of improving the quality of the gas by this means. After 100-200 g/m<sup>3</sup> of steam had been supplied to the gasifier, the H<sub>2</sub> content in the gas produced increased by a factor of almost two. (RZ)

- (251) Barnes, A.L., and A.M. Rowe, Jr.  
 FEASIBILITY STUDY OF IN SITU RETORTING PROCESS FOR OIL SHALE  
 Soc. Petrol. Eng. J. 8 (3), 231-40 (Sept. 1968)

Heat transfer study was made of hot gas injection into oil shale through walls interconnected by vertical fractures; how retorting efficiency was affected by injected gas temperature, injection rate, system geometry, cyclic injection and time were investigated; results from this study show that rate of retorting oil shale is direct function of both injection temperature and rate, and theoretical producing air-oil ratio (AOR) is inverse function of temperature; they indicate that injection temperatures on order of 2000°F or higher may give theoretical AOR's in economic range. (EI)

- (252) El'bert, E.I. and I.A. Panfilov  
 UNDERGROUND GASIFICATION OF COAL — AN ADDITIONAL SOURCE OF CHEMICAL PRODUCTS  
 Pererab. Tverd. Topl., Kemerovo, No. 1, 175-85 (1968)\*

Qualitative and quantitative characteristics of the gas produced by *underground* gasification of coal are given as are the qualitative and quantitative characteristics of some of its components comparing with analogous products of the coking of coal. It is shown that the gas of *underground* gasification is an additional source of chemical products. Analysis showed possible ways of processing the more valuable components of the gas by increasing the power (capacity) of active Podzemgaz stations. (RZ)

- (253) El'bert, E.I. et al  
 ECONOMICS OF COMPLEX PROCESSING OF THE CHEMICAL PRODUCTS OF THE UNDERGROUND GASIFICATION OF COAL  
 Kompleks. Ispol'z. Khim. Prod. Podzemn. Gazif. Kuznets Uglei, Kemerovo, No. 3, 79-87 (1968)\*

The authors note the expediency of capturing and reprocessing all products whose content in gas is sufficient for industrial extraction. The cost of the gas is reduced by complex processing of the chemical products of *underground* gasification of coal employing hydrocracking of tar and crude benzol, at the same time increasing the capacity of the station for gas production to four trillion cubic meter per year. (RZ)

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\*Original article not available

1968 (Continued)

- (254) Friedman, Sam, Paul S. Lewis, Richard D. Graves, and Raymond W. Hiteshue  
REACTION OF COAL WITH STEAM AT HIGH PRESSURES  
Bur. Mines Rep. Invest. 7209 (December 1968)

The Bureau of Mines conducted experiments using bench-scale apparatus to explore the effect of large changes in process variables on the yield and composition of the gases produced by passing 800°C steam through a fixed bed of Pittsburgh seam (hvab) coal. The total yield of combustible gases increased throughout the given range for the following variables: Superficial steam velocity increasing from 0.02 to 0.12 fps, pressure increasing from 1000 to 6000 psig, residence time increasing from 0 to 60 minutes, and temperature increasing from 800° to 900°C; however, a greater increase in the yield of hydrogen in comparison with the increase in yield of methane reduced the gross heating value of the gas to around 470 Btu per scf at conditions giving the maximum yield. (BuM)

- (255) Hanbaba, Peter, Harald Juentgen, and Werner Peters  
NONISOTHERMAL NONSTATIONARY MEASUREMENT OF ACTIVATED GAS DIFFUSION IN SOLIDS, PARTICULARLY BITUMINOUS COAL  
Ber. Bunsenges. Phys. Chem. 72 (4), 554-62 (1968)

A method for the measurement of diffusion coeffs. for the activated diffusion of gases in porous solids is given. The nonstationary diffusion of the gas from the granule of solid, which occurs with simultaneous desorption, is measured by a temperature increase that is proportional to time. This nonisothermal procedure has the advantage that the desorption process occurs completely within finite times of measurement, and the activation energy of the diffusion process is obtained at the same time. As an example, the desorption of satd. hydrocarbons (methane to butane) from coal is treated. The rate-detg. step is the activated diffusion through narrow passages which are statistically distributed within the granule. Good agreement is obtained between theory and experiment. The dependence of the activation energy of the various gases studied on the gas cross section shows that for coal the size of the narrow passages are in the same range as the size of the mol. diams. (4-6 Å). The granulation dependence gives information on the distribution of the fissures within the particle. (CA)

1968 (Continued)

- (256) Konieczynski, Jan and Szczepan Tengler  
COAL GASIFICATION IN THE UNITED STATES  
Chemik (Gliwice) 21 (8), 281-5 (1968)

Research on novel methods of gasifying coal in the United States is reviewed. (CA) (Original article translated)

- (257) Lavrov, N.V., G.O. Nusinov, and D.K. Semenenko  
SOME RESULTS OF EXPERIMENTAL UNDERGROUND GASIFICATION OF LIGNITE (BROWN COAL)  
Khim. Tverd. Topl. No. 1, 113-20 (1968)

Summary. Bibliography of 23 references. (RZ)

- (258) Orenbakh, M.S.  
CHANGE IN THE POROUS STRUCTURE OF COALS DURING PREPARATION FOR COMBUSTION  
Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk No. 1, 143-6 (1968)

Heating to ignition, i.e., 500°, generally maintains the pore structure in all coals. In the interval between 300 and 1100°, coke from lignites preserved the original macropore structure of the coal, although up to 50% of the volatile matter was released, a behavior attributed to shrinkage which accompanied the yield of volatiles. A portion of the coke pore system, like that of the coal, accessible to measuring by Hg injection, had an internal surface of 7.2 m<sup>2</sup>/g of which 3.46 m<sup>2</sup>/g was of pores < 0.01-μ diam. and 2.6 m<sup>2</sup>/g was of 0.01-0.04-μ diam. The pores of anthracite coals and of their cokes were generally not connected to each other or to the exterior surface. Here, too, the pore structure remained almost const. up to 1100°, but the volatile yield was negligible. The pore surface of the coal and coke of > 1-μ diam. was only 50 cm<sup>2</sup>/g, indicating a low reaction capability. Slow heating swelled the large pores, which were formed by the air bubbles during the liq. phase. Additional heating developed the micropore structure with attendant coke shrinkage. The coke of the Kuznets bituminous SS coal, although neither dense nor monolithic, was strong, and its pore structure different from the coal's. The pore volume and size distribution remained almost constant up to the liquid phase. This volume, increasing sharply at 450-500°, was little affected by further heating to 900°, although a high amount of volatiles was released at > 500°. A large system of micro- and transitional pores was formed in the coke by heating the SS coals.

1968 (Continued)

- (258) (cont'd) The large pores in the coke were developed at  $> 500^\circ$ , with twice the volume from rapid heating to  $900^\circ$  than from slow heating. Even lignite showed a plasticity phase at the higher rate. Slow heating released volatiles from the large pores and fractures; the heat shock during rapid heating acted on the pore walls. The volume of fine and transitional pores increased in lignite along with the volume of the large pores and provided a large combustion surface. The bituminous and anthracites, lacking a developed macropore system, reacted in combustion primarily with a geometric surface; the lignites, with their specific pore structure, reacted on a volume basis, hence, with rapid ignition. The high heat shock during the liquid phase increased the pore volume of all coals. Although the volume of the SS coals was twice that of the lignites, their volatiles were about one-half, factors which are associated with high plasticity. Heat shock of anthracite coke had little effect on total porosity increase, due to low gas separation and weak plasticity. The reaction characteristics of coke must be considered carefully in designing a heating process. (CA)

- (259) Pacl, V.  
THE PRESENT STATE OF DEVELOPMENT AND SOME NEW INFORMATION ON THE UNDERGROUND COAL GASIFICATION IN CSSR AND OTHER COUNTRIES  
Shornik, Section K. (sic) 14 (1), 103-14 (1968)\*

- (260) Padovani, C.  
SYNTHETIC METHANE FROM CARBON FOR AMERICAN GAS PIPELINES  
Riv. Combust. 22 (12), 682-5 (1968)

The use of methane gas from various sources is compared with the use of electricity in the United States. Developments in the production of gas from coal are described and the importance of coal and natural gas as sources of methane is discussed. (CA)

- (261) Riedl, R.J. and J. Vodsedalck  
EFFECT OF OPERATING CONDITIONS ON THE FORMATION OF METHANE IN PRESSURE GASIFICATION  
Plyn 48 (7), 226-9 (1968)

Pressure gasification of brown coal using O and steam during actual plant production of crude utility gases was followed for 2.5 years. The desired conditions were to reduce ballast gases ( $\text{CO}_2$

1968 (Continued)

- (261) and increase the content of CH<sub>4</sub>. A relation connecting partial  
(cont'd) pressure of H in the generator and CH<sub>4</sub> in crude gas was found. When the gasification ratio is lowered, the partial H pressure increases and also the formation of CH<sub>4</sub> due to the higher rate of steam decomposition. This correlation was found for gasification ratios of 4.7 to 7.1 kg. steam/m<sup>3</sup> O. (CA)

- (262) Risser, Hubert E.  
GASIFICATION AND LIQUEFACTION – THEIR POTENTIAL IMPACT ON VARIOUS ASPECTS OF THE COAL INDUSTRY  
Illinois State Geological Survey Circular No. 430, (1968) 28 pp

This publication emphasizes that researchers estimate that coal conversion processes can provide gas and gasoline at costs approximately equal to those of natural gas and gasoline from crude oil. The thick, low-cost, western coal fields tend to be in an especially favorable position from a cost standpoint. The nation's reserves are adequate, the author says, to provide all the coal that may be required for liquefaction and gasification for several centuries. Tremendous investments, large numbers of men and huge acreages will be needed for the mining of this coal.

- (263) Yanagimoto, Takeichi, Arata Tomisaki, and Masaki Komatsu  
COAL COMBUSTION GAS. III. SPONTANEOUS COMBUSTION AND UNDERGROUND GASIFICATION OF COAL  
Kyushu Kosan Gakkai-Shi 36 (9), 307-14 (1968) (in Japanese)

Gases from combustion of powd. coal with different ash contents (9-27 wt. %) in an air stream at 700-1000° were studied to obtain fundamental exptl. results for combustion control of *underground* gasification. Effects of ash content, humidity, air flow rate, and combustion temp. on calcd. calorific values of the gases and the equil. const. were observed. The log of the equil. const. is nearly proportional to the combustion temp. (CA)

- (264) Wold, J.S. and T.C. Woodward  
PROJECT THUNDERBIRD  
World Oil 166 (6), 111-2+ (1968)

The project is in the Powder River basin of Wyoming in an area underlain by > 20 billion tons of coal. The 5 coals are in the Tertiary Fort Union Formation. The energy may have > 2x the Btu value of all proven oil reserves in the U.S. The total coal interval 1000-2000 feet deep may be the the thickest in the Western hemisphere. A 50-kiloton nuclear test would create an

1968 (Continued)

(264) immense *underground* coke oven. The gas could be drawn off and  
(cont'd) upgraded at the surface, and gas and liquids then shipped by  
pipeline. (FA)

(265) Yanagimoto, Takeichi, Masaki Komatu, and Arata Tomisaki  
SPONTANEOUS COMBUSTION AND UNDERGROUND GASIFICA-  
TION OF COAL  
Kyushu Kozan Gakkai-Shi 36 (3), 99-108 (1968)

After heating coal to 300° in an air stream, the relation between  
the composition of the product gas and the reaction temperature  
was studied. Constituents of the product gas were N, O, CO<sub>2</sub>,  
CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>3</sub>H<sub>6</sub>, etc. The amounts, which are  
single-valued functions of the components, varied with the tem-  
perature, the air flow rate, and the humidity. (CA)

- (266) Averitt, Paul.  
**COAL RESOURCES OF THE UNITED STATES – JANUARY 1, 1967**  
 Geol. Surv. Bull. No. 1275 (1969)

The coal resources of the United States remaining in the ground on January 1, 1967, totaled 3210 billion tons. This figure comprises 1560 billion tons estimated to be present in unmapped and unexplored areas. About half of the tonnage is recoverable. The United States contains about 17 percent of the world's coal resources as determined by mapping and exploration, and about 20 percent of the world's estimated total resources. On a uniform Btu basis, coal constitutes 73 percent of the United States fossil fuel supply, whereas petroleum and natural gas together constitute only 9 percent, and oil in oil shale constitutes 17 percent.

- (267) Gamburg, D. and H.V. Lavrov  
**GASIFICATION OF SOLID FUEL MINERALS**  
 Khim. Tverd. Topl. No. 2, 74-83 (1969)

A survey concerning chiefly the aspects of coal gasification for large power plants and for use as process and town gas. A brief characterization of the most important methods of the gasification was given. (CA) (Original article translated)

- (268) Gamburg, D.  
**STRUCTURAL CHARACTERISTICS OF COALS FROM THE KANSK-ACHINSK BASIN IN RELATION TO THE PROBLEM OF THEIR GASIFICATION AND CONSUMPTION**  
 Gorenje Tverd. Top., Tr. Vses. Konf., 2nd 1965, pp 165-71 (1969)

The relation between the temperature of gasification and sp. surface of the Donetsk anthracite and coke from Irsha-Borodmsk coal, was studied in the range 750-1300°. With increasing temperature of gasification, the sp. surface decreased at the same degree of gasification. At temperatures > 1000°, sp. surface of ash was lowered by sintering. (CA)

- (269) Greene, Gordon W., R.M. Moxham, and A.H. Harvey  
**AERIAL INFRARED SURVEYS AND BOREHOLE TEMPERATURE MEASUREMENTS OF COAL MINE FIRES IN PENNSYLVANIA**  
 Proc. VI Symposium Pennsylvania Society of Engineers (1969)

Aerial infrared surveys were made in 1966 and 1967 over 22 coal mine fires in Pennsylvania. Fires at shallow depths (less than 10

## 1969 (Continued)

(269) meters) were easily detected. Fires at intermediate depths (between 10 and 30 meters) were detected when heat was carried to the surface by convection in open cracks, or if the fire had been burning long enough (several years or more) to permit heat to reach the surface by conduction. Fires at depths greater than 30 meters were detected only when the heat reached the surface by convection in open cracks. Conducted heat from depths greater than 30 meters requires a decade or more to be detected at the surface. The surveys successfully defined the limits of shallow fire areas and revealed fires in several areas previously thought to be free of fire. Interpretation of geothermal profiles made in boreholes at one site showed that temperatures within the mine quickly rose 7°C when the ventilation system was shut down about 10 years previously, and that the mine fire reached the area near the observation borehole approximately a year before the temperature measurements were made in 1966.

