Underground Coal Gasification

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Underground coal gasification (UCG) is a method whereby the mining and conversion of coal are accomplished in a single step. Many field tests of UCG have been operated worldwide since the 1930's with varying degrees of success; based on this experience (especially in the USSR and United States), a field design which is applicable to a wide range of geological conditions and coal properties has evolved. This review discusses the rationale of this design and provides a physicochemical interpretation for the operation of a UCG system. Pertinent field and laboratory results as well as formal mathematical models of an in situ gasifier are evaluated as part of the analysis.

SCOPE

There are presently many coal reserves in the world which are not economically recoverable using conventional mining techniques. Underground (in situ) coal gasification offers a potentially economic means of extracting the energy content from such coals while, at the same time, eliminating many of the health, safety, and environmental problems of deep mining of coal. A significant amount of field testing of underground coal gasification, especially in the USSR, has occurred in the past 50 yr, and the low Btu gas process is currently in commercial use at several sites in the USSR. UCG is presently of great interest in North America, where seven field tests are in operation. Recent cost estimates for producing low, medium, and high Btu gas by UCG show that it is more economically attractive than conventional mining followed by first generation surface gasification for thick western coal seams between 200 and 2 000 ft deep.

The development and utilization of UCG in this country has, however, been hindered by a number of unsuccessful field tests, incomplete knowledge about Russian UCG technology, and a general lack of understanding about field design principles and the physicochemical processes involved. However, recent translations of the Russian technical literature have provided a significant body of information about Russian operating experience for a wide variety of geological conditions and coal properties. In addition, the U.S. Department of Energy has operated extremely successful field tests on Wyoming coal in the last 4 yr. Hence, a nominal field design can be performed using existing technology. Commercialization of UCG in the United States and Canada awaits economic optimization of the process design as well as a clearer picture of the role and economics of alternative energy sources, especially coal, as substitutes for oil and gas.

The objective of this review is to present the basic field design for UCG and the logic behind it and to provide an interpretation of the chemistry and physics of UCG. Ultimately, such an analysis is the basis for evaluating the technical and economic feasibility of a candidate site for underground coal gasification.

CONCLUSIONS AND SIGNIFICANCE

The design of an underground coal gasification (UCG) system is a formidable one in view of the performance requirements, since there are very few adjustable parameters in comparison to a surface gasification plant. The system must be designed so that it operates in a predictable and controllable manner, yet it must be insensitive to variations in geological conditions and coal properties. The field design methodology, which evolved in the USSR and is currently in use in the United States, is presented in this review. Important considerations in this methodology include gas leakage, fluid dynamics and control, coal surface area and permeability, phenol contamination of the subsurface, control of product gas rate and composition, seam thickness limitations, sensitivity to coal swelling and flame front channeling, and predictability and reproducibility of operation. A number of different field designs, some involving underground labor, have been tested over the past 50 yr. These are briefly reviewed, but only the most successful methods, namely, the stream method (for steeply dipping seams) and the percolation or linked vertical well method (for horizontal seams), are described in detail. The essential design features for both types of seam conditions are shown to be the same.

Possibly the most critical step in a successful UCG operation is the enhancement of the permeability of the coal seam prior to gasification. This step, called linking, is desirable both technically and economically, since it allows the use of high flow rates at low pressure drops during gasification. The rationale of various linking procedures and their effect on gasification operating conditions and control of the process are described. Four linking methods (drilling, hydraulic fracturing, electrolinking, and countercurrent cumbustion) are discussed in detail. For shrinking or mildly swelling coals, countercurrent (reverse) combustion is the technique of most interest.

An understanding of the chemistry and physics of UCG is imperative for the successful implementation of a UCG system. Pyrolysis, char combustion, and gasification occur in different zones in the process; the effects of chemical reaction kinetics and thermodynamics on the product gas quality are discussed. Design and operating conditions

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for maximizing the gas quality are presented. Also of importance in UCG are the plastic properties of coal, since controlled flow through the coal seam is a prerequisite to successful operation.

The physicochemical interpretation of UCG presented in this review has been verified by field tests in both the USSR and the United States. It is clear from the test data that seam thickness and water intrusion are very important in the operation of the UCG system. Although there is a significant data base for the use of the linked vertical well method in the USSR, seven linked vertical well field tests, both in the private and public sector, are presently underway in North America, with two other tests in planning stages. These tests are designed to gain more information about performance of UCG for American coals and seam conditions, as well as to evaluate the economic and environmental viability of UCG for western countries. Contributions of these tests to the existing basis of technology for UCG are evaluated in this review.

The modeling of field and laboratory results has been of great interest recently, especially modeling of product gas composition and sweep efficiency, subject to the many process variables involved. The concept of an in situ reactor is introduced, and several recent models postulated for this system are analyzed. A comparison of fixed-bed and channel gasifiers with regard to gas composition and channel growth are discussed; both of these entities are controlled by heat transfer phenomena involved in the energy balance.

The near term commercial application of UCG in the United States will be limited to western coal seams at least 5 ft thick. The most attractive locations are in Texas and Wyoming; the use of the existing technology on eastern coals is difficult because of the swelling nature of these coals. However, because the available UCG technology is based on the production of low Btu gas and mine-mouth utilization (probably electric power generation), there is tremendous incentive for developing a viable UCG design for Eastern coals. There is limited information on use of in situ gasification with enriched air or oxygen for synthetic gas production, but research and development are underway on this prospect.

BACKGROUND

Underground coal gasification (UCG) has as its objective the recovery of the energetic and chemical content of coal without using conventional mining techniques. The process requires injecting a gaseous mixture containing varying amounts of nitrogen, oxygen, steam, and carbon dioxide into a coal seam properly prepared for gasification. The coal is ignited, and the injected gases sustain a reaction zone that moves along the seam where the coal is pyrolyzed and partially combusted (gasified). The primary product gases, comprised of carbon monoxide, carbon dioxide, hydrogen, methane, and other higher molecular weight hydrocarbons, are obtained in a readily usable form for the production of electric power or the manufacture of chemicals.

UCG is a process which should be considered as an economic competitor with shaft mining but probably not with surface (strip) mining. The successful application of this method would provide a low or medium Btu gas which is relatively easy to clean (for sulfur compounds) and at the same time eliminate many of the health, safety, and environmental problems associated with conventional deep mining of coal. UCG also has the potential to recover efficiently the energy from deep, thick coal deposits as well as steeply dipping seams, which are not economical to mine using conventional schemes.

HISTORICAL DEVELOPMENT OF UNDERGROUND COAL GASIFICATION

The evolution of field technology for UCG is active today, and an analysis of the historical evolution of various field designs is helpful to understanding the critical features of the process. The idea of underground coal gasification is not new, dating back to over one century ago. Sir William Siemens of Great Britain first suggested the idea in 1868, and the Russian scientist Mendeleev is also credited with early propositions (1888) regarding underground gasification. The Russian interest in this utilization method can be traced to the ideology of Lenin, since it was a way to liberate the workers from the drudgery of coal mining. Lenin also pointed out that this approach would not be attractive to the capitalist mine bosses in Europe and America, since constant unemployment there always made certain that the manpower required for conventional mining was always available.

Historical reviews of technology development for UCG can be found in several references: the A. D. Little Report (1972), Wang (1969), Capp et al. (1963), and Elder (1963). The first Russian tests in the 1930's were classified as shaft methods since they required underground labor and were, in effect, a compromise between conventional mining and gasification. Three methods of shaft gasification were tried: chamber, borehole producer, and stream (A. D. Little, 1972; Elder, 1963). In the 1940's Russian scientists concluded that shaft gasification methods offered no economic or labor advantages over conventional deep mining. However, in spite of this conclusion, some field experiments involving shaft methods were later operated in the 1950's in Great Britain.

Shaftless methods, on the other hand, require no underground labor and use surface equipment only. For these

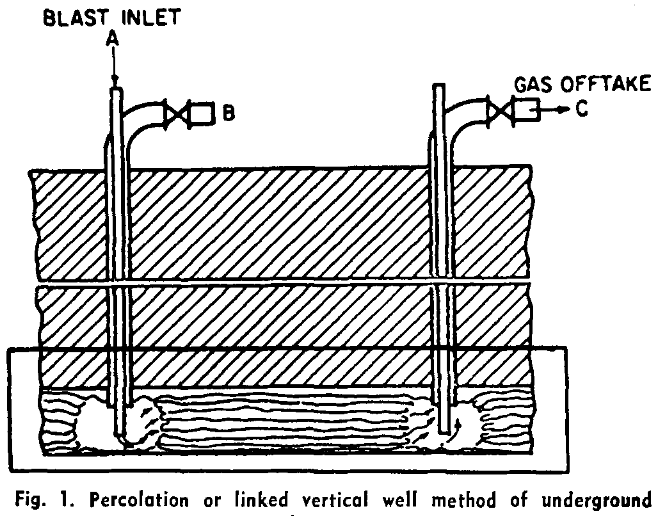


Fig. 1. Percolation or linked vertical well method of underground coal gasification.

methods, the underground preparation of the seam and gasification are performed using drilled holes. Two effective gasification methods were eventually developed, one for horizontal seams and the other for steeply dipping seams. The percolation or linked vertical well method, a schematic of which is shown in Figure 1, was developed in Russia in the 1940's for horizontal seams. The coal seam is penetrated by vertical boreholes spaced 50 ft or more apart, usually in a rectilinear pattern. The coal seam can be ignited electrically, by a propane burner, or by placing a combustible material at the bottom of one well. Gasification takes place between different pairs of boreholes, which communicate initially by the flow of air. Gases produced in the combustion zone travel through the coal seam and are collected at the production well. Before gasification can proceed successfully, however, a path of enhanced permeability (low resistance) must be created in the coal seam between the boreholes for the purpose of operational control. Otherwise, the process would have to operate at high pressure and low flow rates, and gas would not flow directly between injection and production holes. This process is referred to as linking; various methods of linking are discussed later in this review. For steeply dipping seams, the Russians developed a version of the stream method which utilized surface operations only. Seam preparation for the stream method is performed similarly to the percolation method.