(270) Karn, F.S., R.A. Friedel, and A.G. Sharkey, Jr.  
COAL PYROLYSIS USING LASER IRRADIATION  
Fuel 48 (3), 297-303 (1969)

Coal pyrolysis at coking temperatures yields gases that are high in CH<sub>4</sub> but very low in C<sub>2</sub>H<sub>2</sub>. Coal irradiated with laser light can produce gases rich in C<sub>2</sub>H<sub>2</sub>. The C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> ratio was directly related to the light flux at the surface of the decompg. coal. Temperatures cannot be measured directly, owing to the small crater size and the short-duration of the laser pulse, but were estimated from equil. data. Temperatures can be changed by varying the energy of the laser beam, the laser focus, and the type of laser (ruby, Nd, CO<sub>2</sub>). As the light flux increased to 375 kw/cm<sup>2</sup>, the C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> ratio increased from zero to 3.6 for Pittsburgh seam (hvab) coal. Temperatures were established as 1160-1250° based on the gas composition and published equil. data. Due to coal volatility, temperatures are lower than expected. Higher coal temperatures, leading to gases even richer in C<sub>2</sub>H<sub>2</sub> can be expected by irradiating coal in a pressurized system. As coal rank decreased, the yield of gaseous product increased and yields of C<sub>2</sub>H<sub>2</sub>, H, and HCN reached a maximum for a high-volatile bituminous coal. Separated macerals were irradiated. As the H and volatile matter in the maceral increased, the product gas volume increased and the C<sub>2</sub>H<sub>2</sub>/CH<sub>4</sub> ratio decreased. Particle size studies indicated a modest increase in CH<sub>4</sub> and an increase in C<sub>2</sub>H<sub>2</sub> for the smaller particles. (CA)

1969 (Continued)

- (271) Klima, J. and K: Prasek  
PRODUCTION OF GAS BY HIGH-PRESSURE GASIFICATION OF COAL  
Monogr. UVP 12 (1969)\* (In Czech) 175 pp

- (272) Koranda, J.  
RESEARCH ON UNDERGROUND GASIFICATION OF COAL IN CZECHOSLOVAKIA  
Sb. Prace U.V.P. No. 13, 138-46 (1969)\*

Period covered is 1956-1964.

- (273) Peters, W.  
NEW TECHNOLOGIES  
Glueckauf 105 (25), 1283-6 (11 December 1969)

MHD energy conversion and gasifying coal using heat from nuclear fission. (FA)

- (274) Rauk, Jerzy  
DETERMINATION OF TEMPERATURES IN UNDERGROUND GAS PRODUCERS ON THE BASIS OF MEASUREMENTS OF THE DEGREE OF SWELLING OF ROOF ROCKS  
Przeł. Gorn. 25 (2), 90-4 (1969)

The temperature dependence of the swelling degree of rocks was used for determination of the temperature of the gasification process in gas generators installed in a coal seam with air as an oxidizing agent. This dependence was determined by measuring the swelling degrees and temperatures under laboratory and mine conditions. The roof rock was of a clay-slate type containing SiO<sub>2</sub> 53.80, Al<sub>2</sub>O<sub>3</sub> 16.38, Fe<sub>2</sub>O<sub>3</sub> 7.82, CaO 0.70 MgO 2.39, SO<sub>3</sub> 0.38, S 1.21, and ash 92.67%. The swelling degree in gas generators was 1.4-3.6, corresponding to 1050-1200°; but in the majority of cases 1.4-2.4 and 1050-1150°. The maximum swelling degrees and temperatures were observed 11-25 m from the cold-air inlet. The calorific value of the gas was 650-750 kcal/m<sup>3</sup> for gasification at 1050° and 850-1100 kcal/m<sup>3</sup> at 1300°. (CA) (Original article translated)

1969 (Continued)

- (275) Yoshida, Kunio and Daizo Kunii  
GASIFICATION OF POROUS CARBON BY CARBON DIOXIDE  
J. Chem. Eng. Jap 2 (2), 170-4 (1969)

A method of analysis is presented for the reaction between a porous solid and a gas when the diffusion resistance is significant. The kinetic expression used is linear with respect to the concentration of the reacting gas. As a typical example, experiments of gasification of graphite spheres with  $\text{CO}_2$  were carried out and the results were compared with the proposed model, where the change of the porous structure due to the reaction  $\text{C} + \text{CO}_2 \rightarrow 2\text{CO}$  is considered. The computed values agreed favorably with the experimental data for the early stage of the reaction. (CA)

- (276) Alpern, B.  
TECTONICS AND GAS DEPOSIT IN COALFIELDS. A BIBLIOGRAPHICAL STUDY AND EXAMPLES OF APPLICATION  
Int. J. Rock. Mech. Mining Sci. 7 (1), 67-76 (1970)

Paper analyses influence of tectonic structure (folding, faulting) of coal deposits as well as fissuration of coal seams on concentration of methane in coal seams, based on several cases taken from coal fields of Soviet Union and France. (EI)

- (277) Averitt, Paul  
STRIPPING-COAL RESOURCES OF THE UNITED STATES -  
JANUARY 1, 1970  
Geol. Surv. Bull. No. 1322 (1970)

The amount of coal mined and potentially mineable to strip-mining methods has increased steadily throughout the years, concomitantly with an impressive increase in the size and efficiency of strip-mining machinery. An analysis by States of the geologic and technologic sources of information on stripping coal indicates that as of January 1, 1970, the remaining recoverable resources of stripping coal in the United States in the 0- to 150-foot-thick overburden category totaled 128 billion tons. This figure is 29 times the cumulative strip-coal production from the beginning of mining to January 1, 1970, and it is 690 times the 1969 strip-coal production of about 185 million tons. These convenient simplified comparisons are an aid in appreciating the magnitude of the stripping-coal resources, but they do not represent life expectancy because the rate of production and the estimated size of the resource will surely change in the future. The total estimated recoverable stripping-coal resources are widely distributed in 26 States as tabulated herein, but significantly large amounts are concentrated in (1) Northern Great Plains region of western North Dakota, eastern Montana, and northeastern Wyoming, (2) the Illinois basin, and (3) the north half of the Appalachian basin.

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\*Original article not available

1970 (Continued)

- (278) Barth, Guenther et al  
ADVANCE DEGASIFYING OF COAL SEAMS BY HYDRAULIC FRACTURING  
Bergbauwissenschaften 17 (1) 7-11 (1970)

A review of 21 references.

- (279) Campbell, G.G.  
EVALUATION OF OIL-SHALE FRACTURING TESTS NEAR ROCK SPRINGS, WYOMING  
Bur. Mines Rep. Invest. No. 7397 (June 1970)

Research to develop an *in situ* retorting recovery method for oil shale has involved field testing of fracturing techniques for creating fluid-flow paths in impermeable oil shale. Electro-linking, hydraulic fracturing without and with sand propping, and explosive fracturing with a liquid explosive were tested in a 25 ft square, five-spot pattern. Among cited techniques hydraulic fracturing with sand propping created horizontal fractures with desirable flow capacity that has been significantly increased by detonation of nitro-glycerin, displaced in the natural and hydraulically induced fracture systems. (EI)

- (280) Femmer, U., F.H. Franke, and M. Meraikib  
TECHNOLOGICAL PROCESS ANALYSIS OF THE GASIFICATION OF RAW COAL USING NUCLEAR ENERGY  
Atowirt. Atomtech. 15 (5), 240-2 (1970)

The manufacture of gases from coal and lignite by nuclear energy is reviewed. (CA)

- (281) Karn, Fred S., Andrew G. Sharkey, R.A. Friedel, and A.F. Logar  
COAL INVESTIGATIONS USING LASER IRRADIATION  
Bur. Mines Rep. Invest. 7328 (1970) (PB 190031)

Coal was rapidly heated to extreme temperatures by laser irradiation. Low-rank coals with high volatile content gave the highest total gas yields. Medium-rank coals gave the highest yields of H and C<sub>2</sub>H<sub>2</sub> and low-rank coals gave the highest yields of CO and CO<sub>2</sub>. Macerals gave gases of approximately the same composition, but the total gas yield increased in the order fusinite, micrinite, vitrinite, and exinite. Total gas and C<sub>2</sub>H<sub>2</sub> yields varied inversely with

1970 (Continued)

- (281) particle size. Addition of Ar, He, or N increased yields of H, C<sub>2</sub>H<sub>2</sub>, and total gas. Ni and Pt had little influence on the rate of coal decomposition. Total gas yield increased with total energy of irradiation and the C<sub>2</sub>H<sub>2</sub>-CH<sub>4</sub> ratio increased with concentration of energy. The irradiation temperature was studied and a material balance calculated. (CA)

- (282) Karn, F.S., R.A. Friedel, and A.G. Sharkey, Jr.  
DIFFUSION STUDIES OF LIGHT HYDROCARBON GASES THROUGH COAL  
Bur. Mines Rep. Invest. 7441 (October 1970)

Measurements were made of the flow of helium, methane, ethane, butane, and toluene through thin disks of coal. All measurements were made on a dense layer in the Pittsburgh seam identified as attritus. Flow increased with pressure differential and temperature. At room temperature and a pressure differential of 1 atmosphere flow rates along the bedding plane of Pittsburgh seam coal were helium  $881 \times 10^{-10} \text{ cm}^2 \text{ sec}^{-1}$ , methane  $1.2 \times 10^{-10} \text{ cm}^2 \text{ sec}^{-1}$ , ethane  $0.54 \times 10^{-10} \text{ cm}^2 \text{ sec}^{-1}$ , n-butane  $0.35 \times 10^{-10} \text{ cm}^2 \text{ sec}^{-1}$ , and toluene  $0.8 \times 10^{-10} \text{ cm}^2 \text{ sec}^{-1}$ . Flow rates were 50 percent lower across the bedding plane of the coal than along the bedding plane. Activation energies were 3.9 kcal mole<sup>-1</sup> for helium and 13.6 kcal mole<sup>-1</sup> for methane, with diffusion measured either along or across the bedding plane. (BuM)

- (283) Risser, H.E.  
COAL GASIFICATION  
pp. 150-2 in McGraw-Hill Yearbook of Science and Technology (1970)

- (284) Sanada, Yuzo  
GASIFICATION OF COAL WITH LASER LIGHT IRRADIATION, PLASMA JET, AND DISCHARGE-GENERATED EXCITED SPECIES  
Nenryo Kyokai-shi 49 (520), 580-91 (1970)

The principles of lasers, plasma jets, and microwave and glow discharges, and of their application to coal gasification are reviewed, with 25 references. (CA)

1970 (Continued)

- (285) Squires, Arthur M.  
KEEPING SULFUR OUT OF THE STACK  
Chem. Eng. 77 (9), 181-9 (27 April 1970)

This discussion of high-pressure gasification of fossil fuel to facilitate the removal of S as  $H_2S$  by scrubbing before combustion includes both a general discussion and an example of a proposed installation at Lunen in Westphalia which will generate 170 Mw. The unit will incorporate Lurgi gravitating-bed pressure gasifiers in which a high-volatile coal will be blown with steam and air at 20 atm. Combustion gases at  $820^\circ$  emanate from a high-pressure boiler which operates a 95 Mw steam turbine to drive a 74-Mw gas turbine. The survey includes a discussion of: coal gasification in a fluidized bed, cutting fines loss, schemes for high-pressure fluidization, O vs. air, S removal, and auxiliary equipment for desulfurizing. (CA)

- (286) Lombard, David B.  
COAL BREAKAGE WITH NUCLEAR EXPLOSIONS FOR IN SITU  
GASIFICATION  
Geo-Resource Associates, Arvada, Colorado, June 30, 1971  
(Final Report to the Division of Peaceful Nuclear Explosives, Atomic  
Energy Commission, under Contract AT (26-1)-544)

This study examines the concept of breaking *underground* coal deposits with nuclear explosions in order to provide fracture permeability for subsequent *in place* treatment. The treatment would presumably be aimed at converting the coal to methane gas. The coal of the "Thunderbird" lease in the Powder River Basin of Wyoming is used as the basis for the study. Nuclear breakage of *underground* coal deposits is probably technically feasible.

- (287) Stewart, I. McC.  
DIFFUSION ANALYSIS OF SEAM GAS EMISSION IN COAL MINES  
Can. Inst. Mining Met. Bull. 64 (708), 62-70 (1971)

The characteristic flow-time patterns for various types of openings and the features of coal and seam that influenced the gas diffusivity were discussed. Incremental gas flow measured from a borehole closely predicted the actual flow from the heading measurements. (CA)

b. The Patent Literature

Great Britain

(288) 941,805 (Nov. 13, 1963), Sinclair Oil & Gas Company, *Recovery of Hydrocarbons*.

This patent describes a method for recovering hydrocarbons from *underground* petroliferous formations, such as oil shale strata, which have an effective gas permeability of less than 10 millidarcies.

Input and output wells are drilled into the formation and are corrected by fractures created by hydraulic or pneumatic methods or by the drilling of horizontal boreholes. Fractures may be propped open with sand or other granular solids that do not impede fluid flow.

A fire is ignited in the input well and maintained at about 700°F by a mixture of fuel and combustion-supporting gases. With the application of a low-pressure differential between the wells, the hot combustion exhaust gases are forced through the fractures to the output well, transmitting heat to the fracture walls in the process. The heating of the passageways in the formation is continued until conductive heat transfer raises the temperature of the formation to about 700°F all the way from the input well to the output well. Hydrocarbons in the kerogen of the shale which are liquified and/or gasified are removed at the output well, leaving the heated zone with increased permeability. The increased permeability and maintenance of a temperature of 700°F in the passageways enable hydrocarbons extracted during a subsequent high-pressure gas sweep or burning wave treatment to flow easily to the outlet well without congealing and clogging the passageways.

(289) 962,985, July 8, 1964, Sinclair Oil & Gas Company, *Recovery of Hydrocarbons from Subterranean Shale Formations*.

A heat fracturing process is designed to increase the permeability of *underground* shale formations of low natural permeability (e.g., less than 10 millidarcies) prior to *in-situ* retorting of the shales. Fractures in the shale stratum are created using high temperatures without the need for high pressures.

A mixture of combustible gas and combustion supporting gas (e.g., air) is supplied through a well bore penetrating the shale stratum and burned, heating the shale adjacent to the bore to a temperature of 1000° to 1800°F. Combustion exhaust gases conducted from the stratum through the base are mixed with a cool inert gas above the stratum to lower the exhaust gas temperature to below 500°F to prevent damage to the well. After the shale bed has been heated long enough to

\* In numerical order.

create a fracture system, the now accessible hydrocarbons in the formation may be extracted by treating the formation with a gas sweep or a moving hot zone process.

If the shale lies at considerable depths, heat fracturing may be carried out several times with the burner at different levels before beginning burning wave retorting or other treatment methods for hydrocarbon recovery.

- (290) 1,010,023, Nov. 17, 1965, Shell International Research Maatschappij N.V., *Heating of Underground Formations.*

This patent describes *in-situ* methods for thermally gasifying or liquifying minerals or hydrocarbons in *underground* formations (e.g., coal) in which combustion fluid fuel (e.g., methane) is injected into the formation through a well at one point, and an oxygen-containing fluid (e.g., air) is injected through another well at another location. At some point along the contact zone where fluids mingle into a combustible mixture, they are ignited by a down-hole heating device. The combustion front which then propagates along the contact zone is moved into various parts of the formation by varying and coordinating the injection rates of the two fluids. Liquid and gaseous combustion and heating products are discharged through a production well situated at a third point. The initial permeability of the formation can be increased by hydraulic fracturing or *underground* explosions prior to thermal treatment or by explosive fracturing caused by the mixing of the two fluids during the thermal treatment.

- (291) 1,018,011, Jan. 26, 1966, Deutsche, Erdol-Aktiengesellschaft, *Process for Deriving Values from Coal Deposits.*

A bituminous coal seam is provided with a supply borehole and several withdrawal boreholes for the production of gas of high heating value by *in-situ* partial combustion of the coal. After a heating device (e.g., a controlled nuclear reactor) is placed in the supply bore, a liquid (e.g., water, hydrocarbons) is passed through the bore, heated and vaporized by the device and forced under pressure to the seam. The hot vapors preheat, fissure and devolatilize the coal. To further improve the permeability of the seam, the nuclear heat device is allowed to go uncontrolled and explode, or charges are detonated in the supply and/or withdrawal boreholes. Air, oxygen, or oxygen-enriched air is injected under pressure through the supply bore into the preheated, permeable seam and ignited, gasifying the coal by partial combustion. Small portions of the seam are worked systematically and successively to maintain the combustion temperature at about 900°C and to insure a high CO/CO<sub>2</sub> ratio in the product gas discharged from withdrawal bores.

- (292) 1,030,749, May 25, 1966, Deutsche, Erdol-Aktiengesellschaft, *Process for Exploitation of Underground Solid Bituminous Strata.*

Bituminous strata are prepared for subsequent gasification by injecting through boreholes and under pressure a mixture of gases which are non-combustible (e.g., methane, air, oxygen) and heated (350°C) hydrocarbons which are condensible (e.g., benzene, a mixture of 15% pentane and 85% heptane) under conditions present in the strata. The strata are fractured by the heat and pressure of the mixture, and the hydrocarbons condense in the cooler portions. A solution of oxygen-releasing compounds (e.g.,  $K_2NO_3$ ) and explosives in volatile solvents (e.g., benzene, xylol, toluol) is then injected, followed by a hot hydrocarbon fluid which vaporizes the solvent or by another solvent which reacts with it to cause precipitation of the oxygen-releasing compound and explosive. A mixture of hydrocarbon gas and air is then injected, spontaneously igniting the precipitated explosives and by the thermal strains produced thereby widening the fractures and further increasing the porosity of the coal. Preheated air or oxygen-enriched air is introduced through treatment boreholes for sustaining and propagating combustion, and the vapors and gases produced are withdrawn through "cleavage line boreholes."

- (293) 1,080,853, Aug. 23, 1967, Deutsche, Erdol-Aktiengesellschaft, *Method of Degasifying Coal Seams.*

This patent describes a method for removing explosive gases (e.g., methane) from the unfractured parts of underground coal strata to improve the safety of subsequent mining operations.

A tubed and cemented borehole is drilled into the coal bed and is perforated by sandblasting at the depth at which fracturing of the bed is desired. Substances having a low boiling point (i.e., refrigerants, such as ammonia,  $CO_2$ ,  $SO_2$ , LPG, monafluorodichloromethane, etc.) are pumped as liquids under high pressures into the bed to fracture it. The higher temperatures prevailing in the bed after it is fractured serve to volatilize these substances which, along with the methane naturally in the coal, are pumped or drawn by suction from the borehole and separated for recovery of the refrigerant.

- (294) 1,120,384, July 17, 1968, John Watson Taylor, *Improvements Relating to Underground Gasification of Coal.*

After the exposure of a face of an *underground* coal seam, a movable furnace wall structure made of metal or refracting material is installed parallel to the face, extending the full height and length of the face and forming a completely enclosed furnace space. Streams of oxidants (e.g., air oxygen, steam,  $CO_2$ ) are directed into the space to support combustion.

The furnace wall is articulated and flexible and is equipped with self-advancing apparatus (e.g., hydraulic rams) for maintaining a selected distance from, and parallelism with, the coal face as it is consumed and retreats during combustion. Suitable sensing devices associated with the wall automatically monitor the operations and permit above-ground remote control of the gradual advance of the wall, the self-advance of roof supports linked with the wall and the self-adjustment of spring-pressed or flexible liners for maintaining a sealed contact between the wall and the roof and floor. Partitions can be used to compartmentalize the furnace space.

Conduits attached to and extending along the length of the wall-roof support assembly distribute the oxidant stream and/or a portion of the product gases into the space and over the inner face of the wall to prevent heat and chemical corrosion. Other conduits convey hot product gases to the surface without a loss of heat by employing insulation or a fluid heat transfer medium. The arrangement of conduits and inlets and outlets through the wall permits continuous, uniform, controlled and efficient gasification of the coal.

(295) 1,122,091, July 31, 1968, Equity Oil Company, *Recovery of Petroleum Products from Oil Shale*.

Six insulated extraction wells are drilled into an oil shale stratum in a hexagonal pattern around a single injection well, with their upper lengths parallel to the injection well but with their lower sections angled toward and intersecting it at its base. Natural gas heated to a temperature of between 662°F and 932°F and containing methane as a principal constituent is pumped through the injection well under a pressure of 150 to 500 psig into the shale treatment zone. The hot natural gas penetrates natural pores and artificially produced openings and by its solvent-stripping action thermally decomposes and extracts the organic components of the shale (i.e., kerogen). Injection pressure is pulsated to allow the gas to periodically flush the decomposition products from the rock pores, insuring intimacy of contact between the gas and shale. The gas circulates freely into the treatment zone and serves as a carrier for decomposition gases and vapors pumped through extraction wells to the surface, where organic solutes are separated and the natural gas solvent is recycled.

#### Japan

None identified in the period searched (1 January 1955 through 30 July 1971).

## Poland

- (296) 35,353, February 25, 1953, Central Mining Institute, *Method for Producing Heating Gas by Underground Gasification of Coal and Apparatus for Making Same.*

This patent describes a method and apparatus for converting combustion gases produced by the *underground* gasification of coal into heating gas in a mobile generator constructed on the surface. All or a part of the combustion gases are conducted to the generator by a borehole pipe.

- (297) 41,705, February 3, 1959, Central Mining Institute, *Method for Contacting Steel Electrodes with Coal Bed in Process of Underground Electrocarbonization of Coal.*

This patent describes a method for contacting steel electrodes with a coal bed in the process of *underground* electrocarbonization of the coal. A tar material is injected into the borehole, and into it is placed a specially formed (e.g., cylindrical) electrode connected to an electrical conductor (cable). The tar serves to provide an electric linkage medium for conveying current from the electrode to the intersected coalbed.

## U.S.S.R.

- (298) 124,575, October 14, 1955, G.O. Nusinov, et al, *Method of Underground Coal Gasification.*

A blast of air is heated and injected through rows of inlet boreholes through the degassed portion of the coal seam and into the combustion chamber. To improve the conditions for an efficiency of gasification, the air blast is drawn into the block of burning coal toward outlet holes situated two or three rows from the row of inlet holes. Part of the product gases is recovered through rows of boreholes between the inlet and outlet rows.

- (299) 162,619, August 24, 1962, V.V. Zhukov, *System for Underground Gasification of Coal.*

A currently known system for *underground* coal gasification involves drilling vertical or inclined holes on a grid and gasifying rectangular blocks of coal between adjacent holes. With this method the maximum width of seam that can be gasified (i.e., maximum width of combustion chamber) is 8 to 10 meters.

In the proposed system a zig-zag row of holes is drilled so that, if the structure of the coal is uniform, adjoining blocks gasified between three neighboring holes in the row are arranged at an angle of  $120^\circ$  to each other. The angles between adjoining blocks and the distances between adjacent drill holes and between adjacent rows of holes are determined by the structural features of the coal bed, and by the requirements (and limitations) of *underground* gasification technology. The system is claimed to achieve a reduction in the cost of drilling operations required.

(300) 183,873, July 5, 1962, D.P. Oktyabrskii, *Aerodynamic Gasification of Coal*

According to Author's Certificate No. 119,647, reduction of iron ore is achieved simultaneously with the gasification of coal process. Ore of particle size 50-100 $\mu$  is heated to 500-88 $^\circ$ C, mixed with 10-15% (by weight) powdered lime and injected into the treatment zone of the coalbed along with an oxygen blast. The process may be accelerated by addition of 1-2% finely divided  $K_2CO_3$  to the ore. At a reaction temperature of 2000 $^\circ$ C the iron formed is molten and flows to the bottom of the zone. Mineral impurities in the reactants vaporize and then condense to form a light ash which is extracted with the gas stream. The process is most suitable for coals of low moisture and low ash content.

(301) 194,222, April 11, 1966, M.K. Revva, *Equipment for Underground Gasification*.

This patent describes apparatus for use in gasifying natural solid fuel beds, such as coal, in steeply dipping strata. A tube for air blast is inserted in a borehole in the fuel bed. The tube is equipped along its length with slits or perforations which are opened automatically, triggered by the heat of an approaching fire front, and thus release an air stream immediately into or near the fire zone. The apparatus brings about stabilization of the gasification process as the coalbed is continuously burned out.

#### United States

(302) 2,780,450, Feb. 5, 1957, F. Ljungstrom, *Method of Recovering Oil and Gases from Non-Consolidated Bituminous Geological Formation by Heating Treatment in-situ*

This patent describes an *in-situ* method of producing valuable organic bituminous oils and gases from a non-consolidated, relatively impermeable tar sand which is overlain and/or underlain by more permeable geological formations.

Electric heating elements, introduced through tubes inserted into wells penetrating the strata, serve to ignite the tar sand, after which combustion and gasification by pyrolysis is maintained at about 300 to 400°C by regulating the quantity of oxygen or air supplied to the combustion zone. By pressurizing the oxygen stream, the underlying or overlying formations are fractured to assist the subsequent propagation of the combustion zone and heat front. Alternatively, the pyrolysis product gases are allowed to accumulate and thereby exert pressure to fracture the formations. By suddenly increasing the pressure on the oxygen stream the tar may be made to ignite spontaneously, negating the requirement for electric heating elements. Transfer of heat from the combustion zone through the tar sands brings about pyrolysis of the thickly liquid, tar-like bituminous substances in the sands into thin oil and gases which are conducted through the now-permeable sands and are recovered through exhaust tubes.

If the inflow of groundwater to the area being pyrolyzed is high, and/or if lateral gas and oil losses are high, the area being pyrolyzed is surrounded by a barrier of frozen soil and groundwater created by cooling tubes inserted into a circle of boreholes. The boreholes are later used for supply tubes for the oxygen (or air) stream as the heating front advances.

(303) 2,946,382, July 26, 1960, M.R. Tek, et al, *Process for Recovering Hydrocarbons from Underground Formations*

This patent describes a process for recovering hydrocarbons from permeable *underground* formations containing combustible carbonaceous material (e.g., oil). An arrangement of wells is cased within the formation, and the casings are perforated at various levels. A fluid is pumped through the perforations at a sufficient rate to create a system of horizontal, overlapping fractures distributed throughout the formation, and fine granular material (e.g., sand) introduced with the fluid serves to prop open the fractures.

A gas or liquid (e.g., combustion gas or superheated steam) is heated either at the surface or by means of a gas or electric downhole heater and is injected into the fractures. The hot fluid drives volatile hydrocarbons from the formation as it is advanced from the injection well to recovery wells. Alternatively, a combustion front is initiated in fractures, sustained by air injected through a well, and driven upward or downward, counter-current to the flow of air through the formation to recovery wells, heating and extracting the hydrocarbons as it advances. After the front has "reached the recovery wells, its direction is reversed to recover the coke or oil left behind as residue from the initial combustion process.

It is claimed that the process minimizes heat loss to surrounding strata and that it recovers hydrocarbons from porous oil-bearing formations more efficiently and rapidly than other methods.

(304) 2,967,052, Jan. 3, 1961, F.W. Crawford, *In-Situ Combustion Process*

An improved method is described for drilling an ignition borehole and simultaneously initiating *in-situ* combustion and movement of the combustion zone through a carbonaceous formation.

A ring of injection wells is provided around a single ignition well drilled to the top of a carbonaceous stratum, or rows of injection wells are provided, separated by parallel rows of ignition wells drilled to the top of the stratum. The distances between injection and ignition wells range from 5 to 25 feet but may be 50 feet or more if the formation is highly permeable. For carbonaceous materials of very low permeability (e.g., coal seams), hydraulic or pneumatic pressure is applied at several levels within the injection wells to create a system of horizontal fractures, which are propped open by injected sand or by rubble formed during pneumatic "fluttering."

As the ignition wells are drilled into the carbonaceous stratum by means of a flame drill, oxygen-containing gas (e.g., air) is injected to initiate combustion of the stratum around the boreholes. Subsequent to ignition and as thermal drilling proceeds, air is injected through adjacent injection wells and flows through the stratum to the ignition boreholes, advancing the combustion zone toward the injection wells countercurrently to the flow of air.

(305) 3,010,707, Nov. 28, 1961, E.M. Craighead, et al, *Recovery of Resins and Hydrocarbons from Resinous Type Coals*

Injection and production boreholes are drilled into a seam of impermeable resinous coal, and the seam is horizontally fractured at its top and bottom to establish passageways between the boreholes. Steam at a temperature of 550-800°F is injected continuously through the fractures from one borehole to the other until the seam is permeable from top to bottom between the wells. The steam partially distills the coal and thereby extracts certain liquid resins and hydrocarbon fuel gases, leaving behind a residue with higher permeability (e.g., 300 millidarcies). Combustion is initiated in fractures in the porous coal at the bottom of an injection borehole and is driven as a front vertically through the coal by injecting a concurrent or countercurrent stream of air. Hydrocarbon gases generated by combustion are recovered through production wells arranged in circles around or in rows alternating with the injection wells. Packing or perforated casing is provided to prevent injected air from bypassing the combustion zone.

(306) 3,017,168, Jan. 16, 1962, D.E. Carr, *In-Situ Retorting of Oil Shale*

An access shaft and several recovery wells are constructed from the surface into an oil shale stratum, and blind *underground* boreholes are drilled from the bottom of the shaft horizontally into the shale. After fracturing the stratum, a mixture of oxygen-rich gas (e.g., air) and fuel gas (e.g., propane, butane or LPG) is injected under pressure through a pipe in the shaft and is ignited at the mouth of the blind boreholes, initiating combustion of the shale. Preheated air by itself or admixed with recycled product gas or fuel gas, is supplied continuously to the boreholes to maintain combustion and to cause it to advance through the stratum. Condensable oil vapors, non-condensable gaseous products and combustion gases produced by the pyrolysis of the kerogen in the shale are extracted through groups of recovery wells and separated on surface installations.

(307) 3,034,580, May 15, 1962, F.E. Frey, et al, *In-Situ Combustion of Lignite*

This patent describes a method for the autogenous *in-situ* retorting of lignites containing at least 10 wt percent oxygen.

Ignition wells and offset recovery wells are provided into the lignite bed, arranged either in rings or alternating rows. A drying gas (e.g., air) is injected and forced under pressure through the bed to drive out moisture, dry the lignite and heat it to 600°F. Ignition is then established in the wall of the ignition well with the aid of air and possibly an iron-containing combustion catalyst. After ignition, the flow of air is terminated and combustion is sustained by oxygen present within the lignite. Inert, oxygen-free gas (e.g., combustion gas) is periodically or continuously injected to flush out through offset wells by the hydrocarbon gases and liquids produced by combustion.

(308) 3,048,225, Aug. 7, 1962, Alfred D. Reichle, *Catalytic In-Situ Combustion*

Rings or alternating rows of injection wells and recovery wells are provided into strata of a permeable hydrocarbon-containing material and the material is then dried out. The strata are ignited in the recovery well(s) and a combustion-supporting gas (e.g., air or oxygen-enriched air) containing at least 0.05 to 1.5 vol. percent of iron pentacarbonyl ( $\text{Fe}(\text{CO})_5$ ) in vapor form is injected through the injection well(s), during the combustion front counter-currently to air flow. In the warm strata ahead of the leading edge of the front,  $\text{Fe}(\text{CO})_5$  decomposes to Fe and CO and the Fe is deposited in the carboneous material. The precipitated Fe catalyzes the advancing combustion zone reactions, reducing the temperature in the zone by 70° to 100°F and increasing its propagation rate by about 15%. As a result of the lower combustion temperature and faster advance rate, a smaller portion of the carboneous deposit is consumed in the process and a greater amount of hydrocarbons and fuel gas is recovered in a shorter period of time.