The Soviets gained extensive experience in operating the percolation and stream designs for UCG. The amount of effort expended and degree of success achieved by the

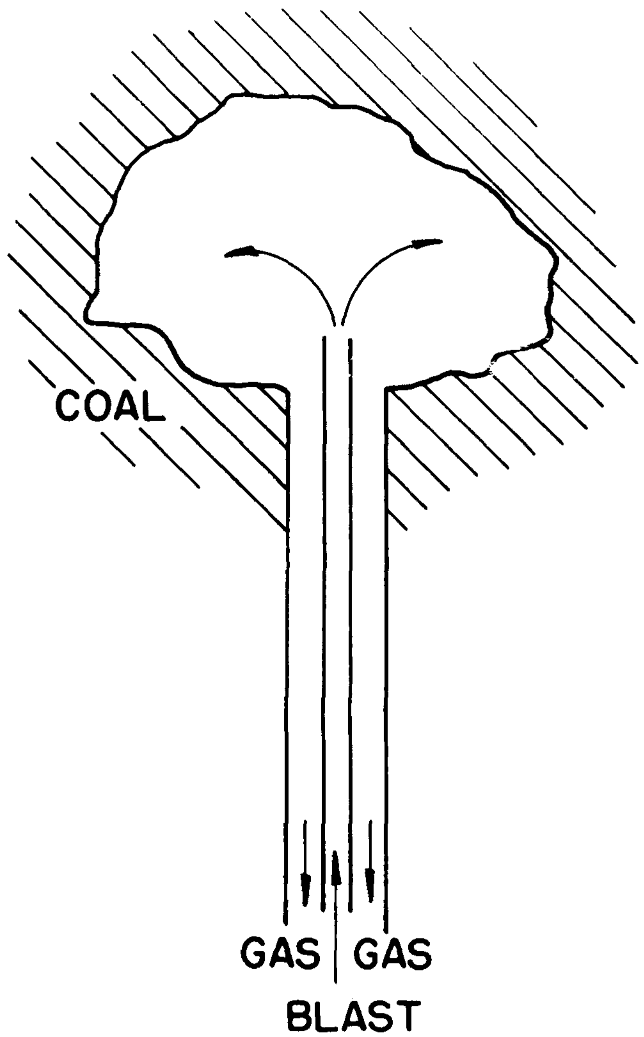


Fig. 2. Blind borehole method of underground coal gasification.

Soviets (having constructed and operated several commercial plants) far exceeds the summation of efforts by other nations. Their efforts peaked in the mid 1960's, and it has been estimated that as many as 3000 people were employed in these efforts in the 1960's. The results of most of the Russian tests are available in the Russian literature; summaries of the recent translations of Russian articles have been given by Gregg et al. (1976) and Dossey (1976).

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

One of the interesting aspects of the evolution of UCG is that information on the Russian efforts was not widely disseminated. Roughly parallel to the Soviet tests, field work was carried out from 1945 to 1965 in the United States, United Kingdom, Poland, Belgium, Czechoslovakia, Japan, Italy, and Morocco (Wang, 1969; Capp et al., 1963; Elder, 1963; A. D. Little, 1972). The most significant efforts (besides in the USSR) occurred in England and the United States. Because these tests were performed without benefit of detailed data on Soviet field tests, they did little to advance the state of the art. In fact, the general lack of success of these tests lent the impression during that period that in situ gasification was not a viable process.

Experimental work in England was begun in 1949, and the field test results have been well documented by Gibb (1964). Several gasification methods were tried, including the borehole producer (a shaft method) and the blind borehole. The coal seam studied was horizontal but only 3 ft thick. In the blind borehole technique, the coal seam served as a batch reactor (Figure 2) with expanding walls. Air or oxygen was injected into a cavity, reacted with the coal, and the product gases were recovered through the outer shelf of a concentric pipe. The average heating value obtained over a 4 mo period was below 675 kcal/m^3. The project experienced many problems, including excessive water leakage into the system and oxygen bypassing and recycling of gases in the cavity, which caused oxidation of carbon monoxide to carbon dioxide and hydrogen to water and excessive gas outlet temperatures. Piping failures were commonplace at these high temperatures. Injection of steam reduced the high temperatures, but this was not considered to be a very productive operating strategy. Similar experiences occurred with the borehole producer method, since this system operated much like a channel gasifier. Coal recoveries as high as 84% were obtained, but the average heating value of the gas still did not exceed 675 kcal/m^3.

The tests in the United States were conducted in Alabama by the Bureau of Mines from 1948 to 1962; test results have been summarized by Elder (1963). The coal gasified was high volatile A bituminous in a horizontal seam. This coal was a swelling coal, which tended to lose permeability as it was heated up. Hydraulic fracturing was required in order to create permeability. Leakage of gases to the surface was quite excessive, owing to the shallow depths, high operating pressure (due to low permeability), and an extensive fracturing program (some fractures penetrated the overburden). Typical heating values with different injected species included air (405 kcal/m^3), 34% oxygen enriched air (450 kcal/m^3), 34% oxygen-43% nitrogen-25% steam (990 kcal/m^3), 65% oxygen-30% steam (1 215 kcal/m^3), and steam only (1 350 kcal/m^3). Various gasification and seam preparation methods were attempted, including electrolinking, hydraulic fracturing, and reverse combustion. Heating values as high as 1 000 kcal/m^3 were obtained, but 30% gas losses were reported.

The tests in Great Britain and America in the 1950's and eary 1960's indicated the potential difficulties which can occur with UCG:

1. Leakage of product gases out of the gasification area through natural fractures and the porous coal seam can contribute to a low recovery of product. Artificial fracturing to improve the permeability of the coal can create additional fissures. Leakage of gases to the atmosphere causes unsafe working conditions.
2. Leakage of water into the gasification area consumes thermal energy and can extinguish the reaction.
3. The heating value of the product gas can be rather low and decrease with respect to time, owing to bypassing of the oxidation zone. Much ungasified coal can remain. The combustion process is difficult to control.
4. Roof collapse can occur in varying degrees over the gasification area. This phenomenon can accelerate gas leakage and can initiate surface subsidence and groundwater inflow.

On the other hand, scientists in the USSR have demonstrated that these difficulties, if not eliminated, can be minimized. As will be explained later, proper design (especially coal seam preparation) is of paramount importance in order to eliminate operating problems. It is evident from a review of field test data that operating problems are concatenated, and field design must be performed as precisely as possible. However, there is a significant body of field information in existence, such that nominal field designs are possible for a variety of coal properties and geological conditions.

During the past decade, a revitalization in the interest in UCG has occurred in North America, as indicated by the operation of seven field tests in 1978. Most of these tests are using the percolation (linked vertical well) method. The lack of success of UCG in the 1950's in Alabama has been a major obstacle to the initiation of new field tests in the United States, but the reasons for the failure of this test and others like it are reasonably well understood, especially with the availability of information on the Russian tests. Current and future field tests should provide data for the technical and economical optimization of the linked vertical well method of gasification.

COVERAGE OF PRESENT REVIEW

This paper will review the design principles of the Soviet technology, the current programs in the United States, and will give a discussion of approaches to modeling UCG systems, including both field and laboratory research, with specific reference to the physicochemical considerations involved in an underground coal gasification system. Thus, detailed discussion of subsidence and environmental aspects of UCG systems is not given here. An attempt is made to limit the discussion to the development and logic of the most successful approaches to UCG. There have been a very large number of UCG experiments worldwide (successful or otherwise) which added little to the Soviet technology. A complete listing and discussion of all these experiments is beyond the scope of this paper but is available in the review articles cited earlier.

We have divided this review into seven sections. The following section summarizes the important features of the field design of a UCG system. Desirable operating conditions (flow, pressure) and the effect of seam preparation on the operating conditions will be discussed. Limitations of the design will be pointed out. Methods of linking (directional drilling, countercurrent combustion, electrocarbonization, hydraulic fracturing) and physical considerations in their usage are presented. We compare the design for horizontal and steeply dipping coal seams with pertinent illustrations. It concludes with a discussion of how the design affects sweep efficiency and product gas composition.

Then, a physicochemical interpretation of underground coal gasification in terms of chemical thermodynamics and kinetics of the important reactions is presented. Much of what is stated in this section is also applicable to conventional moving bed gas producers. Subsections are devoted to the effects of coal pyrolysis and char combustion, and the influence of pressure, temperature, and water influx on product gas heating value is quantified. This section concludes by comparing the preceding theoretical interpretation with field results. Also of importance in UCG are the physical properties of candidate coals, especially the plastic behavior, which have a profound influence on the feasibility of UCG. A swelling coal cannot be gasified in situ using the Russian technology.

Current field testing activities in the United States and Canada are reported in a fifth section. New (second generation) UCG approaches undergoing testing are discussed, and the contributions of ongoing tests using the linked vertical well method are reviewed, especially with regard to the energy balance for UCG. The interpretation of these tests as well as the Russian field data is presented with more mathematical rigor in a sixth section, which deals with mathematical modeling. A number of successful chemical reactor models for UCG have been developed recently. The problems of treating the time varying phenomena (for example, expanding and propagating reaction zone, changing system boundaries) and their effects on product gas composition and recovery (sweep) efficiency are analyzed. The gas quality, thermal efficiency, and sweep efficiency are the keystones of economic potential of the process, and thus mathematical models can be instrumental in optimizing a UCG system. Finally, the enumeration of heat transfer phenomena and their effects on both thermal and sweep efficiency is given.