(309) 3,072,186, Jan. 8, 1963, Harry W. Parker, *Recovery of Hydrocarbons By In-Situ Combustion*

Rows or rings of injection and recovery boreholes are drilled into a carbonaceous stratum, and a combustion zone is established in the stratum at the recovery well(s). Air or oxygen-enriched air and a low-ignition-point fuel are fed either as a mixture through one injection borehole or separately through adjacent boreholes, to move the combustion zone through the stratum counter-currently to the flow of the mixture. Hydrocarbons in the stratum are heated and driven into production well(s) by the combustion. The fuel used may be any vaporizable or natural gaseous fuel having an ignition point below 400°F, such as carbon disulfide (preferred), propylether, benzaldehyde and/or ethylether. An excess of oxygen relative to the gaseous fuel is maintained, the amount of fuel ranging from 0.25 to 7 vol. percent of the air-fuel mixture. All of the fuel is consumed in the leading edge of the combustion front, thereby increasing the rate of advance of the front, lowering the temperature within the combustion zone and reducing the energy loss to surrounding strata.

(310) 3,087,541, April 30, 1963, E.R. Elzinga, *In-Situ Combustion Process*

This patent describes a two-stage thermal method for secondary recovery of petroleum from partially depleted, permeable *underground* oil sand reservoirs. In the first stage a combustion zone is established within the reservoir near injection wells. Then, combustion-supporting gas (air) is introduced behind the combustion front to drive it, the combustion products and the oil vapors produced in the high-temperature zone preceding the advancing front toward production wells, leaving behind an overburdened region. The second stage is initiated when the combustion front reaches the production wells, spaced 300 to 3000 feet from the injection wells, and while the initial combustion of reservoir oil continues. Combustible gaseous or liquid fuel (e.g., product gas recycled from production wells) is introduced under pressures of 100 to 1000 psig into the top of the sand, and oxygen-containing gas is introduced at the bottoms of the sand, before the temperature in the burned zone has dropped below the ignition temperature of the fuel. The fuel and oxygen are continuously injected to secure combustion in the area burned out in the initial stage. The heat front operated by combustion moves downward into oil-saturated sand below the burned zone, reducing the viscosity of additional quantities of oil and driving it toward the production wells. The injection fuel and oxygen is controlled to secure maximum utilization of oxygen and to minimize corrosion due to combustion in the producing well.

- (311) 3,237,689, March 1, 1966, Clarence I. Justheim, *Distillation of Underground Deposits of Solid Carbonaceous Materials In-Situ*

A plant is constructed *underground* for the *in-situ* distillation of the bituminous content of bitumen-impregnated materials. The plant consists of *underground* workings including a man-way or shaft extending from the *underground* area in the deposit to the surface, and a chamber at the bottom of the man-way. The chamber is surrounded by a heat-insulating wall so as to form a thermal room insulated from the deposit and man-way. A heat-retarding passageway through the wall is provided for operating personnel. Heat sufficient in temperature and quantity to decompose and progressively distill the bituminous content of material surrounding the room is generated by a nuclear reactor having a fluid-circulating coolant system located in the room. Means for introducing and controlling the heat generated are described.

- (312) 3,279,540, Oct. 18, 1966, M. Lange, et al, *Process for the Exploitation of Bitumens-Containing Strata by Underground Preparation and Gasification*

Essentially the same as Brit. 1,030,749, May 25, 1966. (292)

- (313) 3,283,814, Nov. 8, 1966, G. Schlicht, et al, *Process for Deriving Values from Coal Deposits*

Essentially the same as Brit. 1,018,011, Jan. 26, 1966. (291)

- (314) 3,298,434, Jan. 17, 1967, T.T. Graham, *Gasification of Coal*

This patent describes methods based upon the use of one well bore sunk into a coal seam as injection and production well or the use of a number of production and injection wells between which connecting channels are established by mining, hydrofracturing or electrolining-carbonization. The selected seam must be overlain by overburden suitable for containing the pressures applied in the process.

Air is injected through the injection well, and the coal is ignited; thereafter, air and steam are injected alternately, the air cycle raising the combustion zone temperature to 2200°-2600°F and the steam cycle lowering it to 1600°-1700°F. Periodically, the injection well is refluxed to clean it of fluid condensates which have collected and to remove the fluid products of combustion from the vicinity of the flame front. Measurements of the temperature and analyses of the gaseous content (especially CO and CO<sub>2</sub>) of the fluids from the flame front indicate the temperature at the flame front. The time of injection of alternate steam and air is varied to maintain the flame front temperature at desired levels (between 1832° and 2600°F) and to thereby control the conditions for coal combustion. Fuel gas (primarily CO and H<sub>2</sub>) and volatiles are recovered during the steam cycle, and volatiles (e.g., N<sub>2</sub> and CO<sub>2</sub>) are recovered during the air cycle.

Alternatively, air and steam may be injected as a mixture, their ratio in the mixture being controlled to maintain the flame front temperature at 1900°-2600°F, as indicated by analysis of the reflux gas. After the flame front reaches the production well(s) it is returned towards the injection well(s) by returning the coal at 3000° to 3400°F to produce additional fuel gas.

Gasification and recovery of tars and gases may also be carried out in a single pan of the flame front operating in the 2500°-2600°F temperature range.

(315) 3,362,751, Jan. 9, 1968, W. Tinlin, *Method and System for Recovering Shale Oil and Gas*

An *underground* system of interconnected tunnels, galleries and shafts is excavated in an oil shale formation. The tunnels are 50 to 100 ft long and are uterated over one another, separated by 30 to 50 vertical feet. They are drilled with opposite directions of slope (about 1 to 2 inches per foot), so that their ends converge toward a point where tunnels enter some level are joined by galleries and where upper and lower tunnels are connected to the surface by shafts.

Heat is applied to the shale in the vicinity of the tunnels by passing through air and steam which is superheated to about 1200°F by an external heat source, such as a three-stage oil furnace. As the heat permeates the shale surrounding the upper (heating) tunnel and raises its temperature to 1000°F, liquified oils and vapors are driven out of the rock and flow through conduits freely (by gravity) along the backward slopes of the tunnel toward a vertical or inclined vapor shaft. Liquid oil fractions flow down the shaft to a return tunnel and dump for recovery, and gaseous fractions are exhausted up the shaft. Vapors condensing in the shaft flow down to the return tunnel; at the top of the shaft condensable hydrocarbon vapors are condensed and uncondensable vapors are collected by an off-gas flue. Through the operation of valves, condensers, glues and air control locks the flow of convection air through the system is regulated for maximum heat utilization and oil recovery. Oil recovered from the sump may be used as fuel for the external heat source.

A modification of this system involves the use of a molten metal as the heat transfer medium which, with a connection flow of air, raises the temperature of the shale to 1800°F.

(316) 3,395,756, August 6, 1968, Hans Lange, et al, *Process for the Exploitation of Bitumens-Containing Strata by Underground Preparation and Gasification*

A continuation-in-part of U.S. Patent No. 3,279,540: (312)

The principal objective is to apply double thermal impact to prepare a coal deposit for gasification while the deposit is in the plastic temperature range.

A heat transfer medium consisting of a mixture of incondensable gases and condensable hydrocarbons is heated to 350°C by a nuclear reactor or other heat source (e.g., electrically energized immersion heater) and is introduced into the deposit through treatment boreholes under pressure sufficient to fracture the coal (20-35 atm per 100 m of deposit depth). Incondensable gases may be inert gases, light hydrocarbons (e.g., CH<sub>4</sub>), N<sub>2</sub>, O<sub>2</sub> or air, and condensable hydrocarbons are those with a B.P. between 250° and 300°C (1 atm), such as benzene, a mixture of 10% pentane and 85% heptane. The percentage of incondensibles in the mixture is 20 to 30% by weight. In addition to fracturing the coal, the mixture heats the coal adjacent to fractures to just below its softening point (340° to 425°C). Small explosions may be set off in boreholes to further open up the fissures, and cool liquid light hydrocarbons are introduced to cool the area around the boreholes.

A mixture of oxygen-carriers (e.g., KNO<sub>3</sub>) or explosives (e.g., TNT, black powder or a mixture of 1 kg benzene and 1.1 kg oxygen 95%) is dissolved in low-boiling-point (less than 100°C) liquid hydrocarbon solvents, such as benzene, xylene and toluene, and is injected. Subsequently resumed injection of the hot hydrocarbon heat transfer medium serves to volatilize the solvents and precipitate the explosive or oxygen carriers. A mixture of air and hydrocarbon vapors is introduced under pressure, igniting and burning the mixtures previously precipitated in fissures in the coal. The applied pressure keeps the fissures open and maintains porosity of the coal through its plastic phase until the upper temperature limit (425°C) is exceeded, the desired porosity is achieved and combustion products are collected from recovery boreholes. Oxidizing agents (e.g., preheated air) are finally introduced to commence combustion of the heavy pervious coke resulting from the pervious steps and to extract bituminous materials by gasification.

The control of combustion and gasification is described in U.S. 3,283,814 (313)

(317) 3,506,309, April 14, 1970, Hans -- Joachim Von Hippel, *Method and System for Gasifying Underground Deposits of Coal*

*Underground* channels are drilled or excavated to form a network in a coal seam, ranging from a single channel connecting an inlet and an outlet shaft to a complex arrangement of channels connecting the bottoms of a plurality of outlet shafts situated around centrally located inlet shafts. Air and a suitable fuel are burned in a combustion chamber in an inlet shaft, producing hot CO<sub>2</sub> gas which flows into the connecting chamber, where it reacts with the coal face to form hot CO gas. The CO is sufficiently hot to extract from the coal nearly all volatile substances, such as CH<sub>4</sub> and others, which improve the quality of the final product. The CO gas, tars and other substances are periodically withdrawn by suction through the outlet shaft(s); up to 50% of the CO may be supplied to the burner in the inlet shaft to react with air to form CO<sub>2</sub> for the process. An

emulsion of coal dust in water may be used as fuel for the burner to enrich the final product in  $H_2$ ; pure  $O_2$  may be used instead of air for the burner in order to produce combustible gases of very high quality.

(318) 3,497,335, February 24, 1970, J.W. Taylor, *Underground Gasification of Coal*

The same as British Patent No. 1,120,384, July 17, 1968. (294) tion 2b(1)(g).

(319) 3,563,606, February 16, 1971, Howard V. Sears, *Method for In-Situ Utilization of Fuels by Combustion*

Passages in intersecting sets of parallel rows are formed by directional borehole drilling so that they extend from the surface downward in an arcuate or inclined direction to a seam of combustible material and then for several hundred feet through the seam in a horizontal direction, with overlapping portions of adjacent boreholes in the same row being coextensive for 20 to 50 feet. A suitable fuel is forced down to the seam through an air supply pipe in one passage and ignited there by an electric cable equipped with spark plugs and supported by a stream of oxygen. To initiate a combustion chamber, air is supplied through the pipe; a blower is used to draw out the combustion products through the annulus between the pipe and passage wall. After combustion is well established, progressive burning away of the material is brought about by using one borehole from the chamber for air supply and another borehole from an intersecting (perpendicular) row for exhausting combustion products to the surface for recovery, separation and processing. Although the combustion chamber thus formed tends to expand in all directions or in an elongate shape as the air supply pipe is gradually withdrawn, its rate of burning and expansion are controlled and the burning face of the seam kept straight by regulating the rate of air introduction.

The combustion of coal or other material of the seam is incomplete, producing a gaseous fuel such as  $CO$  or  $H_2$  rather than incombustible combustion products such as  $CO_2$  or water. Collapse of overburden into burnt-out passages does cause some surface subsidence but does not impede the supply of air, the combustion or the withdrawal of combustion products. Small-diameter observation wells or thermocouples situated along the air supply pipes can be used to determine how rapidly the combustible material is being burned away and how far burning has progressed.

The process makes more attractive the utilization of deposits that would otherwise be untapped, such as seams too thin to be mined economically, materials with high content of sulfur or other deleterious elements and materials overlain by overburden which cannot be stripped economically. The materials might include coal, lignite, peat and oil-bearing strata.

Where passages (e.g., shafts, tunnels) are being excavated in a coal seam, a gas-moving device is used with an arrangement of directionally drilled boreholes to maintain reduced pressures in the passages and to draw out from the seam ahead of the working face any noxious gases (e.g., CH<sub>4</sub>, CO) which would enter the passages from pockets that are intersected or are otherwise connected to the passages by fissures or porous zones within the seam. The process therefore minimizes the likelihood of noxious gases entering the excavation, making *underground* mining safer.

- (320) 3,598,182, August 10, 1971, Clarence I. Justheim, *Method and Apparatus for In-Situ Distillation and Hydrogenation of Carbonaceous Materials*

This patent describes a method of distilling and hydrogenating the hydrocarbon content of carbonaceous materials where in hot hydrogen is introduced into the carbonaceous material in sufficient quantity and at sufficient temperature to concurrently release and distill the hydrocarbon content. Preferred apparatus for practicing the method includes a source of hydrogen, means for varying the temperature of the hydrogen, an *underground* chamber in the carbonaceous material, and means at the face of the shale for regulating the temperature of the hydrogen.

#### West Germany

- (321) 1,102,901, Feb. 21, 1957, G.J.W. Solomonsson, et al, *Recovery of Combustible Substances from Carbonaceous Deposits (see Israeli 8616)*

Valuable liquid and gaseous products are recovered *in-situ* from various geological formations, e.g., shale formations, for sand and sulfur deposits, which are covered by an overburden of limestone. A heating element consisting of three concentric tubes is inserted vertically into the deposit, carrying a supply of fuel and air or oxygen-enriched air to the reaction zone. A limited heating zone is created which is movable along the element for a distance of 20 to 100 meters.

- (322) 1,003,387, Feb. 28, 1957, Frederik Ljungstrom, *Methods of Producing Liquid and Gaseous Fuels from Underground Bituminous Deposits In-Situ (see Sweden 159,785)*

A tar sand (e.g., Athabasca sand of western Canada) is subjected *in-situ* to partial prepyrolysis by heating elements lowered into boreholes. Heavy oil in the sand is converted into light oils of lower viscosity and gas. The products are not removed from the pyrolysis zone but are forced under high pressure into the surrounding sand, where they dissolve into unpyrolyzed heavy oil. In this manner the tar sand is transformed into a formation from which it is possible to produce oil by conventional wells.

- (323) 1,008,861, May 23, 1957, G.J.W. Sollomonsson, *Methods of Producing Hydrocarbon Materials from Tar Sands In-Situ (see Israeli 8617)*

Tar sand deposits containing fine quality sand, viscous black tar, and  $H_2O$  are pyrolyzed *in-situ* to yield vapors of hydrocarbons such as  $CH_4$ , heavy petroleum hydrocarbons, oxygen, nitrogen, and sulfur compounds, phenols,  $NH_3$  and  $H_2S$ . Holes are drilled by directing a stream of oxygen-containing, hot gas mixture toward the sand. This initiates combustion of the tar between sand grains, which are freed and pneumatically transported to the surface by the ascending current of combustion gases; it also results in cracking of tar in the sands surrounding the hole. Virgin tar sand can also be treated to 250-400°C through numerous marble tubular heating elements.

- (324) 1,026,471, March 20, 1958, Tyril A. Masterman, *Methods for Underground Gasification of Coal*

A gasification reaction is initiated at the blind end of borehole extending within a coal seam, as in German patent 1,022,740(122). A supply pipe with heating elements inserted in it is installable in the basehole. Liquid or gaseous fuel (e.g., propane) is fed into the pipe from the surface and ignited electrically by the heating elements, creating a fire zone within the pipe. A stream of inert gas (admixed nitrogen and combustion exhaust gas) is injected at a rate of 5.66 m<sup>3</sup>/hr, rising to a temperature of 550°C as it passes through the fire zone and transferring heat to the coal at the end of the basehole. The temperature of the gas is controlled by changing the stream's velocity, by changing the gas stream composition or by changing the rate of fuel injection into the heating elements. After ignition, air is introduced into the gas stream and heated to sustain combustion. When the reaction is well established, a temperature of 800°C in the treatment zone is maintained by terminating the heating of the gas stream and eventually by terminating inert gas entirely, leaving only an air blast. The amount of air injected to the burning coal is increased or decreased to control the reaction.

- (325) 1,496,385, (Offenlegungsschrift)\*, Feb. 27, 1969, Jakob Burr, *Methods for Exploiting Underground Coal, Oil Shale or Other Fuel Resources*

Coal and similar carbonaceous materials are subjected to low-temperature (500-600°C) carbonization *in-situ* to produce a gas which is pumped to the surface and then processed to yield derivatives such as automobile gasoline.

\* By German patent practice, "Offenlegungsschrift" are pending patent applications open to public scrutiny.

A supply pipe is inserted down a shaft and into the marked-out portion of an abandoned coal mine. The shaft is sealed. The remaining parts of the seam (e.g., pillars) are ignited and the gases produced by carbonization are withdrawn through the pipe. The crude tons and other materials formed during carbonization are also pumped to the surface and processed there.

(326) 1,292,733, April 17, 1967, John Watson Taylor, *Methods and Equipment for Underground Gasification of Coal*

The same as Britain 1,120,384, July 17, 1968. (294)

(327) 1,571,201, (Offenlegungsschrift), August 8, 1961, Deutsche Erdol AG, *Methods for the Exploitation of Bituminous Formations by Preparation of the Formation and Underground Gasification.*

The same as Britain 1,018,011, Jan. 27, 1966. (291)

(328) 1,571,202, (Offenlegungsschrift), December 5, 1961, Deutsche Erdol AG, *Methods for the Exploitation of Bituminous Formations by Preparation and Underground Gasification*

The same as Britain 1,030,749, May 25, 1966. (292)



## **APPENDIX C RELATED TECHNOLOGY**

As part of our appraisal of underground coal gasification, we have reviewed technology in several related areas where recent developments might be able to indicate new techniques or provide potentially useful information.

### **1. THE USE OF EXPLOSIVES IN LINKING**

In addition to the non-explosive shattering techniques used to render a body of coal more homogeneously permeable to enhance gas/coal contact, it may be worthwhile to consider explosion techniques. Having the coal in a thoroughly fragmented, or rubbled, condition could offer benefits, such as the following:

- Increased air acceptance rate of the seam, thereby increasing the rate of gas production.
- Improved control of the burning rate, thereby making the prediction of process variables and processing results more accurate.
- Simultaneous subjection of more and larger areas of the coal bed to the gasification process, thereby increasing production capacity.
- Increased distance between boreholes, thus reducing drilling and its concomitant capital costs.
- Increased control and predictability of the burning zone character and form, thereby reducing the likelihood of leaving pockets of unburned coal.

According to the literature the reduction of coal in situ to a thoroughly fragmented condition has not yet been accomplished successfully. During early experiments in Russia, charges of dynamite were implanted ahead of the reaction zone to produce coal breakage, but the explosions and resulting breakage produced inconclusive results.

Adequate breakup requires an appropriate explosive action – i.e., the development of steep “pressure-time” gradients throughout the coal seam. For example, the emplacement of a large charge of explosive at the bottom of a hole drilled into a zone of coal would seem to be inappropriate to produce anything but the fragmentation of the coal in a rather small zone surrounding the charge.

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An appropriate approach to obtaining good breakup of a mass of coal would seem to be the permeation of the coal body with a liquid explosive, emplaced by a hydraulic-fracturing technique, for example. This could be achieved in a one-step operation by incorporating the explosive in the fracturing medium, if it could be made insensitive enough to withstand safely the rigors of injection under pressure. If an explosive is to serve such a purpose, it should meet the following criteria:

- It should be insensitive enough to withstand handling and pumping throughout the fracturing phase.
- It should be sufficiently sensitive to be detonated completely, without failure to propagate the shock wave, after emplacement.
- It should have good brisance, or shattering power.
- Its rheological and viscous properties should be capable of being tailored to optimize its acceptance by different kinds of coal beds.
- Its critical diameter (the diameter below which propagation fails) should be as small as possible so that the explosive-filled "capillary" zones within the coal seam would also undergo detonation.

Another appropriate approach could be based on the use of a "Sprengel" - type explosive mixture - i.e. a two-component mixture, each of which is by itself non-explosive. Each component would be injected into the seam separately, and only after the mixing occurs would detonation be possible. Several Sprengel-type liquid mixtures are known, (e.g., Dithekite). It seems reasonable to expect that with experimentation the liquid compositions can be modified to obtain the properties (e.g., viscosity) required for effective permeation and explosion of the coal.

Relatively new classes of compositions, known as "Slurry Blasting Agents" (SBA's) and "Slurry Explosives" (SE's) already exist and have been field-tested. These are "gelled" explosives and could well lend themselves to injection applications in a manner analogous to the gels already tried in the preparation of hydraulic-fracturing fluids.

SBA's consist of aluminum-sensitized or organic-fuel-sensitized ammonium nitrate, dispersed in water and thickened or gelled with hydrophilic gums and crosslinking agents. SE's are of higher strength than the SBA's and differ in that they are sensitized with explosives such as TNT. Both the SBA and the SE classes are generally less sensitive to initiation than are other explosives, and are, therefore, less hazardous to handle.

However, no experience seems to exist describing their use as a combination explosive and hydraulic-fracture fluid. Thus the development of such an application would be a candidate experimental program, because the high density and the low critical diameter of SBA's and SE's seem to fit their use in the fragmentation of confined bodies of coal underground. Also, SBA's sensitized with organic fuels are insensitive mixtures by normal explosive standards, and are less powerful than the SE's. Their greater insensitivity could also make them candidates for formulating combined explosive and hydraulic-fracture fluids. Moreover, techniques now are available for regulating insensitivity (as well as properties of detonation velocity and bulk strength) through aeration and particle size selection. SE's sensitized with TNT have been used with great success under conditions of high pressure (e.g. in deep well and underwater blasting).

Another liquid-explosive formulation of recent development now in both production and the field testing stage is "Astrolite." This explosive is a Sprengel-type mixture and appears to be based on reactions involving hydrazine. There are two versions of Astrolite ("A" and "G"). The "A" type appears to be based in powdered metals, probably aluminum. The manufacturers appear to be reluctant to release further details, except that, as of May of 1970, Astrolite was to undergo evaluation in a project for injection into oil and gas bearing strata. The technique for injection and the results are not known at this time, but they would bear on whether Astrolite could be used as a Sprengel explosive in a two-stage hydraulic-fracture explosion scheme for the purpose of controlled coal fragmentation. An attractive feature of Astrolite as well as for slurries is that in the field they lend themselves readily to automatic mixing and loading in high volume.

Another approach to linking by explosion could be to utilize the technique of "pulsed water infusion." The conventional purpose of this technique is dust control (e.g., in European underground mines). In this technique, a high explosive (waterproof) is placed in a borehole which is filled with water and sealed. The firing of the charge produces a high-pressure impulse, which is transmitted to the water within the cracks of the coal, thereby enlarging the cracks and somewhat fragmenting the coal. The pulsed water infusion step could be followed by explosive blasting with SBA's or SE's.

Finally, an appropriate technique could be the injection of a liquid explosive in a path between boreholes produced by electrolinking. The Bureau of Mines has successfully used such a method for increasing the permeability of oil shales prior to in-situ retorting (279).

## 2. THE USE OF LASERS IN DRILLING

During the past few years, a number of different types of lasers have become industrially useful tools. Small helium-neon gas lasers are now widely employed for meteorological purposes, such as the measurement of distances to very high accuracy, and also as a simple means for laying out a straight line. Higher power lasers are used for machining. Pulsed lasers, with neodymium glass or ruby rods, are used in the sizing of diamond dies, in the trimming of precision electrical resistors, and in similar applications. Continuous wave CO<sub>2</sub>-gas lasers have been or are used to cut paper, fabric, and plastic; to weld and cut special alloys; and to grow single-crystal fibers of ruby and other high-melting-point materials. There has also been considerable activity in the development of CO<sub>2</sub>-laser weapons.

There appear to be two main fields where a laser could help in gasifying coal underground. One is in surveying, where a small helium-neon laser could position boreholes, could measure verticality and straightness of holes, and could guide special tools to drill offset holes. Such a laser has an advantage over a theodolite or a level, in that, instead of viewing along a line, its extremely narrow beam of light is easily visible over hundreds of feet. To position some device with respect to this straight line, one needs only to observe the beam on a white target (or one can employ an automatic photocell device). A trained operator is not required.

The other could be in the linking of boreholes, an application for a high-power CO<sub>2</sub>-laser. Except for drilling, conventional linking procedures do not produce straight line paths between the boreholes to be linked. CO<sub>2</sub>-lasers, either alone or, more likely, in conjunction with electro-linking, might be useful to control path geometry.

Very high continuous output powers (up to 1 KW) are now available from industrial CO<sub>2</sub>-lasers because of their high efficiency. Also, their long-wavelength output (10.6 microns) is typically reflected by metals, while at the same time this output is highly absorbed by almost any non-metallic substance. For the same reason, however, the long wavelength limits the choice of suitable materials for mirrors, lenses, and windows in the optical systems which focus and direct the output. A good window and lens material is rock salt (NaCl) but it is hygroscopic. Germanium optics are rugged and readily available but they are susceptible to thermal runaway (i.e., above 40°C, their absorption at 10.6 microns increases catastrophically). Gallium arsenide does not have any of these problems, and should be considered to be a candidate material.

Tunneling by lasers has been studied\* but drilling of deep holes in coal seams apparently has not. The power output of industrially applicable systems, presently around 1 kilowatt, is expected to reach 10 kilowatts in a few years. Even

\*Work reported by M.I.T. Civil Engr. Dept. for U.S. Dept. of Transportation Technical Clearing House

PB-173-368	Nov.	1966
PB-174-245	Jan.	1967
PB-179-205	May	1968
PB-178-987	May	1968
PB-187-274	April	1969

such power levels, however, would still not be high enough to vaporize sufficient amounts of coal — i.e., to drill a hole in coal in the same fashion as lasers are now used to drill microscopic holes — at acceptable drilling rates. Although such an approach would be straightforward, the method would most likely encounter problems in very deep holes, because the vapor will eventually block the beam from the laser either by scattering or by absorption. Continuous drilling action will be impossible without some provision for purging.

Alternatively, one could supply air or oxygen to the coal face using the laser only to initiate and to direct the combustion process — i.e., a combustion-drilling process. The problem of scattering by smoke and of absorption by the  $\text{CO}_2$  in the combustion products would remain to be solved. One could, for example, think of a “drill” pipe with a laser beam going down its center and air being blown through it to the face. The drill pipe would carry a reamer rather than a bit and the combustion would take place a few feet ahead of the pipe. The hot gases would then return to the surface in the reamed space around the drill pipe. Obviously, a severe problem will be caused by the hot combustion gases, which will heat up the drill pipe and probably cause the coal around the pipe to continue to burn. The problem perhaps might be solvable by adding nitrogen to control the oxygen content of the air.

A simpler solution could be to direct the laser at the coal face in an oxidizing atmosphere and to burn until absorption blocks the beam. Then one would flush with nitrogen and repeat the process. Experiments would have to show how deep a hole could be drilled by such a method. An intermittent process such as this would be well suited to lasers that will emit very-high continuous-wave power, but cannot sustain their full output for more than a few seconds or minutes. Certain gas-dynamic  $\text{CO}_2$  lasers — at present mostly considered for weapons — are of this class.

### 3. LARGE-SCALE USE OF OXYGEN AS THE GASIFICATION AGENT

The use of enriched air, or oxygen-steam mixtures would increase the heating values of the product gases, but availability of low-cost (tonnage) oxygen is a significant consideration. The current industrial method for making oxygen is based on cryogenic technology, and plants of this type operate efficiently in the range of 1500-2000 tons of oxygen per day, a scale not available 20 years ago. The limit appears to be based on the maximum available size of steam-turbine-driven air compressors. Larger plants than these would require multiple units. The cost of oxygen per ton increases substantially in the smaller plants (i.e., less than 1500 tons of oxygen per day).

Enriched oxygen streams containing 65-95% oxygen can be produced by pressure-swing adsorption. The process is based on selective adsorption of nitrogen on molecular sieves under pressure, the removal of the oxygen-enriched stream and desorption of nitrogen under vacuum. Plants based on this approach could produce enriched oxygen streams economically at capacities of 100 tons per day of oxygen or less, and could be attractive for development work on new or improved methods, or if underground gasification were to be applied to supply gas mixtures solely for chemical production.

#### 4. SUBSIDENCE AND ITS DETECTION

Removal of a mass of coal by combustion is likely to lead to roof collapse, and roof collapse to subsidence in the overlying rock mass up through to the ground surface. Subsidence in coal mining districts is well known and preventive measures are usually taken during the mining operations by preserving pillars. Other techniques, such as backfilling with waste or quarry rock and construction of supporting structures are sometimes used. Preventive measures of this kind may not be feasible in the underground combustion operations; therefore, close surveillance of roof collapse would be important for determining the harm that may be done to the gas/coal contact mechanism. Detection of subsidence would be important to indicate that operations to prevent roof collapse have not been successful.

The principal method of determining the amount and extent of subsidence is precise leveling. Repeated surveys of established benchmarks covering the area yield contour maps permitting a graphic representation of the progress of subsidence in the affected area. The main limitations of the leveling method are its slowness and its cost; field crews must periodically survey the area. The detection accuracy of the method is, at best, a few millimeters in elevation, depending on the quality of equipment, experience of the crews and time available for the field work. Thus the leveling method does not detect incipient subsidence nor does it quickly and accurately indicate the rate of subsidence.

It would be desirable to supplement the periodic field surveys with continuous monitoring of subsidence by means of recording instrumentation. However, it would only be economically practical to use such instrumentation to cover some of the sites – they could be selected on the basis of the expected effects or the criticality of their location.

Recording tiltmeters are perhaps the most suitable of the presently available instrumentation. Tiltmeters of various types (pendulums, water or mercury tubes, for example), are commercially available and achieve resolutions, typically, of a small fraction of a second of an arc, which is a far better accuracy than that of the

leveling method. The U.S. Geological Survey has used tiltmeters to monitor the inflation and subsidence caused by volcanic activity at the Kilauea volcano in Hawaii. Costa Rican authorities installed and operated a new type of tiltmeter at the Arenal volcano in Costa Rica after its explosion in 1969. The records obtained over seven months of continuous operation clearly indicated several episodes of inflation and subsidence associated with the movement of magma in the underground reservoirs.

To date, however, tiltmeters have not found general use in monitoring mining operations. But some work in this direction is being done at the Mining Research Laboratories of the Bureau of Mines in Denver, Colorado.

## 5. MONITORING THE COMBUSTION FACE

The monitoring process should result in continuous and almost instantaneous knowledge of the position and temperature of the coal face. Methods for achieving this could be based on electrical, seismic, acoustic, and infrared radiometric approaches.

### a. Electrical Methods

No passive electrical methods (i.e., depending on the detection of electrical signals generated by the combustion face) appear to have promise of monitoring the combustion face of an underground gasification installation. Geological prospecting has been done by electric-potential mapping, using the telluric method (ground electric currents), but since the ground currents vary both seasonally and diurnally, they are not reliable. Measurement of the electrochemical potential generated by underground combustion is probably not practical. The maximum voltage to be expected here is on the order of a volt and the dipole field will increase as the cube of the distance from the site. Potentials already found in the ground are on the order of tenths of volts, so at relatively short distances from the combustion face the noise background could be inseparable.