This review is concluded with a section on the future of UCG in North America; a brief inventory of research needs is also given.

THE FIELD DESIGN OF AN UNDERGROUND COAL GASIFICATION SYSTEM

The Problem

The task of designing a successful underground coal gasification system is a formidable one in view of the performance requirements. One is attempting to carry out a fairly complicated chemical process (gasification) with very few adjustable parameters compared to a surface plant. With a surface plant one has the option of designing the dimensions as well as other operating parameters of the reaction vessel. It is also possible to control the rate and nature of the coal fed to the vessel in terms of its particle size, ash content, and moisture content as well as to blend different types of coal as needed. Heat transfer from the gasifier can be controlled. However, no such adjustable parameters are available in designing an underground coal gasification system. Despite this, performance requirements in terms of the quality of the product are determined by the user and remain essentially the same. It is clear that in order to achieve this goal, a great deal of engineering skill is required.

The underground portion of the system must be designed so that it operates in a predictable and controllable manner in spite of the fact that as the combustion zone moves through the coal seam, seam thickness, ash content, moisture content, natural permeability, overburden nature, etc., can change significantly. If most of the coal is removed, the process is further complicated by roof subsidence. Since there is so little control available after the process starts, the basic system design has to be inherently stable or insensitive to such changes. The tools of design are also limited by the requirement of no underground labor; that is, access to the coal is limited to drilled holes. It is surprising, with all these requirements, that such a system is possible. However, the Soviets have demonstrated the concept with numerous operating plants.

It is the intent of this section to present the basic Soviet UCG designs for horizontal and dipping coal seams as well as the logic for the designs. Such systems must be designed to deal with all the physical and chemical processes affecting their operation in a manner that will optimize their economics. This may require dealing with certain problems in a less than optimum manner so that others are satisfied and the overall system is optimized.

The Soviet System for Underground Coal Gasification

The Soviet underground coal gasification systems for horizontal and steeply dipping beds, which are essentially the same basic design at different angles to the surface, are deceptively simple. However, it has been demonstrated repeatedly that they can be made to operate successfully in an extremely complex environment, a burning coal seam with a subsiding roof. The basic system design can also be transferred from one coal seam to another with reasonably predictable results, in spite of the wide variations in the geological conditions that exist among coal seams.

It is important to understand why the Soviet design works so well. This can be done by identifying the large number of physical phenomena that must be dealt with in any successful design and then explaining how the Soviet design deals with them. Such a listing is presented below. It will be followed by a more detailed description of the system.

Gas Leakage. One design requirement of an underground coal gasification process is the minimization of the loss of both the injected blast and the product gas. Because gas losses increase with the square of the pressure, maintaining a gas tight zone is very difficult. As coal is removed, the roof must eventually subside, especially where a high fraction of the coal is recovered over a large area. Such subsidence forms very permeable cracks to higher formations, sometimes all the way to the surface, allowing gas to escape from the process zone.

The extent of these leakage cracks is unpredictable as the combustion zone moves across a coal seam; therefore, it is important to design the system with a minimum sensitivity to such leaks. The only way to accomplish this is to operate the system at the lowest possible pressure and to ensure that the permeability in the coal between the injection and exhaust holes is always much higher than the permeability through subsidence cracks. The Soviets accomplish this by establishing highly permeable paths in the coal (linking) between the injection and exhaust holes before gasification and operating at the lowest pressure that is consistent with production requirements. They also seal the cracks at the surface by bulldozing them full of mud.

Gas Flow Rate at Low Pressure. A high gas flow rate is necessary to compensate for the water intrusion rate. It is also needed to maximize the eventual channel width and thus the resource recovery for each line of drilled holes as well as for achieving an economically high production rate. This requirement is tightly coupled to the gas leakage problem discussed above because increased flow rates require increased pressure drops. The high gas flow rates can be maintained with minimum leakage only if the permeability between the injection and production holes exceeds some minimum value. The Soviets generally use gas flow rates of 3 000 to 10 000 m^3/h, with driving pressures that do not exceed 2.54×10^5 Pa (2.5 atm.).

An additional advantage of these low operating pressures is the possibility of using high capacity, relatively inexpensive blowers to supply the air, although this is not as important when oxygen/steam is used.

Directional Control of Gas Flow. Directional control of gas flow is essential to a reproducible system. Only by establishing flow control with the consequent reproducibility can we begin to engineer a system that maximizes resource recovery or optimizes the economics (these two criteria may not lead to the same system). This requires a means of control that is insensitive to variations in geology or coal type.

The Soviets achieve directional control by using highly permeable linkage paths with predetermined spacing at the bottom of the coal seams. These paths render the gasification process insensitive to variations in the natural coal permeability. Thus, after the initial scaling data are obtained, it is possible to design the required predictable system. The directional control of the gas flow also ensures that the gas will flow into the exhaust pipe instead of spreading uncontrollably throughout the formation.

Surface Area and Permeability. High permeability is needed for the reasons stated above. The high surface area, consisting of a coal rubble zone without bypass channels, is generally needed for efficient gas-solid reactions. In such reactions, the rate of reaction is limited by the available surface area of the coal because this is where the initial reactions must take place. In the Soviet system for horizontal coal seams, the linkage channels are placed along the bottom of the seam so that the flame front undercuts the coal. The coal then falls into the void and forms rubble. In the system for steeply dipping beds, rubble is formed by coal falling into the void created at a bottom manifold where combustion is initiated.

Liquid Control. One of the primary effects of liquids (water and pyrolysis tars) on the propagation of the flame front in a horizontal seam (without linkage channels) is to cause the flame front to move preferentially along the top of the coal seam. This occurs because liquids are much more dense than the gases and migrate to the bottom of the seam. The gas flow, and thus the flame front, then traverse the top of the seam.

The difficulty that arises is that once a channel is formed across the top of the seam, the coal ash tends to seal the bottom of the channel, preventing further combustion of coal and resulting in very poor resource use. The Soviet process minimizes this effect by forming the channel at the bottom of the seam during the preparatory linking step. The channels are kept hot enough throughout the gasification process so that any liquids intruding into the region, as well as liquids formed by pyrolysis, are carried out as vapors. The channels thus remain clear to gas flow with the additional benefit that the removal of the liquids as vapors permits recovery of the economically valuable coal tars.

Phenol Contamination. The mechanism for total liquid removal described above also removes phenols formed in the pyrolysis of the coal. The phenols are never allowed to condense but are removed almost immediately as vapors. The efficiency of this removal is enhanced by a steam flush. Because the intruding water is vaporized deeper in the coal seam (farther from the hot channel) than where the phenols are formed, the steam flows into the channels through the phenol forming zone. This effectively flushes out these potential aquifer contaminants into the hot channel where they then flow to the surface in the gas stream. Thus, a minimum quantity of phenols remains in the ground after gasification, reducing aquifer contamination.

Access Pipes. A major portion of the cost of the underground coal gasification system is associated with the access pipes. Thus, it is important to maximize the spacing and probability of survival of the piping during the gasification process for greatest resource recovery. In addition, subsequent removal of the casings for reuse might be desired. This importance of maximizing the total resource utilization as well as the quantity of coal obtained per hole dictates the trade off between fractional recovery and hole spacing.

The Soviet designs place the access holes so that they are out of the (moving) subsidence zone until they are no longer needed. This increases the probability of the survival of the pipes and makes it possible to pull the casing for reuse. The exhaust pipes are also cooled with a spray of water at the bottom of each pipe. This prevents the pipes from separating from the cement that seals them to the formation. However, care must be taken in order not to overcool the gases, since the coal tars could condense in the pipes and plug them. The Soviets found the best operating temperature range to be between 100° and 200°C.

It is difficult to prove that the pipe spacing was maximized for the Soviet system. However, certain features are essential for a large pipe spacing. A highly permeable channel between the injection and exhaust holes permits high gas flow rates at low pressure drops. The reproducibility of the system also allows the optimization of the pipe spacing.

Coal Seam Thickness. The Soviets have found no maximum limit in thickness of coal seams for their processes. They have operated in seams up to 20 m thick with no indication that they were approaching a limit. However, the Soviets have found that there is minimum thickness limit of about 1 m. Below that point, the heating value of gas becomes too low (using unenriched air for gasification).

No Men Underground. The present Soviet design requires no men underground during gasification; this was not true of the British design or of earlier Soviet systems. Initially, this desirable requirement was dictated more by Soviet politics than by technology. To support the principles of Marxism as viewed by Lenin, the goal was to take miners out of the coal mines and thus improve their lot. This move was intended to prove that a communistic society was more concerned with the welfare of the worker than were societies based on capitalism. However, from a safety standpoint, this requirement of no men underground is an extremely important technological advance because once gasification is initiated, it is essentially impossible to guarantee that toxic product gases will not leak into adjacent mine workings.

Multilayered Coal Seams. The Soviet system has been used to sequentially gasify multiple layers of coal, beginning with the top seam and working down (Koranda, 1969). This permits a more complete and economical use of available coal reserves.

Continuous vs. Intermediate Load System. The Soviet system sweeps in a continuous manner across a coal seam (as opposed to a batch system), and thus it can be used for electrical base load demands. However, there is also a need for electricity on an intermittent basis to supply peak loads. Under some circumstances, the gasification system can be turned on and off in time periods as short as a few hours. Thus, the system could prove useful for meeting intermittent electricity demands.

Constant Gas Composition. The design of the Soviet system permits the maintenance of a product gas composition that is quite constant in its heating value as a function of time. This is primarily due to the hot gases flowing through a continually forming, high surface area rubble zone of coal. (This subject will be discussed in detail later.)