Active electrical methods, on the other hand, do show some promise. With an electrothermal approach, one could monitor the position of the combustion face by measuring temperature in the surrounding material. An obvious method would be to use numerous thermocouples strategically placed. This technique would be sensitive to temperature changes. A less sensitive technique would be to use a pair of nichrome wires with fusible shorting links that melt at a known temperature to indicate the approach of the fire zone.

The resistivity of coal deposits and adjacent strata is quite variable, and is largely due to impregnation by ground water, whose resistivity is inversely proportional to its ionic content. (Typical values for resistivity are shown in

Table C-1.) Differences in resistivity might provide a basis for monitoring the combustion face.

**TABLE C-1**

**ELECTRICAL RESISTIVITY OF COAL AND ROCK STRATA**

<b>Material</b>	<b>Resistivity (ohm-meters)</b>
Coal	100 to 1000
Sediments	10 to 100,000*
Wet limestone	100 to 1000
Clays	1 to 100
Graphitic shales	0.1 to 100
Pyrite ore	0.01 to 1000

\*distribution peaks at 100 ohm-meters

Differences in resistivity have been used to determine when a drill bit leaves the coal seam. In one case, an electrode was attached to the drill and a tenfold increase in current was measured when the drill entered the more highly conductive strata. In geophysical prospecting, current may be passed between two distant electrodes and an electric potential map of the intervening region obtained. Alternating current is usually employed to obtain greater sensitivity in detection, and to avoid induced polarization. Electrical power on the order of one to ten kilowatts is used. The penetration depth into the ground is approximately one-half the separation between the current electrodes: that is, at the midpoint one-half of the current passes above this depth and one-half passes below.

In a geologically well-surveyed region, a network of current and voltage electrodes could be designed and located to indicate the advance of the combustion zone. The changes in the potential field due to the consumption of the coal or due to dehydration around the fire zone, or both, might generate the required information. Also, carbon and coal resistivity drop rapidly as the temperature is raised. Thus, the hot coal in the fire zone would act as a highly conductive anomaly, and this might be detected either potentiometrically (as described above), or inductively by a large search coil (as in a mine detector).

The use of these active electrical techniques in combination with a high-speed data processor would seem to offer a means of securing instant knowledge of the location and shape of the combustion face, but considerable development appears necessary to reduce any of the techniques to practice.

## b. Active Seismic Methods

Active seismic techniques seem to offer considerable promise in providing a means of locating the combustion front in underground coal gasification because of the drastic changes that should occur in seismic propagation constants at the combustion region. Thus, seismic energy propagating from the unburned region into the burning, or burned, region would encounter a substantial change in elastic parameters. This change would cause some of the impinging seismic energy to be reflected back from the combustion region. This returned energy could then be monitored and processed to yield information concerning the location of the transition region represented by the combustion interface. Extensive work in oil-well and in shallow geological prospecting provides considerable experience and data suitable for application of active seismic techniques to the location of a region representative of the coal/ash interface produced in underground gasification.

In terms of implementing such a scheme, non-explosive seismic stimulus devices would appear to be more attractive than explosive types, for many reasons. They would do no damage, present no safety hazards, and their stimulus would be uniform. Two general types of stimulus equipment which would appear to be applicable are the impulsive type, such as a drop hammer, and the swept-sine-wave-source type, such as a "vibroiseis."

Regardless of which stimulus is used, the seismic source would be installed in one of the boreholes near the periphery of the region that is to be gasified. At two or more locations in the same or other boreholes, elementary seismic receivers would be installed. They would receive "smeared-out" pulses, whose time delay with respect to the transmitted pulse is proportional to the distance the seismic wave travels from the source to the interface and thence to the receiver. For a single receiver, for each such time delay there is a parabolic surface of ambiguity. The position of the combustion interface can be determined by finding the regions of intersection of sets of parabolic surfaces for the various receivers. For a continuous swept-frequency seismic source, the same process can be used: the received frequency becomes a measure of time delay, or travel distance.

Although the system appears to have promise for either type of stimulus, in assessing its utility to solve the combustion face location problem one must consider a number of factors:

- *The seismic wave propagation velocity.* The effective propagation velocity must be determined beforehand in order to obtain accurate interface locations.

- *Multi-path problems.* The receivers will be responsive not only to seismic energy reflected from the combustion interface, but to the seismic energy reflected from all interfaces that the seismic energy encounters as it propagates. Thus, the energy returned from the combustion interface would have to be sorted out from a very large energy return from other interfaces. It may be necessary to preserve the received signal and make comparisons as time elapses. It seems reasonable to expect, however, that the major source of changes in the received signals results from the one thing that significantly changes in the coal medium, and that is the position of the combustion interface.
- *Seismic interference.* There will be both man-made and natural seismic disturbances in the medium. The active seismic system must function in the presence of these disturbances which include microseisms, vehicular traffic, earthquakes, and machinery noises.

The seismic system would probably rely heavily on computer-based data reduction, this reduction being necessary because of the very large amount of data that must be processed to yield quick combustion front position estimates, and also because many geometrical loci must be generated and analyzed for coincidence to determine these position estimates.

#### c. Passive Acoustic Methods

The use of a passive acoustic system seems to be a promising approach to locating the combustion front. The basic phenomenon upon which this system relies is the fact that the combustion process releases acoustic energy. Some of this acoustic energy propagates through the gas and some propagates through the coal bed. Whether one thinks of the energy propagated in the solid medium as acoustic or seismic is not relevant.

The attenuation of acoustic energy travelling in a medium like coal at what are normally regarded as acoustic frequencies is well known to be significant. Furthermore the fact that the basic source of the acoustic power (the combustion front) will have components in a wide frequency range means that propagation in the solid medium should certainly be expected for distances of perhaps hundreds of feet. One approach could be to use geophones attached to the walls of the boreholes that are set in at the boundaries of the coal region being gasified to pick up the snaps, pops, and cracks of the combustion.

Consider the electric waveforms produced by the geophones in response to their detection of the acoustic waves in the medium. For discrete, short-duration energy releases at a point in the combustion front, the response at a geophone will occur at a time delay proportional to the distance that the wave travels to reach the given geophone. If the responses of two geophones are compared, there will be a time difference between arrival of the pulses. Knowing the velocity of propagation, it is possible to determine a hyperbolic surface which represents all possible loci for the position of the energy source. In turn, a second hyperbolic surface is generated by the time difference of a second pair of responses. The intersection of the surfaces is a line. Using six pairs of signals from four geophones, one would eliminate ambiguities in position and be able to identify a single point in the medium as the source of the initial energy release. Repeated application of this process should result in a definition of a surface at which the combustion process is occurring.

If individual events cannot be separated in the geophone signals, the signals from pairs of geophones can be cross-correlated. Such processing of a pair of signals produces a hyperbolic volume of ambiguity and the superposition of the six sets of hyperbolic volumes results in a region of non-ambiguity, which should be the region of combustion.

Although this method appears to have considerable promise, its practical application depends upon several significant influences. Among these are acoustic signals in the medium that are not related to the combustion process, but are due to natural and man-made disturbances. One of the natural sources is the micro-seisms always present in the earth. Two prime examples of man-made disturbances are the compressors used to provide air flow to the fire, and the noise that air introduces into the medium as it flows to the fire and as it returns from the fire carrying the products of combustion.

Other influences of importance are the properties of the medium, particularly, the velocity of propagation of acoustic waves. Because the coal region is bounded within a relatively small volume, the problems of echoes and multi-paths also must be dealt with. Also, the acoustic strength of the source that the combustion process represents needs to be evaluated. If this source proves to be the dominant one in the responses obtained at the geophones, then the technique is promising. On the other hand, if this source is weak, it would render the technique unusable. More likely, the strength could be found to lie in between these two extremes, so that a careful separation of the signals from the natural and man-made background noises would be required.

#### d. Infrared Radiometry

Remote infrared radiometry can conveniently be used to detect temperature anomalies of the order of one-tenth of a degree centigrade. It is limited by weather, rain and fog (clouds, if aircraft are used), and by natural temperature gradients. To minimize the latter and to reduce the background as much as possible, predawn observations are often used. The technology is advanced and appropriate radiometers can be obtained commercially. The spectral band from 8 to 13 microns is generally used as it is relatively free from atmospheric interferences and coincides with the maximum in thermal emission from terrestrial surfaces. This technology would be very useful for monitoring of underground gasification of shallow seams. Green, Moxham and Harvey (269) in a study of coal mine fires, report quick detection when the overburden does not exceed 10 meters. At greater depths, direct thermal diffusivity is much too slow and cracks or boreholes would be needed to permit the thermal energy to reach the surface by convection in a reasonable time. Natural cracks, if present, would be expected to wander, making it impossible to locate the fire precisely.

The only practical way of using this technology for surface monitoring of the gasification process for deep mines would be to sink a number of boreholes into the area. But, in this case, infrared imagery would appear to provide no advantage for deep fire location over the use of thermocouples.

### 6. MONITORING COAL REMOVAL

As in the monitoring of the combustion face, continuous knowledge of coal removal helps ensure that coal is not bypassed.

#### a. Gravity Surveys

Gravity surveys have been reported to be one method of studying the amount and extent of removal of coal mass during the burning process (USBM-288). Whether gravity methods are indeed feasible might be answered by considering a simple model, as follows.

A thin slab of mass of density contrast,  $\Delta\rho$ , and thickness,  $\ell$  (ft), lays horizontally beneath the (horizontal) ground surface at depth  $h$  (ft). This will cause a gravity anomaly,  $\Delta g$  (in gravity units, one G.U. = 0.1 mgal):

$$\Delta g = 2 G \Delta\rho \ell \left[ \frac{\pi}{2} + \tan^{-1} (x/h) \right] \quad (1)$$

$G$  is the universal gravitational constant and  $x$  is the distance between the observation point and the edge of the slab, measured at the surface.

The presence of the underground slab (coal seam) and the change in its density (by burning) can be conveniently detected only at its edge by determining a gravity anomaly profile at the surface. From Equation (1) and under the assumption that  $l \ll h$ , one can derive an estimate of the magnitude of the anomaly as

$$\Delta g \approx \frac{\Delta \rho l}{14} \quad (2)$$

Thus, for instance, for a seam 14 feet thick having a density difference  $\Delta \rho = 1 \text{ gm/cm}^3$ , the anomaly would amount to 1 G.U., or 0.1 mgal (independent of depth). Change in  $\Delta \rho$  resulting from gasification would lead to a change in  $\Delta g$  of this order of magnitude.

Determination of gravity profiles is routinely done to one mgal accuracy. Resolution of temporal and spatial changes on 0.1 mgal level would require extremely accurate and competent field work. Therefore, gravity surveys, while conceivable, do not seem very practical for monitoring progress of the underground gasification process.

#### b. Carbon Balance

The removal of mass from an underground coal seam can be calculated on the basis of a carbon balance and the coal recovery can be calculated from information regarding the location of the firefront.

Because coal seams are generally of a uniform thickness, a more or less constant quantity of coal is associated with a unit area. This amount of coal can be determined with a fair degree of accuracy during the preliminary development of the gasification system by drill core analysis, chemical analysis, and the like. If the position of the fire front is known at any particular time and the area swept by the fire front is known, the coal recovery can be calculated. Excessive leakage of product gas would affect this calculation, and methods of estimating leakage and composition would have to be developed.

### 7. DETECTION OF LEAKS

Leakage of reactant gas can be calculated on the basis of an oxygen balance, a nitrogen balance or preferably by employing a small quantity of an inert tracer gas (e.g., helium).\*

Product gas leakages from the boreholes and gasification zone through fissures in the surrounding rock and soil are not only wasteful of product gas, but because carbon monoxide is toxic, they represent a health hazard. Detection of abnormally high amounts of either CO or H<sub>2</sub> would probably be the best method

\*Radioactive tracers have been used to monitor and study gas streams (19, 38, 143). Krypton was used for monitoring the leakage in the United Kingdom (160).

of leak detection, since the natural abundance of these two gases in the atmosphere is very low (about 1 ppm.). It would be desirable to be able to monitor the gas indicative of leakage at very low levels so that even small leaks could be detected with minimum difficulty. Searching for abnormally high concentrations of CO with a device based on infrared spectrometry would appear to be an attractive solution to this problem.

The technique can be implemented in a variety of ways involving either active or passive systems. Spectrometers of various types (nondispersive, conventional and interferometric) have been used to detect trace amounts of various toxic gases. All of the techniques rely on the spectral structure inherent in the vibrational or rotational motions of all molecules, except the noble gases and homopolar diatomic species (e.g., N<sub>2</sub> and O<sub>2</sub>).

Passive techniques depend on a natural temperature difference between the gas in question and its background. Such temperature differences generally occur for the atmospheric gases, but are somewhat dependent on the local conditions including the meteorology of the area. Active techniques utilize a hot source in the same manner as with conventional spectrometers and, if possible, include a long path through the area in question. Typical detectable concentrations are in the 0.1 – 100 ppm level. Hydrogen can not be detected by infrared techniques.

Leak detection could be performed by periodically monitoring the area of interest with a portable infrared spectrometer which continually sampled the air near the surface of the ground.

Remote detection schemes which would be much less laborious and would permit more frequent, even unattended area surveillance can be envisioned. For example, a centrally located infrared source (probably a laser) could be aimed sequentially at a large number of mirrors (or retroreflectors) placed around the periphery of the area. An infrared spectrometer mounted with the infrared source could pick up the radiation returned from the mirror and detect the presence of carbon monoxide in the path the radiation had traversed. Limited amounts of development have been done on such "searchlight" techniques and further evaluation of their applicability to leakage detection would appear to be warranted.

## 8. MONITORING PRODUCT-STREAM COMPONENTS

In monitoring the product stream from an underground coal gasification process, one is primarily interested in the reaction products CO, H<sub>2</sub>, CO<sub>2</sub>, perhaps CH<sub>4</sub> and other hydrocarbons and a tracer gas. It is also necessary to monitor unreacted O<sub>2</sub>, H<sub>2</sub>O and nitrogen. Each of these gases is normally present at a concentration of greater than 1%, so that a detectability of 0.1% should be generally sufficient.

Historically, high percentages of these gases have been measured gasometrically. A gas sample is taken, passed through a series of reagents, and the volume changes produced on reaction with each reagent are related to the concentration of a given gas. Since such gasometric techniques require a great deal of time-consuming manual labor, the use of automated instrumental techniques in this application seems appropriate.

Three techniques — mass spectrometry, gas chromatography, and infrared spectrometry — are each capable of measuring a number of the specific gases of interest, and have all been used to a limited extent in process monitoring applications. Other, simpler techniques have been developed specifically for process monitoring of some of the gases individually. The applicability of these techniques to the measurement of each of the gases of interest is shown in Table C-2.

Thus, a number of gas analytical techniques appear to be applicable to monitoring the coal gasification product stream for quick determination of gas compositions. The operating principle and some of the limitations of each technique are discussed briefly in the following subsections.

#### a. Mass Spectrometry

In mass spectrometry a sample of the gas is leaked into the evacuated ion source of the spectrometer, where it is bombarded by a stream of electrons. The resulting ions are of different masses. Using spectrometer techniques such as quadrupole mass filtering, or electrostatic and/or magnetic deflection, one can selectively detect the various ions that are produced.

In principle, a single mass spectrometer can measure virtually continuously each of the species of interest in this application. However, there are a number of limitations. Since nitrogen and carbon monoxide both have the same nominal molecular weight of 28, a spectrometer of higher resolution, and hence more complexity, is required to resolve the actual small difference in molecular weight between these two gases. In practice, it is difficult to analyze water with the mass spectrometer because water has a strong tendency to be adsorbed on the interior surfaces of the instrument. To measure hydrocarbons in general, unconventional spectrometer operating procedures must be employed.