Reproducibility, Predictability, and Control. The performance of the process design is reproducible and predictable within reasonable limits from one generator to another within the same coal seam, as well as when transferred from one coal bearing area to another. Only minor modifications are needed to adapt this design for operation in widely varying coal types. Adequate controls are available to achieve a constant gas quality and high resource recovery; 75% or more of the coal is commonly consumed with between 50 to 70% of the heating value of the consumed coal recovered as heating value in the product gas (Kreinin and Revva, 1966; Gibb, 1964).

Minimum Sensitivity to Coal Swelling. The large channels formed in the linking phases minimize the probability of plugging by moderately swelling coals.

Minimum Sensitivity to Flame Front Channeling. The Soviet system makes no attempt to avoid the natural tendency of flame front channeling (Gregg, 1974); in fact, it encourages it. However, the gas quality is insensitive to such channeling because the channels through the coal seam are very long, undercutting the coal and becoming filled with coal rubble.

Simplicity of Design and Operation. The Soviet system design and operation are exceptionally simple, deceptively so. The only technology required is the drilling of a simple pattern of holes (although slant drilling is not always easy) and the handling of compressed air. The end result is that the gasification process is insensitive to the many uncontrollable physical phenomena that might otherwise influence the process. Such simplicity and insensitivity make the process technically feasible.

Enhanced Coal Permeability

Although gas can be made to flow in coal beds using only naturally occurring permeability, these permeabilities have never been high enough for a large scale gasification process without initial enhancement. This is due to not only the low initial permeability of a coal bed, but also to the fact that a cocurrent combustion process tends to plug the coal bed with liquids that condense downstream from the combustion zone. There are a limited number of methods that have been successfully employed to enhance the permeability of a coal bed before gasification. It is the nature and limitations of these methods that dictate a major portion of the remaining process design.

The four methods that have been employed with varying degrees of success are directional drilling, countercurrent combustion, electrolinking, and hydrofracking followed by countercurrent combustion (Kreinin and Revva, 1966). The primary feature that characterizes these methods is that they form narrow, highly permeable, approximately cylindrical channels. It is evident how this is achieved by a drilled hole, but it is not so apparent why countercurrent combustion and electrolinking also form these channels. This will be explained in some detail below. However, it is important first to emphasize that these proven successful methods for permeability enhancement in coal beds form narrow linear channels of high permeability. They do not create planes of permeability or increase the permeability of the bulk of the coal seam (volume permeability enhancement). Thus, the total system design must be compatible with and effectively utilize this feature.

Directional Drilling. Drilling vertical holes down to the coal seam involves no novel technology and will not be discussed. The drilling advancement developed by the Soviets for underground coal gasification is the technology of drilling along a coal seam at varying angles to provide a gasification channel in the coal. The techniques used for both steeply dipping and horizontal coal beds are described in considerable detail by DeCrombrugghe (1959) and Arinenkov (1960). After trying a number of approaches, the Soviets presently employ downhole electric motors that allow them to drill directionally curved holes with radii of curvature as small as 600 m. The drill is guided with the aid of a downhole compass and a pendulum. The data from the compass and pendulum are transmitted to the surface over the power lines for the drill motor. For steeply dipping coal beds, the directionally drilled holes are usually straight but at an appropriate angle to the surface so that the drilled holes remain in the coal seam. However, for horizontal beds, the drilling is begun at an angle to the surface and is then curved into the coal seam. Holes with diameters of 0.3 m and as long as 100 m have been drilled in the coal seams by this technique. When fully developed, the penetration rates were expected to reach 3 to 10 m/h (DeCrombrugghe, 1959).

Linking by Countercurrent Combustion. The differences between countercurrent and cocurrent combustion processes are very significant when applied to underground coal gasification. Cocurrent combustion is a process by which the flame front and gas flow propagate in the same direction and the rate at which the coal is consumed determines the flame front velocity. As the coal is consumed, the combustion zone moves downstream toward the higher concentrations of coal.

However, in countercurrent combustion, the flame front moves in the opposite direction to the gas flow. The velocity of the flame front is determined by the rate at which heat is conducted upstream against the gas flow. Coal upstream is heated to its ignition temperature and ignited, thus depriving the remaining downstream coal (char) of oxygen and causing incomplete combustion of the coal reserve. Thus, a cocurrent combustion consumes essentially all the combustible material in its path, while a countercurrent combustion can pass through a combustible material and consume only a portion of it.

The above description addresses only the differences associated with an idealized one-dimensional combustion process. There are other equally large differences between these two modes of combustion involving their spatial propagation in two and three dimensions. The most significant difference is that countercurrent combustions tend to burn narrow, fixed diameter channels, while cocurrent combustions generally propagate on comparatively broad fronts (Skafa, 1960). The reasons for this difference can be visualized with the aid of Figure 3.

Consider the idealized case presented in Figure 3, where a narrow, highly permeable channel of char or ash extends into a coal seam of much lower permeability. If we draw lines of flow from either point A to point C or from C to A, we see that these flow lines converge at the tip of the channel. Thus, in the region from A to B, the majority of the gas flow is carried by the channel. In the area from B to C, the gas flow distributes more uniformly across the bed, independent of the flow direction. If the coal is ignited in the channel in the region of B, and if the flow direction is from C to A (countercurrent combustion), the flame front at the tip of the channel (at B)

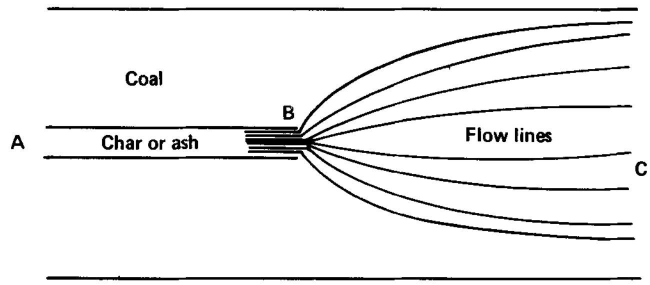


Fig. 3. Channel formation for cocurrent vs. countercurrent burns.

sees a much larger supply of oxygen than will the walls of the channel further toward A. Therefore, as the flame front at the tip progresses toward C, the oxygen starved channel walls do not significantly expand. This countercurrent combustion process creates a channel of a relatively small and constant diameter. In contrast, if the flow direction is from A to C (concurrent combustion), the channel walls will be exposed to the highest concentrations of oxygen, supporting combustion on the walls and thus promoting a widening of the channel.

An additional difference between cocurrent and countercurrent burns has considerable importance to underground coal gasification. Countercurrent burns are not as subject to plugging owing to the presence of a condensing liquid front downstream from the flame front, as are concurrent burns. It is easy to see how a cocurrent burn would be very vulnerable to such plugging. If air contact between two pipes drilled into the coal is established where the air flow is conducted by the naturel permeability of the coal and ignition is initiated at the air injection pipe, the hot gases carrying water vapor and vaporized tars will cool before reaching the exhaust pipe. The cooling of the gases will cause the water and tars to condense and to plug the small cracks upon which the natural permeability of the coal is based.

However, if ignition is initiated at the exhaust pipe and a countercurrent burn is carried out, it is possible to maintain high enough temperatures in the combusted channel throughout the process so that the vapors never condense. If the channel does cool enough to allow some condensation, the condensation will occur in the highly permeable channel that is much more difficult to plug. Similar arguments can be made to illustrate that a countercurrent burn would be expected to be less easily plugged by coal swelling than would a cocurrent burn. However, it is not clear that either will propagate in a swelling coal.

For the reasons presented above, a countercurrent burn is ideally suited for forming highly permeable channels in a coal seam as a preparatory step but cannot be used for gasification in the production phase because of the resulting poor resource utilization. In contrast, a cocurrent burn cannot be used to form the initial gasification channels but can be used in the production phase because it results in high resource utilization. Therefore, both burn methods are used in a gasification process (countercurrent combustion as the linking technique and cocurrent combustion for the production phase).

In practice, the Soviets were able to achieve countercurrent combustion linking rates of 1 to 3 m/d using air (Skafa, 1960). Higher linking velocities could be achieved with oxygen, but the resulting channels were not sufficiently permeable to carry out satisfactorily the following concurrent burn. Apparently, air has an almost optimum oxygen concentration to produce a sufficiently permeable channel at an acceptable channel formation rate.

A very extensive treatment of the Soviet experience in the use of an electric current to establish a highly perme-

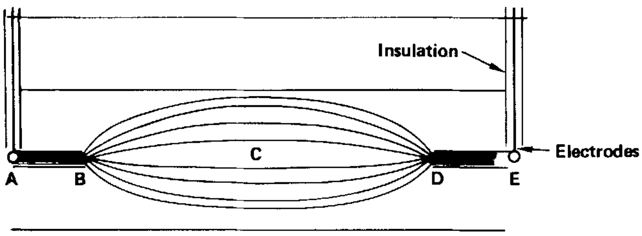


Fig. 4. Electrolinking process.

able channel in coal has been presented by Bondarenko et al. (1959). No attempt will be made here to reproduce or even summarize that work. However, it is useful to explain the electrolinking technique and how, in some circumstances, it can be employed competitively with other linking techniques.

At first glance it appears that it is almost impossible to develop a competitive channel formation technique employing an electric current to char a channel of coal between two access holes. We might expect that the electric power required would far exceed that which would be practical. This would probably be true if the electric current were required to char the entire channel length and width by bringing all coal to charring temperature at the same time.

However, the charring process proceeds in quite a different manner and is in fact, very similar to the mechanism of channel formation for countercurrent combustion (refer to Figure 4). There are certain crucial physical phenomena that must be present for this process to succeed. First, as the coal is heated by the electric current, it must strongly increase in electrical conductivity. Second, the conductivity of the unheated coal must be reasonably high but still much lower than that of the heated coal.