Since the spectrometer operates at a vacuum, a good deal of peripheral vacuum equipment is required. Although low-resolution mass spectrometers are widely employed in industrial leak detectors, few, particularly those with a resolution capable of separating nitrogen and carbon monoxide, are used in process monitoring applications.

TABLE C-2

INSTRUMENTAL TECHNIQUES APPLICABLE TO PRODUCT-GAS ANALYSIS

<u>Gas</u>	<u>Mass Spectrometry</u>	<u>Gas Chromatography</u>	<u>Infrared Spectrometry</u>	<u>Other</u>
O <sub>2</sub>	√√	√√	No	paramagnetic sensor electrochemical sensor
N <sub>2</sub>	√	√√	No	
CO	√	√√	√√	
CO <sub>2</sub>	√√	√√	√√	
H <sub>2</sub>	√√	√	No	direct thermal conductivity
H <sub>2</sub> O	poor	√	√√	various dew point meters
CH <sub>4</sub>	√√	√√	√√	
Hydrocarbons	√	√	√	catalytic oxidation

Note: √ = usable, but with some difficulty

√√ = readily available

Sources: Arthur D. Little, Inc.

NOT REPRODUCIBLE

## b. Gas Chromatography

In gas chromatography a carrier gas (usually helium) flows through a chromatographic column which is packed with finely divided adsorbent material. After emerging from the column the carrier gas then flows through a detector (usually a thermal-conductivity detector for concentrations greater than 0.1%). The gas sample is introduced into the carrier gas stream and is carried into the chromatograph column. The various component gases are adsorbed onto the column packing to various degrees and, therefore, each migrates down the column at a different rate. The component gases emerge from the column and then pass into the detector separately and in sequence. While, in principle, a single chromatograph can analyze a mixture containing all of the gases of interest, the analysis is an intermittent one. The sample is injected and a period of time is required to complete the analysis before the next sample can be introduced. Depending on the detailed design of the chromatographic system, from four to ten analyses per hour of a coal-gasification product stream should be possible.

A relatively large number of gas chromatographs are used in process control, but the detailed design of the unit is usually tailored specifically to the type of analysis to be performed. For coal-gasification product streams, a number of design modifications would probably be required. A separate column and detector operated with nitrogen carrier gas would be desirable for the analysis of hydrogen. Additional small columns, switching valves, and detectors would be added to the basic unit to permit rapid analyses of water and hydrocarbons.

## c. Infrared Spectrometry

Measurement of gases by infrared spectrometry is accomplished by measuring the attenuation of a beam of infrared radiation as it passes through the sample gas. Molecules with a dipole moment (which excludes  $O_2$ ,  $N_2$ , and  $H_2$ ) absorb infrared radiation at wavelengths that are usually specific for each molecule. Using wavelength discrimination, one can selectively measure one gas in the presence of other gases which also absorb infrared radiation. The so-called non-dispersive infrared spectrometer, virtually the only type used in process applications, achieves its wavelength specificity by using gas-filled cells for filtering. In practice, this means that a separate instrument is needed for each gas that is to be monitored. Nevertheless, for the gases for which it is applicable, the non-dispersive infrared spectrometer is a rather rugged and reliable instrument.

#### d. Other Measurement Techniques

For the measurement of the oxygen content of process streams, a number of devices have been specifically designed for industrial applications. One is based on the fact that oxygen is a paramagnetic molecule. Another is based on electrochemical measurements of a solution in which the oxygen component of the process stream dissolves and reacts.

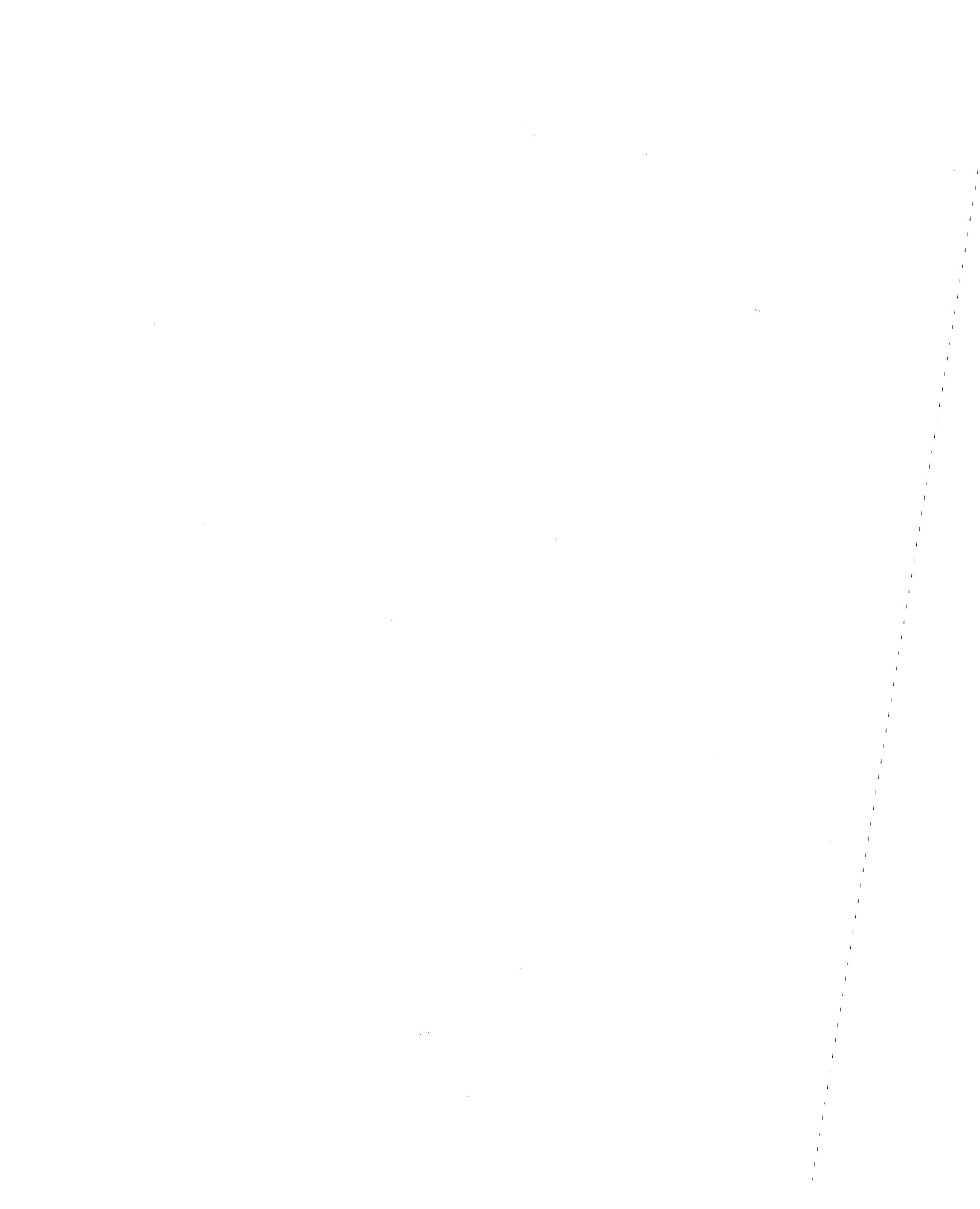
Because the thermal conductivity of hydrogen is markedly higher than that of the other gases of interest to us, the simple, direct measurement of the thermal conductivity of the process stream should correlate well with the amount of hydrogen present and should be affected only slightly by variations in the concentration of the other constituents.

A number of meters designed to measure the dew point of process streams should be able to measure the water content of this product gas stream. One of the devices involves measuring the heat liberated when the water vapor in the stream is adsorbed onto a highly activated desiccant. Another controls the temperature of a mirror so that it is always at the dew point of the process stream. Photoelectric sensing is used to detect the appearance of a cloud of moisture on the mirror when the mirror temperature drops below the dew point of the stream.

Commercially available detectors for determining the presence of explosive atmospheres would be usable for measuring hydrocarbons in concentrations greater than about 0.1%. Such explosive gas detectors measure the heat released when the hydrocarbons in the gas stream are oxidized on a catalytic surface. Since the oxidation requires an excess of oxygen, if the oxygen content is low the use of detectors of this type might require the introduction of some air into the stream to be measured. Special precautions would be necessary to avoid erratic response due to poisoning of the catalytic surface if appreciable amounts of sulfur-containing compounds are present in the product stream.

**APPENDIX D**

**CHARACTERISTICS OF THE COAL  
DEPOSITS IN THE UNITED STATES**



## APPENDIX D

### CHARACTERISTICS OF THE COAL DEPOSITS IN THE UNITED STATES

The characteristics of the coal resources in the United States are well known, reserves are large; all types of coal occur in a wide variety of seam thicknesses, dips, and formations. Coal deposits occur in 35 states, with the majority of U.S. production coming from 23 states. The locations of the coal fields of the United States are shown on Figure D-1. The latest reserve estimates are shown in Table D-1, and brief comments about the coal deposits in each of the major states follow.

#### 1. ALABAMA

Four major coal fields, covering 8000 square miles — Coosa, Cahaba, Plateau and Warrior Fields. Present production mostly from Warrior Field.

**Coosa Field:** Coal medium to high volatile bituminous ash content 4-14%, 13,000-14,500 Btu/lb, sulfur 0.8-4.1%. Four beds 14 inches-12 feet thick. Some steep dips.

**Cahaba Field:** Coal formations horizontal to steep inclines, irregular thickness, and folded and faulted. Most coal high volatile bituminous 3-12% ash, sulfur 0.4-2.1%, 13,200-14,150 Btu/lb. More than 16 coal beds, 3-11 feet thick.

**Plateau Field:** Eight coal beds, average thickness about 27 inches. Medium volatile bituminous, 8-11% ash, sulfur 0.7-3.9%, 12,900-15,000 Btu/lb.

**Warrior Field:** Seven productive coal beds, 1-7 feet thick. Medium to high volatile bituminous ash 2.5-15.9%, 12,300-14,300 Btu/lb, sulfur 0.7-3.1%. Gentle basin structure with horizontal to slightly dipping beds.

Also lignite belt 200 miles long and 30 miles wide. Outcrops up to 12 feet thick; 14% ash and 30% moisture.

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TABLE D-1

COAL RESERVES OF THE UNITED STATES - BY STATES  
(Millions of Tons)

	Overburden 0-3,000 Ft. Thick					Est. Addl. Resources In Unmapped and Unexplored Areas <sup>1</sup>	Est. Total Remaining Resources in the Ground, 0-3,000 ft. Overburden	Est. Resources in Deeper Structural Basins 3,000-6,000 ft. Overburden <sup>3</sup>	Est. Total Remaining Resources in the Ground, 0-6,000 ft. Overburden
	Resources Determined by Mapping and Exploration <sup>2</sup>								
	Bituminous Coal	Sub-Bituminous Coal	Lignite	Anthracite and Semi-Anthracite	Total				
Alabama	13,518	0	20	0	13,538	20,000	33,538	6,000	39,538
Alaska	18,415	110,674	4/	5/	130,089	130,000	260,089	5,000	265,089
Arkansas	1,640	0	350	430	2,420	4,000	6,420	0	6,420
Colorado	62,189	18,248	0	78	80,715	148,000	228,715	148,000	371,715
Georgia	18	0	0	0	18	60	78	0	78
Illinois	139,756	0	0	0	139,756	100,000	239,756	0	239,756
Indiana	34,779	0	0	0	34,779	22,000	56,779	0	56,779
Iowa	6,519	0	0	0	6,519	14,000	20,519	0	20,519
Kansas	18,686	0	6/	0	18,686	4,000	22,686	0	22,686
Kentucky	65,952	0	0	0	65,952	52,000	117,952	0	117,952
Maryland	1,172	0	0	0	1,172	400	1,572	0	1,572
Michigan	205	0	0	0	205	500	705	0	705
Missouri	23,359	0	0	0	23,359	0	23,359	0	23,359
Montana	2,299	131,877	87,525	0	221,701	157,000	378,701	0	378,701
New Mexico	10,760	50,715	0	4	61,478	27,000	88,478	21,000	109,478
North Carolina	110	0	0	0	110	20	130	5	135
North Dakota	0	0	350,680	0	350,680	180,000	530,680	0	530,680
Ohio	41,864	0	0	0	41,864	2,000	43,864	0	43,864
Oklahoma	3,299	0	6/	0	3,299	20,000	23,299	10,000	33,299
Oregon	48	284	0	0	332	100	432	0	432
Pennsylvania	57,533	0	0	12,117	69,650	10,000	79,650	0	79,650
South Dakota	0	0	2,031	0	2,031	1,000	3,031	0	3,031
Tennessee	2,652	0	0	0	2,652	2,000	4,652	0	4,652
Texas	6,048	0	6,878	0	12,926	14,000	26,926	0	26,926
Utah	32,100	150	0	0	32,250	48,000	80,250	35,000	115,250
Virginia	9,710	0	0	335	10,045	3,000	13,045	100	13,145
Washington	1,867	4,194	117	5	6,183	30,000	36,183	15,000	51,183
West Virginia	102,034	0	0	0	102,034	0	102,034	0	102,034
Wyoming	12,699	108,011	4/	0	120,710	325,000	445,710	100,000	545,710
Other States	7/ 618	8/4,057	9/ 46	0	4,721	1,000	5,721	0	5,721
<b>Total</b>	<b>671,049</b>	<b>428,210</b>	<b>447,647</b>	<b>12,969</b>	<b>1,559,875</b>	<b>1,313,080</b>	<b>2,872,955</b>	<b>337,105</b>	<b>3,210,060</b>