Figure 4 describes the process at some time after the power has been turned on. Highly conducting channels from both electrodes appear and gradually grow toward the center until they meet. This mechanism has been verified experimentally (Bondarenko et al., 1959), and the explanations for the progress of this process are similar to those describing channel formation with a countercurrent burn. The channel sections A-B and D-E are highly conducting. Therefore, the current is concentrated into the channels. However, the current spreads out over a larger cross section in the unheated coal (region C). When this happens, most of the potential drops, and therefore most of the energy dissipation occurs at points B and D, where the highly conducting channels connect with the unheated coal.

Energy dissipation in the channels is minimized by the high conductivity of the channels. Energy dissipation in the unheated coal seam far from the channels (region C) is reduced because the large cross-sectional area that carries the current compensates for relatively low specific conductivity of the unheated coal. The combination of high current density and high resistivity of the unheated coal is found only where the current lines converge on the tips of the highly conducting channels. Thus, as the channel tips heat, the coal chars, which increases its conductivity. Each channel is thus extended further into the coal until the two channels meet.

This mechanism of channel formation requires only that the small regions B and D be heated by the electric current at any one time. This requires far less electric power to overcome heat losses than does a process that heats the entire channel length at once. Thus, because of this point heating effect, electrolinking is a competitive linking technique.

The efficiency of the electrolinking process clearly depends on the specific conductivities of the channels and the unheated coal. Energy dissipated in either of these zones is wasted. Only the energy that heats the tips of the channels is used constructively. Therefore, depending on the conductivities achieved, which in turn depend on the nature of the particular coal seam, electrolinking may or may not be the most efficient means to form the linkage channels. The Soviets report that electrolinking was slightly more energy efficient than other linking techniques at Podmoskovia but was significantly less efficient at Angren (Fedorov, 1957; Lyandres and Reznikov, 1958).

The primary problem encountered with electrolinking is that it is very difficult to control. In an idealized and uniform media, the link proceeds in a predictable manner. However, the direction the linking channel follows is strongly inuflenced by anomalous and unpredictable regions of conductivity that are specific to the local geology. This lack of reliability has forced this technique to be abandoned in many cases even though, had it worked, it would have been the most efficient linking process available (Bondarenko et al., 1959).

When this technique is successfully used, the electrolinked channel is usually widened further with a relatively fast countercurrent combustion step before the production phase is initiated.

Hydrofracking. As has been stated above, the choice of linking technique is critically dependent on the physical or electrical properties of the coal seam. If the electrical conductivities of the coal and char are not correct, electrolinking is not acceptable. If the natural permeability of the coal seam is too low, countercurrent combustion linking is not a good approach initially. Directional drilling is one technique that is relatively independent of the coal properties, but in some situations, it is too sophisticated an approach to the problem. Therefore, in some cases, hydrofracking is employed to establish a linking channel. The effectiveness of hydrofracking is independent of both the electrical properties and the natural permeability of the coal. Hydrofracking also requires considerably less sophisticated equipment than is needed for directional drilling, but its lack of control is a definite disadvantage (Kreinin and Revva, 1966).

Essentially, hydrofracking requires the pumping of water down a pipe into the ground. The water is forced out into the coal formation at the bottom of the pipe and forms cracks. Because cracks tend to close after pumping ceases, sand may be added to the water to prop open the cracks. The effectiveness of the operation is often improved by the addition of a thickening agent to increase the viscosity of the water. This improves the sand carrying capability of the water and helps to confine the underground flow to a few major cracks.

Many studies on the use of hydrofracking for preparation of a coal bed for gasification have been conducted (Skafa, 1960; Kreinin and Revva, 1966; Klimentov, 1964). However, it appears that this technique has been employed primarily for steeply dipping beds where it is not essential to ensure that the cracks form at the bottom of the seam or that they form parallel or perpendicular to the bedding planes.

Field Design for Steeply Dipping Coal Seams

A number of approaches to underground coal gasification were investigated by the Soviets in the early 1930's, such as explosive fracturing to prepare the bed (the chamber method) and excavation or drilling of holes from one drift or gallery to another (the borehole-producer method) (Gregg, 1976). Poor economics and unstable operation forced these methods to be abandoned.

The Stream Method. The first design that showed promise is commonly called the stream method. This method, as applied to steeply dipping beds, is illustrated in Figure 5 (Jolley, 1945; Mataveev, 1957). The injection and exhaust holes were drilled from the surface along the coal seam and were connected at the bottom by a mined shaft. Air was used for the gasification process. The flame was initiated in the connecting channel, and it gradually spread over the entire length. The flow was reversed periodically to approximate a horizontal burn. The key feature of this system is that as the coal is consumed, more coal falls into the gasification void. Thus, the coal automatically becomes a highly permeable rubble and is fed into the combustion zone. The coal rubble thus formed has the additional essential feature of providing a large surface area on which the oxidation reactions take place. As a result, the product gas composition remains relatively stable as a function of time. In all further design improvements for both steeply dipping and horizontal coal beds, this self-forming rubble feature (due to undercutting the coal) was retained.

Modifications of the Stream Method. There are two major problems with the stream method as presented in Figure 5 that have been resolved in later designs (see Figure 6). First, there is a tendency for oxygen (air) to leak through the coal between the two access holes, above the region where combustion takes place. This air either consumes part of the product gas or introduces a hazardous level of oxygen into the product gas. Second, there is tendency for the combustion front to channel over the top of coal, resulting in reduced resource recovery and erratic gas quality. In steeply dipping beds, these problems have been resolved by drilling cased air injection holes to the bottom manifold through the overburden. In this manner, the injection holes are isolated from the exhaust holes. The probability of the flame front channeling over sections of the coal is also minimized by permanently fixing the injection point at the bottom of the seam. If the coal seam is thicker than approximately 8 m, it is necessary to drill the injection holes at a slant, under the seam, so that the pipes will not be sheared off by subsidence. However, when these costly slant holes are used, vertical holes are usually drilled to help establish the initial bottom manifold by hydrofracking or countercurrent combustion. The vertical holes are also used in the first stages of gasification (Kreinin and Revva, 1966; Buyalov, 1938).

A phenomenon commonly observed with the stream method is illustrated in Figure 7. The pressure drop often is observed to occur in the lower regions, near the injection point in the region of the flame front. Two factors contribute to this phenomenon: a gas expansion at the flame front resulting from the increase in temperature and in molar quantity of gases and a channel blockage formed by a subsiding roof, restricting the gas flow. If the second factor is the one of importance, not only could the gas flow be restricted in a one-dimensional sense, but severe two-dimensional flow distortion problems could also result. This two-dimensional redirection over a long distance in the coal seam would eventually cause a loss of control over the direction of the gas flow and would result in poor resource recovery. For these reasons, an additional modification has been introduced (see Figure 8). A number of additional gas injection holes are drilled along the dip, intersecting the seam at prescribed intervals from the bottom manifold up to the surface. This modification minimizes the pressure drop along the coal seam while retaining spatial control over the gas flow.

An alternative layout using a directionally drilled hole to form the bottom manifold is presented in Figure 9.

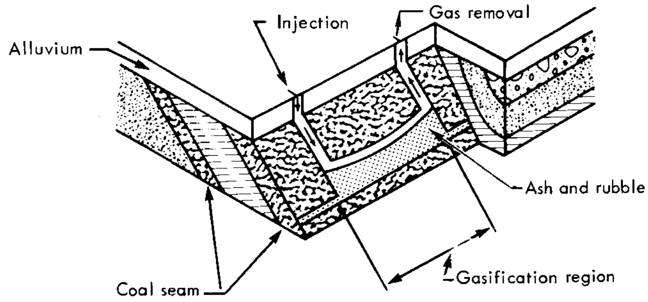


Fig. 5. Stream method for steeply dipping seams.

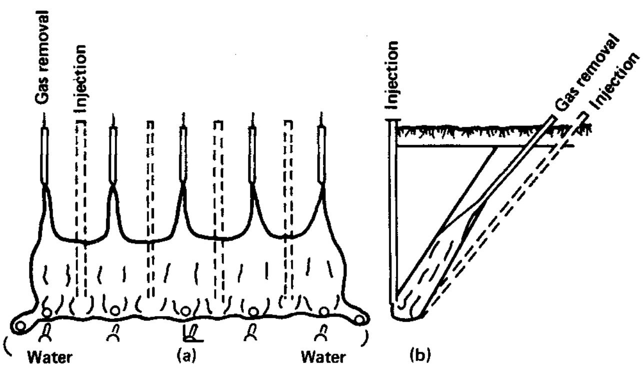


Fig. 6. Typical scheme of an underground gas generator for steeply-dipping coal beds. (a) Plan view (b) End elevation.

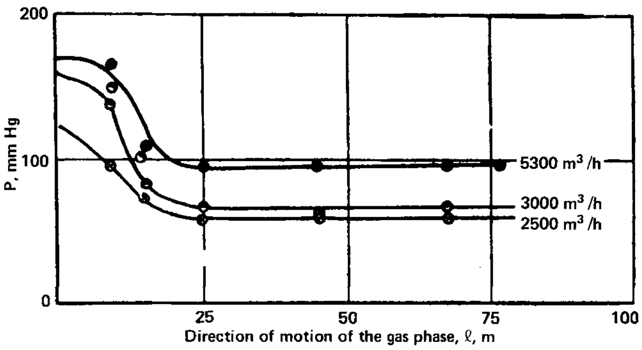


Fig. 7. Change in the pressure (*P*) of the gas phase along the channel length (*l*) of gas generator No. 1 of Yuzhno-Abinskaya station (2500, 3000, and 5300 m^3/h is the channel power expressed as the blast-injection rate).

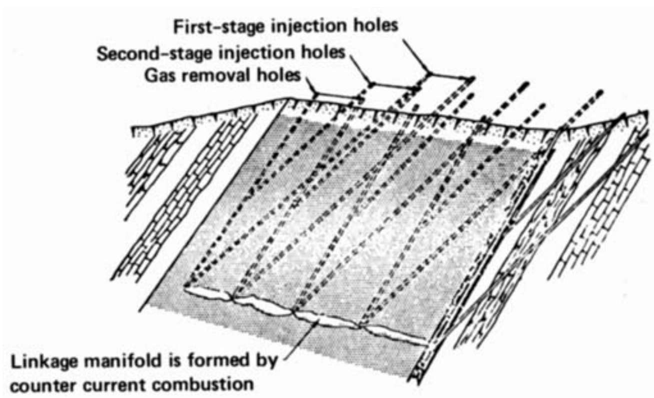


Fig. 8. Preparation of steeply sloping seam at Yuzhno Abinsk.

Field Design for Horizontal Coal Seams

The basic design of the Soviet system for gasifying horizontal coal seams is essentially independent of the linking technique used. Therefore, we will explain the system design in terms of countercurrent combustion and

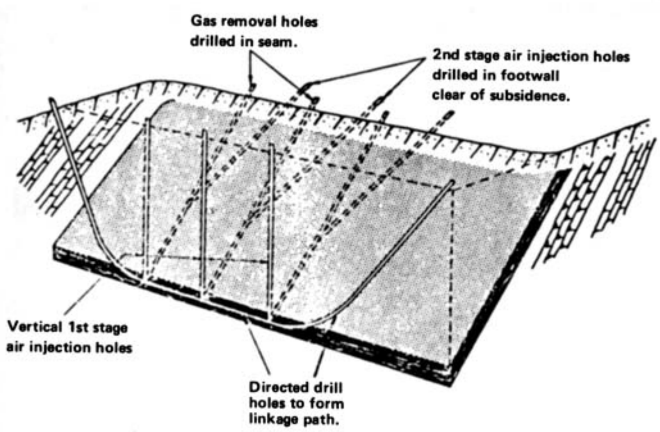


Fig. 9. Alternative layout employing directed drillholes for linkage.

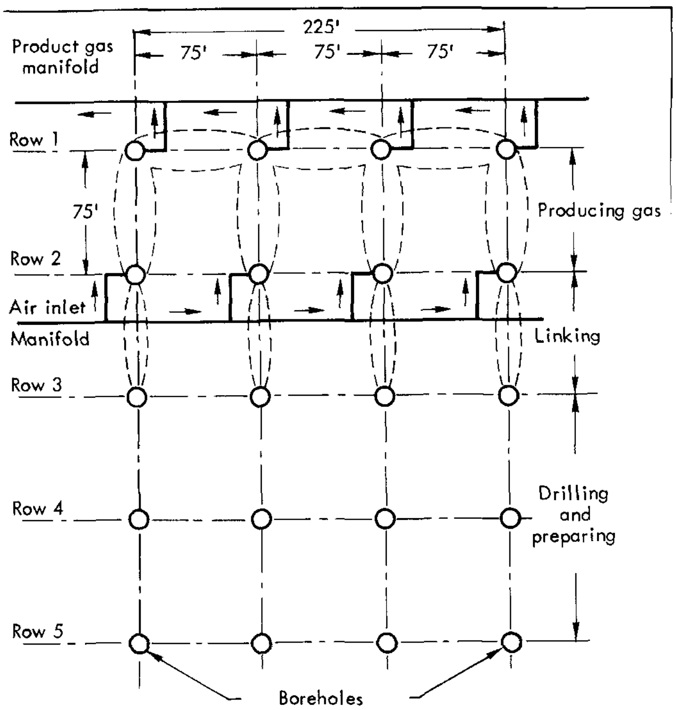


Fig. 10. Plan view of a shaftless generator for a plant in the Moscow region.

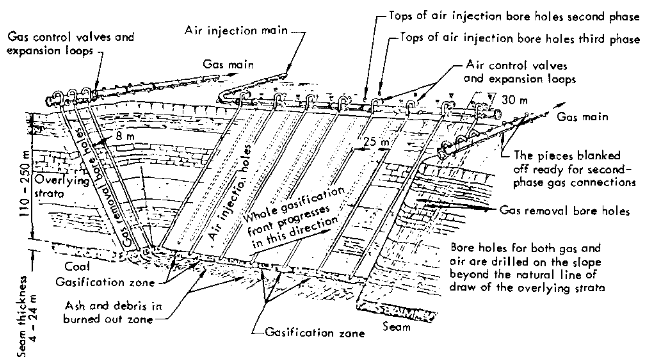


Fig. 11. Projected layout of boreholes at Angren to suit thick brown coal seams and heavy subsidence.

will then generalize to other linking methods. Figure 10 shows a typical plan view of the Soviet process. The dotted lines indicate the location of the underground linking channels formed in the coal by countercurrent combustion. Efforts are made to ensure that these channels are formed at the bottom of the seam. This is accomplished by sealing the access pipes to the coal, two thirds or more of the way down the coal seam. The injected air is thus forced to enter and the product gas must exit at the bottom of the seam. Thus, the linkage channel at least starts and ends at the bottom of the seam, even though it may wander a bit between the pipes.

In Figure 10, the production (cocurrent combustion) phase is shown in the direction of row 2 and row 1. However, in practice, the Soviets conduct the gasification in both directions; the choice is critically dependent on the nature of the roof subsidence. Such subsidence can create leakage paths for the gas as well as obstruct the gas flow, influencing the best direction for the forward combustion gasification step.

Modification for Thick Seams. The modifications in the drilling pattern and operational method used to accommodate thick coal seams are shown in Figure 11. The primary problem encountered for thick seams is that ground subsidence has a tendency to shear off the access pipes. To prevent this, two modifications are made. First, a lateral withdrawal/injection technique is used. In this case, one of the two functions (gas withdrawal or injection) is performed by pipes in a row along the side of the gasification zone. The remaining function is accomplished using pipes in a rectangular pattern, entering the seam directly over the coal to be gasified.

Second, within the framework of this general pattern, all holes are drilled on a slant to keep them out of the subsidence region during their functioning lifetime. When gasification is conducted in this manner, the pipes along the side of the gasification zone are never affected by subsidence, while the pipes in the pattern directly over the coal to be gasified are not affected until after they are no longer needed. Therefore, it is never necessary to operate with a pipe that has been exposed to any ground movement or subsidence (Gibb, 1964).

Using this technique, a cross-flow component is also added to the gas flow which helps recover mounds of coal that might otherwise be left between channels. The slant drilled portion of this design, although fully satisfactory in concept, is not always cost effective, and thus in Soviet operations it has not always been used. In such cases, the lateral withdrawal technique was made to work equally well with a combination of vertical pipes and more extended underground linkage channels that substitute for the slant drilled holes.

Critical Channel Width

The spacing between linkage paths depends on a phenomenon called the critical channel width. If we imagine a channel that is extended indefinitely with a series of drilled holes and operated for a long period of time, we must know how wide the channel will grow. This factor determines the maximum initial spacing allowable between parallel channels for 100% resource recovery. Eventually, the channel will reach a stable width and will expand no further because, as the channel widens, the transfer rate of oxygen to the combusting coal faces diminishes but the conductive and radiative heat losses from the faces remain constant or increase. At a specific width, the critical channel width, it is no longer possible to sustain combustion on the faces, and the channel ceases to widen. The actual critical width is clearly affected by the permeability distribution in the channel after roof subsidence. The critical channel widths for the Soviet gasification stations and for the British experiment at Newman Spinney are presented in Table 1. With air as blast, critical channel widths as great as five to ten times the seam thickness were achieved for thin seams. Widths were further increased by enriching the blast with oxygen. The British employed hole spacings twenty-five times the

TABLE 1. CRITICAL CHANNEL WIDTHS AT SOVIET AND BRITISH COAL GASIFICATION STATIONS

Station	Critical channel width, m	Seam thickness, m
Soviet:		
Tula	18-36	2-4
Lisichansk	9-27 (air blast)	1-3
	19-57 (oxygen-enriched blast)	1-3
Yuszhno-Abinsk	14	2
	32	8
British P-5:		
Newman Spinney	14-19	0.6-0.8

seam thickness with some success but left a considerable amount of coal between the channels (Fedorov, 1957; Gibb, 1964).

Maintenance of Constant Composition of Product Gas

It is very important to operate the gasification system so that the composition of the product gas remains relatively constant with time, maintaining the heating value at a desirable level. This is accomplished by ensuring that the hot gases always pass through a zone that is essentially packed with coal rubble. Such a zone has a large amount of coal surface area available for reaction and permits intimate contact between the hot gases and the coal. The downstream tip section of a long channel during gasification of a thick coal seam is illustrated in Figure 12. (The wider upstream portion of the channel with the additional air injection pipes is not shown.)

An essential feature of this region is that as coal is consumed, initially at the bottom of the seam because of the placement of the linking channel, more coal falls into the growing void. This creates a high surface area rubble bed that can serve as a final reduction zone. Such a zone is highly reactive and, by converting excess carbon dioxide to carbon monoxide ($CO_2 + C \rightarrow 2CO$), is responsible for the uniform quality of product gas.

Further upstream, the channel may widen to many times the coal seam thickness. In this area, coal falling into the growing void at the sides of the channel does not have such an important effect on the product gas composition because of an oxygen bypass at the channel center. A sampling of the upstream gases in the oxidation zone shows low heating values. However, so long as the tip of each channel has a hot and highly reactive zone of coal rubble through which all the hot gases must flow, the product gas will be properly reduced and will have a high heating value that is uniform with time.