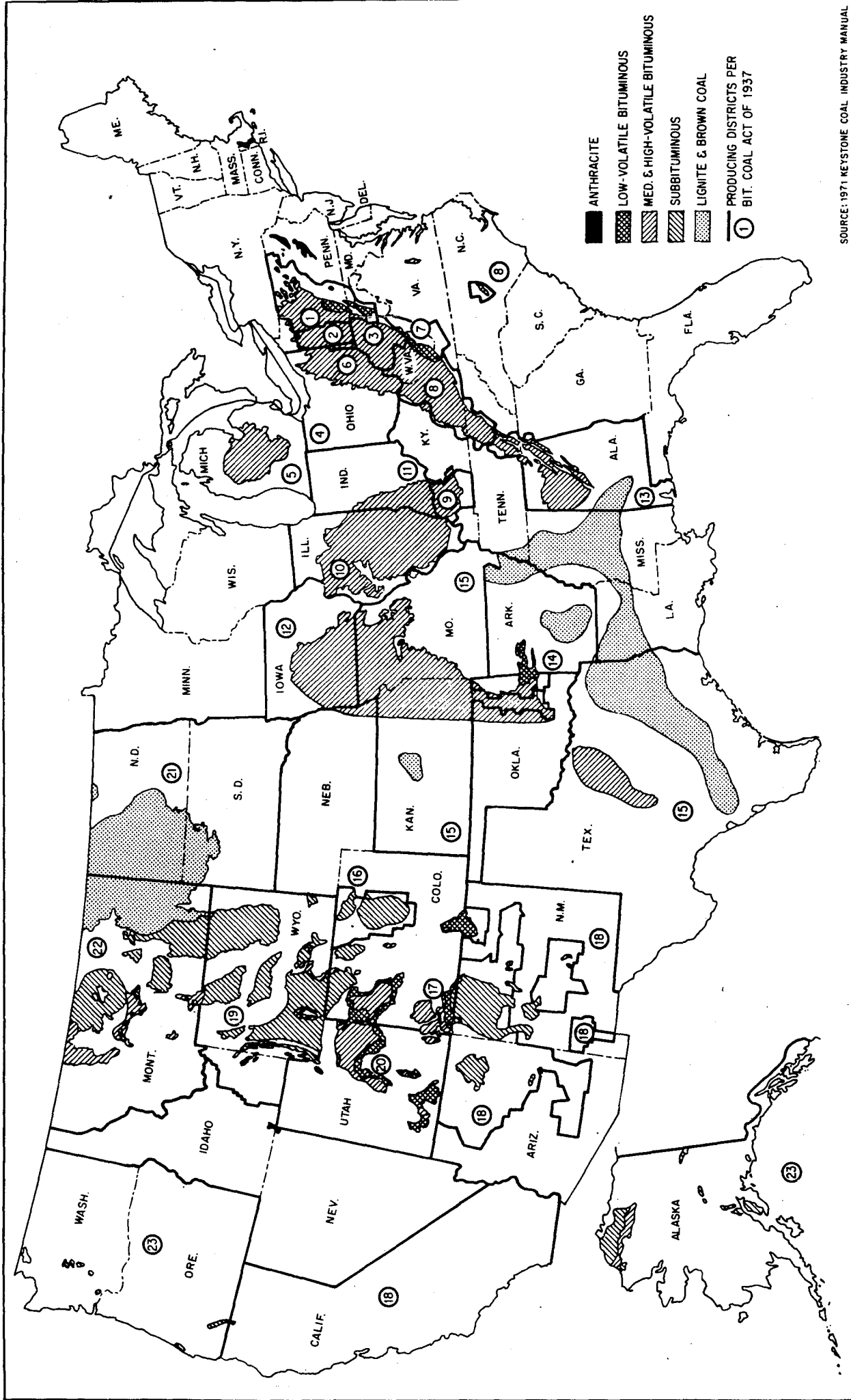
- Figures are for remaining resources in the ground, as of Jan. 1, 1967, about half of which may be considered recoverable. Includes beds of bituminous coal and anthracite 14 in. or more thick and beds of subbituminous coal and lignite 2½ ft. or more thick. (Study by Paul Averitt, U.S. Geological Survey)
- Estimates from published reports of the U.S. Geological Survey and individual State Surveys reduced by production and losses in mining from date of estimate to Jan. 1, 1967. Losses assumed to be equal to production.
- Estimates by H. M. Beikman (Washington), H. L. Berryhill, Jr., (Virginia and Wyoming), R. A. Brant (Ohio and North Dakota), W. C. Culbertson (Alabama), K. J. Englund (Kentucky), B. R. Haley (Arkansas), E. R. Landis (Colorado and Iowa), E. T. Luther (Tennessee), R. S. Mason (Oregon), F. C. Peterson (Kaiparowits Plateau, Utah), J. A. Simon (Illinois), J. V. A. Trumbull (Oklahoma), C. E.

Wier (Indiana), and Paul Averitt for the remaining states.

- Small resources of lignite included under subbituminous coal.
- Small resources of anthracite in the Boring River field believed to be too badly crushed and faulted to be economically recoverable.
- Small resources of lignite in beds generally less than 30 in. thick.
- Arizona, California, Idaho, Nebraska, and Nevada. Bituminous coal in Black Mesa field, Arizona included under subbituminous coal.
- Arizona, California, Idaho.
- California, Idaho, Louisiana, Mississippi and Nevada.

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SOURCE: 1971 KEYSTONE COAL INDUSTRY MANUAL

COAL FIELDS THE UNITED STATES  
Figure D-1

A



## 2. ALASKA

Four major coal fields:

**Arctic Slope Region:** Low volatile coking coal to sub-bituminous and lignite.

**Cook Inlet:** Sub-bituminous coal up to 40 feet thick, dipping 10-15°.

**Nenana:** Sub-bituminous, producing field.

**Mantanska:** High volatile bituminous, 21 beds, 18-22 feet thick.

## 3. ARIZONA

One principal coal field, at Mesa Verde. High volatile bituminous. A number of seams, some up to 9 feet thick. Much of this can be open pit mined.

## 4. ARKANSAS

Three coal seams extending from the Oklahoma Field. Seams up to 8-1/2 feet thick of low volatile bituminous and ranging into semi-anthracite. 3.8-10.2% ash, 12,000-14,600 Btu/lb, sulfur 0.6-3.2%.

## 5. COLORADO

Seven principal coal fields, covering over 20,000 square miles. Large reserves of bituminous and semi-bituminous coals and some anthracite.

**Green River Region:** Most coal is high volatile bituminous coming from seams ranging from 4-1/2 to 23 feet thick. Ash, 3.7-12.6%, 9,590-12,360 Btu/lb, sulfur 0.4-2.5%.

**Uinta Region:** This region actually comprises eight different coal fields ranging from sub-bituminous to anthracite. Seams range from flat lying to completely tilted, folded and faulted. Seams 4-1/2 to 22 feet thick. Some good coking coals.

**San Juan River Region:** Mined seams 5-9 feet thick. High volatile bituminous rank.

**Dakota Sandstone:** Most coals here are thin, discontinuous and of poor quality, but thicker high volatile bituminous coals are available in the Nucla-Naturita area. They have about 11.9% ash, 12,000 Btu/lb, sulfur 0.9%.

**Raton Mesa Region:** Seams of high volatile bituminous 2½-9 feet thick. In Trinidad Field. Some coking coal.

**Denver Region:** Mostly coals of sub-bituminous rank. Mined at depths of 250-450 feet. Seams mined range from 7-10½ feet thick. Ash 4.4-10.1%, Btu 9,060-10,660, sulfur 0.3-0.9%.

**Canyon City Field:** Seams of high volatile bituminous 3.5-8 feet thick.

## 6. ILLINOIS

About 37,000 square miles of Illinois is underlain by coal bearing formations. Mostly all high volatile bituminous coals. Calorific value 11,000 to 14,000 Btu/lb, ash 6-14%, sulfur 0.5-6%, moisture content 6-18%. Some coking coal in southern area. Coals usually overlain by slate or limestone, commonly two feet of slate then thicker limestone. Ten principal seams 18 inches to 25 feet thick. No. 6 seam uniformly 6-7 feet thick and in southern Illinois lies at depths of 650 to 1200 feet. Gently dipping.

## 7. INDIANA

Coals are an extension of the large field in Illinois. The beds and coal seams here dip to the west and southwest at about 25 feet per mile. Nine major coal beds occur 2.5 to 8 feet thick. Generally high volatile bituminous with 6.3 to 12.2% ash, 10,900 to 11,600 Btu/lb, and 1.2 to 3.3% sulfur. Roof rock generally shale.

## 8. IOWA

Coal beds cover 1,300,000 acres in 37 counties of Iowa. Of possible interest are three groups of coal beds.

**Wabanssee Group:** One principal bed 14-18 inches thick in southwest.

**Marniaton Group:** One principal bed about 2-1/2 feet thick.

**Cherokee Group:** Eleven coal beds of some interest. Often lenticular with individual lenses 5 feet thick. Other beds 32 to 66 inches thick. Mostly utility coal.

## 9. KANSAS

Bituminous coal bearing rocks cover 18,500 square miles in eastern part of the state. There are at least 32 coal beds in Kansas and 12 are of some importance. All coal is high volatile bituminous and averages 10,500-13,300 Btu/lb. Seams are 12-60 inches thick. In Northeastern Kansas coal seam depths range from 660 to 1200 feet. North Central Kansas also has a lignite area in a bed 12 to 36 inches thick.

## 10. KENTUCKY

Kentucky has two distinctly separate coal mining regions, the Western and Eastern Regions. The Eastern Region is part of the Appalachian Region plus Pennsylvania, Ohio, Maryland, Virginia, West Virginia, Tennessee, and Alabama. The Western Region is part of the Eastern Interior Basin plus Illinois and Indiana.

Eastern Kentucky coals are generally high volatile bituminous, good for coking coals with less than 10% ash and 3% sulfur. Eastern Kentucky has about 12 major coal seams 22-99 inches thick. The average thickness mined is probably 36-44 inches. Btu values range from 12,500 to 14,000.

Western Kentucky coals are also high volatile bituminous but generally are higher in ash and sulfur content than the Eastern Region coals. Seven major beds varying from 3 to 8 feet thick are known in this region.

## 11. MARYLAND

Coal fields in Maryland cover 455 square miles in the Northwest corner of the state. There are five major fields, with 8 major seams, ranging from 3 to 14 inches thick and bituminous in rank. Ash content is 5.3-15.5%, sulfur 0.6-4.2%, and Btu value ranges from 12,500 to 14,500.

## 12. MISSOURI

Coal beds underlie 23,000 square miles. The beds dip generally in a north-west direction. Much of the coal in the area is generally thin. Mining has been confined to near the outcropping areas.

The state has been divided into 5 coal districts and some 9 major coal beds have been identified. The mined beds are 22 to 57 inches thick. The coals contain 6-16% ash, 2.2-6.9% sulfur, and heating values of 10,500-13,000 Btu/lb.

### 13. MONTANA

Montana has large reserves of sub-bituminous and lignite coals, ranging in thickness from 4 to 80 feet, with 3.9-9.6% ash, 0.5-12% sulfur, and 5600-9500 Btu/lb heating values. Strip mining is carried out in the eastern part of the state but west of Fort Union most of the coals will require underground mining.

### 14. NEW MEXICO

New Mexico has both bituminous and sub-bituminous coals in beds 2 to 20 feet thick. Coals have 3.0-12.5% ash, 0.4-1.6% sulfur, and 9500-13,500 Btu values. In the principal field (San Juan Basin) the coal crops out as a narrow belt around the margin and dips under thick cover toward the center. In the other field (Raton) the coal beds are horizontal or gently dipping westward, and are from 3 to 13 feet thick.

### 15. NORTH DAKOTA

The western part of the state contains about 2/3 of the total United States lignite reserve. It covers about 28,000 square miles. Over 100 beds have been identified, ranging from 4 to 24 feet in thickness. The lignite beds are practically horizontal and are covered generally with an impervious clay layer not very thick in many areas.

Average analyses show 5.6% ash and 0.3% sulfur, 700 Btu/lb, 36.2% moisture and 31.2% fixed carbon.

### 16. OHIO

Coal beds occur under 12,340 square miles of eastern Ohio. Some 54 coal beds are known but only 24 are thick enough to consider as containing potential reserves. These range from 28 to 60 inches in thickness.

The coals are high volatile bituminous fuel coals with 6-9% ash, 1.5-3.7% sulfur, and 12,000-13,000 Btu/lb heating value.

### 17. OKLAHOMA

Some 20,000 square miles of Oklahoma are underlain by coal bearing formations. Most coals are bituminous in rank. There are at least seven important seams, ranging in thickness from 24-72 inches. In one area (Lightning Creek) a 12-15 inch coal seam is strip mined by removing the limestone above it.

A typical analysis shows: 8% ash, 0.9% sulfur, and 13,500 Btu/lb.

## 18. PENNSYLVANIA

Coal beds underlie 33% of the state and are part of the Appalachian coal basin. Some 52 coal seams are known and named in eight fields.

Coals range in rank from high volatile bituminous to anthracite (in the east). Heating values range from 14,700 to 15,800 Btu/lb. Moisture contents range from 0.5-12%, sulfur from 1-3%, and ash from 4-15%. Most of these coals of bituminous rank coke to some degree.

In the main Western bituminous areas the beds dip generally less than 2° and rarely more than 8°. In general, folding and faulting are not serious. In isolated field (Broadtop) dips frequently up to 30° are encountered. These bituminous seams are 16-72 inches thick.

Anthracite in eastern Pennsylvania consists of four fields where much folding and faulting has occurred and dips of 60° are not uncommon. The anthracite seams vary from 3-1/2 to 21 feet in thickness and commonly contain partings of several feet.

## 19. TENNESSEE

Tennessee coals are a part of the Appalachian region and underlie some 5000 square miles in a belt passing through the central part of the state.

The coals are bituminous in rank and have been divided into 9 major districts. Some 11 seams are of importance and these vary from 15 to 72 inches in thickness. Roof rocks are generally shales, sandstones, and slates.

These coals have 2-14% ash, 0.4-4.8% sulfur, and 12,000-14,300 Btu/lb heating value. In some areas the Sewaull seam produces a coking grade coal.

## 20. TEXAS

Texas contains lignite, bituminous and sub-bituminous coals over an area of 75,000 square miles. All current production is from lignites having about 12% ash, 1.0% sulfur, and a 7800 Btu/lb heating value.

## 21. UTAH

Utah coal fields cover an area of 15,000 square miles, divided into 11 principal fields. The coals are of bituminous rank and in one area (Salima and Huntington Canyon) they contain up to 15% resin. Much of the coal is of coking quality. Typical analyses show 5.4 to 6.3% ash, 0.5 to 1.2% sulfur, and 10,700 to 13,200 Btu/lb heating value.

Eight major coal seams are known, ranging from 4 to 30 feet thick. A variety of dips and conditions occur in the seams. For example, the Sunnyside seams are only slightly dipping and the roof consists of shales or sandstones; the Castle Gate seams dip 12% to the North and have good roof and floor conditions, and the Hiawatha seam is 8-15 feet thick, slightly dipping and is overlain by a massive sandstone 40-150 feet thick.

## 22. VIRGINIA

Virginia coal fields are widely scattered and are commonly grouped in three major divisions. In Southwest Virginia high and low volatile bituminous coals occur which are part of the Appalachian Region. The other areas are known as the Valley Fields and the Richmond Basin.

Some 27 seams have been described with thicknesses varying from 1.3 to 8 feet. The coals have 0.7 to 3.7% sulfur, 3 to 10% ash, and 13,000 to 15,000 Btu/lb heating values. Most of the beds are gently dipping.

## 23. WASHINGTON

Most of the coal reserves in Washington occur in a discontinuous belt along the Western edge of the Cascade Range. Formations in all areas have been folded and faulted and often dips of 90° are encountered in the coal seams. Most of the coals are high volatile bituminous with about 10% ash, 0.7% sulfur, and 14,000 Btu/lb heating value.

In the Roslyn Field of Kittitas County beds dip up to 40° and have thicknesses of 15 to 19 feet. In the Centralia area there is a seam 15 to 50 feet thick with a 15° dip. This seam has the composition indicated above.

## 24. WEST VIRGINIA

West Virginia is situated in the central part of the Appalachian Region and coal occurs in 53 of the counties of the state.

Some 62 coal seams out of 117 seams known contain minable coal reserves. Most of this coal is high volatile bituminous and the seams are 2 to 20 feet thick. Typical analyses show 0.6 to 4.8% sulfur, 7 to 17% ash and 12,500 to 15,000 Btu/lb heating value. Bed dips are commonly horizontal or slightly dipping.

## 25. WYOMING

Wyoming contains vast coal deposits in an area of 40,000 square miles. Coals rank from lignite to high volatile bituminous. There are over 40 coal fields in Wyoming with 8 of major interest and importance. In the Powder River Basin the Roland bed has a maximum thickness of 106 feet and in many of the fields beds range from 7 to 118 feet thick. Also in the Powder River Basin near Lake De Smet strippable coal beds over 200 feet thick are being developed. In general roof rocks are shales but some sandstones are also known.

Typical analyses of these coals range from 1-9% ash, 0.3-1.4% sulfur, and 7400-13,400 Btu/lb heating value.

The Wyoming coals occur in broad synclinal basins and around the edges of these basins the coal bearing strata may dip steeply as the result of later uplift of the surrounding mountains but in the central basins the seams are virtually flat-lying.