As the flame front advances and the channel width expands, there comes a point when the rubble zone will no longer hold the composition of the gas constant. At this time, another section is added to the channel (as illustrated in Figure 10) to maintain the required high surface area coal zone. The gasification process can thus be continued indefinitely along a coal seam with excellent control over the uniformity of the gas composition. Fractional resource recovery can be controlled by proper spacing of the parallel channels.

System Efficiency

There are at least two efficiencies of concern for the underground gasification of coal. The fraction of the heating value of the coal that appears as heating value in the product gas must be maximized. Also, we must consider the overall energy efficiency of the plant including the conversion efficiency mentioned above and the energy

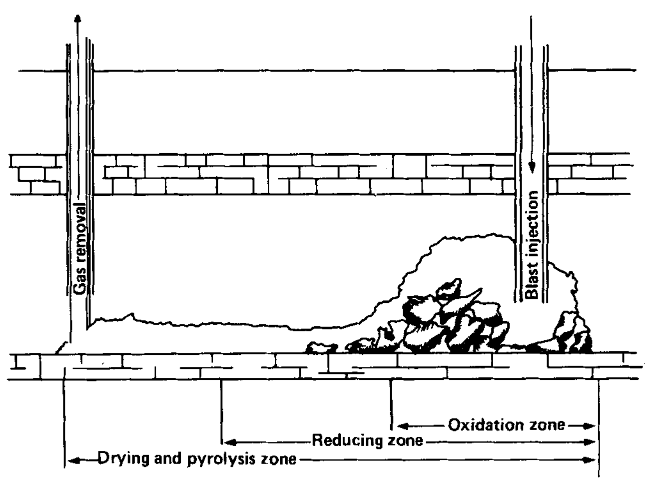


Fig. 12. Conceptual view of a channel during gasification.

required to maintain the gasification station. The Soviets have well documented the coal to gas heating value conversion but report little on the overall plant efficiency. The fraction of coal gasified varied from 50 to 100%, depending on the particular gasification station and on the specific nature of the ground subsidence. Of the coal actually gasified, 50 to 70% of its heating value appeared as heating value in the product gas (Kreinin and Revva, 1966).

THE CHEMISTRY AND PHYSICS OF UNDERGROUND COAL GASIFICATION

Both the chemical and physical properties of coal are important in the analysis of UCG. As previously shown in Figure 12, a useful one-dimensional conceptual model of UCG during forward combustion involves the existence of several distinct reaction zones, namely, oxidation, reduction, and pyrolysis/drying. These are the same zones which occur in moving-bed gas producers, such as the Lurgi gasifier.

Nusinov (1946) and Skafa (1960) have explained qualitatively the major mechanisms of gas formation in underground gasification. Certain zones can be identified when the gas stream is followed along a gallery or borehole in a coal seam under gasification. With air as the gasification agent, the first zone, as shown in Figure 12, is the zone of oxidation, where practically all the oxygen content of the blast is depleted in contact with the coal, and carbon dioxide is formed. As in gas producers, the oxidation zone as measured in a direct line between injection and production hole should be rather short, although this is affected by the presence of the channel. The oxidation zone should also spread out laterally from the inlet.

As long as free oxygen remains in the gas stream, the zone of oxidation persists. Depleted of free oxygen, the stream moves into a reduction zone (600° to 900°C), where carbon dioxide is reduced to carbon monoxide in contact with the hot coke, and water vapor forms hydrogen and carbon monoxide through the carbon-steam reaction. At lower temperatures, carbon dioxide and hydrogen are formed through the water gas shift reaction. While this zone is 2 m or less in conventional gas producers, it may extend further in UCG, yielding more efficient utilization of the heat produced. Owing to these endothermic reactions, the temperature decreases, and the gas enters a zone of dry distillation (200° to 600°C) where it mixes with the volatiles evolved from the coal. Within this zone are formed successive zones of high temperature coking, semicoking, and drying. In the drying zone, water vapor is formed and mixes with the gases of thermal composition. These reaction zones are also established laterally as well as longitudinally, although they are extremely narrow in the lateral direction owing to the low thermal conductivity of coal and the lack of convective movement laterally.

In the following discussion, each zone will be treated separately, since each zone has its distinct chemistry and physics. In addition, effects of linking methods and the physical properties of coal on the operation of UCG will be discussed.

Coal Pyrolysis. In both surface and underground coal gasification, coal pyrolysis plays a very important role in determining the composition of the product gas, since significant amounts of hydrogen, carbon monoxide, methane, and higher hydrocarbons, which can enrich a low Btu gas, are produced. In these processes, the coal located between the oxidation zone and the gas outlet is usually heated by the hot product gases in a reducing environment before it is consumed by oxidation. This is the inherent characteristic of a flame front propagating cocurrently with the gas flow through a rubble zone of coal. When the coal is heated, it undergoes thermal decomposition, releasing a variety of chemical products into the gas stream. A very good brief description of the decomposition for American and British coals has been given in a United Nations Report (1972) and in a recent *AIChE Journal* review by Anthony and Howard (1976).

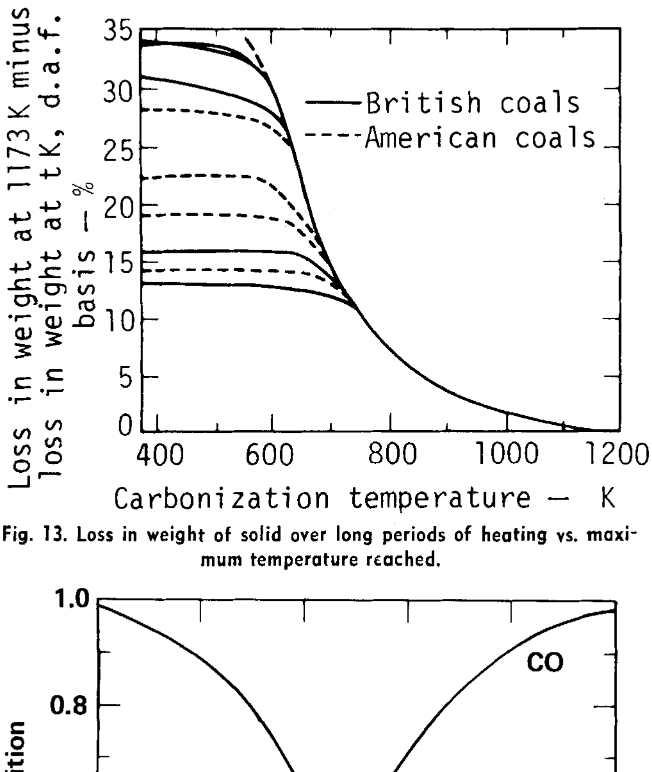


Fig. 13. Loss in weight of solid over long periods of heating vs. maximum temperature reached.

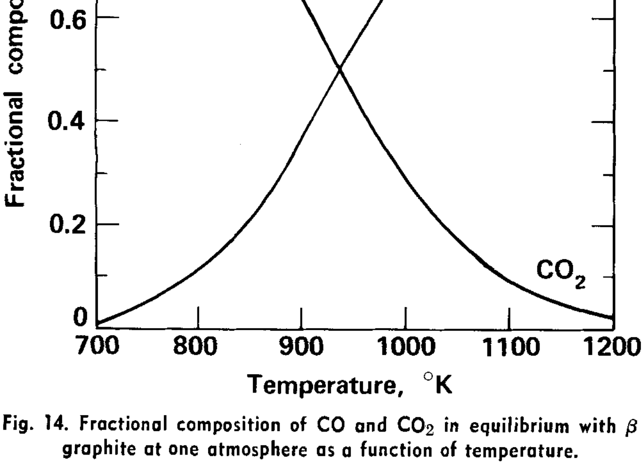


Fig. 14. Fractional composition of CO and CO_2 in equilibrium with β graphite at one atmosphere as a function of temperature.

When the coal is heated, various physical and chemical changes take place in succession. The nature of the changes depends on the type of coal. For the western United States coals, which contain appreciable water, large physical changes due to release of the water can occur below 100°C. Cracking and shrinking of the coal matrix also occur, with a resulting increase in permeability. Chemical changes begin slowly at about 300°C and have the nature of a very mild depolymerization. In this range of temperature, moderate amounts of volatiles trapped in the coal matrix may be released. Consequently, the bituminous vitrinite material (contained in eastern coals) tends to soften and become somewhat plastic. The softening property is most marked in the prime coking coals having 88 to 90% mineral free carbon content. If the temperature is rising steadly as in conventional carbonization processes, resolidification is complete by about 550°C. The fused material has a transient existence and is decomposed continuously to an infusible solid, together with small amounts of vapors and gases, at an increasing rate as the temperature rises above 350°C.

Very small amounts of paraffin hydrocarbons (probably occluded), water, and oxides of carbon are given off well below 300°C. Traces of oily liquid are produced soon after 300°C. Between 350° and 550°C, most of the tar is given off (peak rate at 450°C) together with a moderate amount of inflammable gas; the hydrocarbon gases are evolved mostly between 450° and 500°C. On further heating above 550°C, the semicoke residue that remains shrinks and hardens, giving off gases largely consisting of hydrogen, methane, and oxides of carbon.

Dryden (1957) has shown that the loss of weight over long periods of heating is, for a given coal, characteristic of the maximum temperature reached (Figure 13). The total weight loss due to decomposition is significant, and the data for Soviet coals are similar to that for western United States coals (Skafa, 1960). Clearly, a variety of chemical reactions take place; as the temperature rises, chemical bonds of increasing strength in the coal are broken. The actual chemical reactions appear to be very fast, but diffusion through the solid slows up the evolution of volatiles. It should be mentioned that heating rates underground are rather slow (on the order of 1.0 to 3.0 °C/min), and hence the pyrolysis products are not as sensitive to particle size as in rapid devolatilization (Anthony and Howard, 1976).

Since in the Russian approach the in situ gasifier is operated at low pressures in order to minimize the gas leakage problem, the amount of methane produced via gasification is rather small, certainly comprising less than 1% of the total gas volume for air injection. Hence most of the methane recovered from low pressure in situ gasification will be due to pyrolysis. The exact nature of the pyrolysis products will, of course, be dependent on the coal used and the carrier gas. The interactions of pyrolysis, water influx, and gasification on the product gas composition will be different for forward burning and backward burning, as discussed by Brown and Law (1975).

The Chemistry of Char Combustion

A very extensive treatment of the thermodynamics of coal gasification has been presented by Von Fredersdorff and Elliott (1963). However, a brief outline of certain significant features of the chemistry of char gasification and the implications of these features to the gasification process is presented here.

In most coal gasification operations, the primary oxidation reactions take place mainly between char, the end product of pyrolysis (primarily carbon) and oxygen. There are varying degrees of oxidation of the pyrolysis products, but this effect is neglected here. The primary oxidation reactions that take place are as follows (Von Fredersdorff and Elliott, 1963):

$$C + O_2 = CO_2 + 94.05 \text{ kcal/g-mole} \quad (1)$$

$$C + \tfrac{1}{2}O_2 = CO + 26.42 \text{ kcal/g-mole} \quad (2)$$

$$CO + \tfrac{1}{2}O_2 = CO_2 + 67.63 \text{ kcal/g-mole} \quad (3)$$

The heats of reactions assume all compounds as gases, carbon as B-graphite, and 298.16°K. However, they vary only slightly with temperature and are not influenced by the fact that char has a different heat of formation than does B-graphite (Stephens, 1972).

It can be seen that of Equations (1), (2), and (3), only Equation (2) produces a combustible gaseous product. It is therefore important to understand the conditions that will preferentially produce carbon monoxide instead of carbon dioxide. Figure 14 presents the fractional composition of carbon monoxide and carbon dioxide in equilibrium with B-graphite at 1 atm as a function of temperature. It can be seen that if one wants to produce carbon monoxide preferentially, it is essential to maintain a combustion temperature above 1 000°K.

It should be recognized that while Equations (1) and (2) are heterogeneous, Equation (3) is homogeneous. It is Equation (3) that is responsible for the poor performance of some UCG systems previously tested. As the void space underground grows with the consumption of coal, there is more potential for gas phase oxidation of carbon monoxide to carbon dioxide and the resulting extreme temperatures in the gas phase; this phenomenon is generally referred to as oxygen bypassing and will be discussed in more detail later.

As discussed by Thring and Essenhigh (1963) and Gray, Cogoli, and Essenhigh (1974), the mechanism of the oxidation kinetics consists of chemical kinetic, adsorption, and diffusion regimes. Of particular interest for in situ gasification is the expected particle size, which for UCG will be much larger than for pulverized fuel furnaces. The size of the particles will be controlled by the structural characteristics of the coal, since the rubbleization of the coal seam proceeds by thermal fracturing. It is believed, therefore, that the controlling regime is external molecular diffusion above 1 000°C and chemical reaction and intraparticle diffusion below this temperature. The kinetics for coal gasification can usually be approximated in terms of stoichiometric reactions of carbon, hydrogen, and oxygen (rather than in terms of more complicated chemical constituents of coal).

Historically, there has been some disagreement over the actual mechanism of gas formation in a channel. The discussion centers around where carbon monoxide and carbon dioxide are formed. In producer gas systems (fixed bed), the common conception is that a definite oxidation zone, where the coal is oxidized to carbon dioxide is formed. The carbon dioxide is then reduced to carbon monoxide as the gas passes through the reduction zone of the reactor. However, data obtained by Rossberg (1956) show that simultaneous formation of carbon monoxide and carbon dioxide as a function of temperature (T) occurs according to the equation

$$CO/CO_2 = K \exp(-A'/T)$$

At low temperatures, carbon dioxide dominates, and carbon monoxide production is favored at high temperatures. Therefore, Thring (1952) has modified the two-zone gas producer concept (oxidation of carbon to carbon dioxide, reduction of carbon dioxide to carbon monoxide) and has proposed a three-zone theory to allow for simultaneous primary formation of carbon monoxide and carbon dioxide from coal. Walker et al. (1959) and Sherman and Landry (1963), have also provided an excellent discussion of this subject.

The reduction zone is dominated by

$$C + CO_2 = 2CO - 41.2 \text{ kcal/g-mole} \quad (4)$$

$$C + H_2O = CO + H_2 - 31.4 \text{ kcal/g-mole} \quad (5)$$

The equilibrium relationship between carbon monoxide and carbon dioxide has already been discussed with reference to Figure 12. It is, of course, desirable to reduce as much carbon dioxide to carbon monoxide as possible. Since this reaction is endothermic, it provides a means of utilizing the heat of reaction.

If char is combusted stoichiometrically in pure oxygen in the absence of heat losses, burn temperatures as high as 3 000°K would be expected. This is far in excess of the temperature needed to produce a reaction product of essentially all carbon monoxide. Therefore, such a reaction system is inefficient, since a large fraction (approximately 25%) of the heat of combustion of the char goes into further heating of carbon monoxide rather than producing more of the combustible product. Steam is therefore added to utilize this excess heat of reaction to produce more combustible gas via Equation (5).

In underground coal gasification systems operating below the water table, water is unavoidably added by leakage into the reaction zone from the surrounding formations. In fact, the Soviet experience in the use of air for UCG shows that the natural water intrusion rate can easily exceed the rate which would optimize the thermal efficiency and causes reduced efficiency of the process due to excessive cooling of the reaction zone (Antonova et al., 1967). A similar means of effectively utilizing the excess combustion energy could be accomplished by reducing carbon dioxide to carbon monoxide, as given in Equation

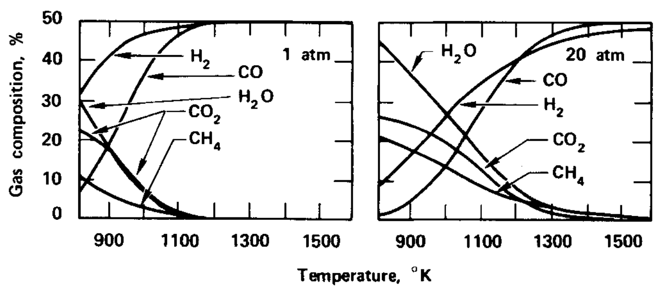


Fig. 15a. Equilibrium gas compositions of the carbon-steam system.

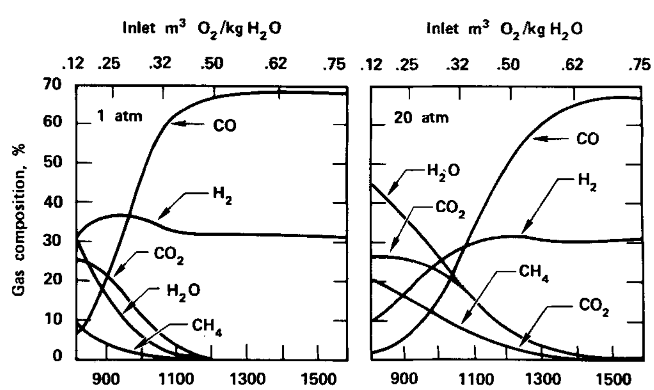


Fig. 15b. Equilibrium gas compositions of the carbon-oxygen-steam system at adiabatic conditions.

(4). In fact, this reaction takes place in long gasification channels to a great extent, since the carbon dioxide formed upstream is reduced to carbon monoxide further downstream.

The introduction of water or hydrogen as a reactant significantly complicates the combustion chemistry. Additional reactions which can occur include

$$CO + H_2O = CO_2 + H_2 + 9.8 \text{ kcal/g-mole} \quad (6)$$

$$C + 2H_2 = CH_4 + 17.9 \text{ kcal/g-mole} \quad (7)$$

Figure 15*a* (Von Fredersdorff and Elliott, 1963) presents calculated equilibrium compositions for a carbon-steam system. It can be seen that one of the primary additions to the list of products is methane, which increases in concentration as the temperature decreases. Figure 15*b* shows the equilibrium compositions for the carbon-oxygen-steam system under zero enthalpy change and the same pressure-temperature conditions as in Figure 15*a*. This more closely represents a possible combusting system than does Figure 15*a*, since no heat is added or subtracted externally. The principle difference between the systems lies in the product gas hydrogen/carbon monoxide ratio at high temperatures. However, the behavior of the carbon monoxide/carbon dioxide ratio vs. temperature as well as the occurrence of methane remains essentially the same. The carbon monoxide/carbon dioxide ratio is also not significantly altered from the case where steam is not present (Figure 14).

One of the most interesting features of carbon-oxygen-steam equilibrium calculations (Figure 15*b*) is that throughout the temperature range considered, the heating value of the product gas does not decrease significantly as the temperature decreases, in contrast to the case where one is considering the carbon monoxide-carbon dioxide-carbon equilibrium in Figure 14. This results from the fact that as the carbon monoxide and hydrogen concentrations fall off with decreasing temperature, the loss in their contribution to the heating value of the product gas is partly made up for by the increase in the concentration of methane.

In the higher temperature ranges, the compositions calculated assuming equilibrium are fairly accurate for most systems. However, as the temperature decreases, the kinetics for the rate of formation of methane become very slow compared to the formation of other components of the system. It is therefore very difficult to predict accurately the optimum operating temperature and thus oxygen/steam ratio for a specific system design using thermodynamic charts. This will depend on the degree of formation of methane at low temperatures which in turn depends on the residence time of the gas as well as the extent of direct methanation of coal to methane, which is catalyzed by coal ash. In some system designs, the amount of methane produced could be insignificant, in which case the combustion temperature should be kept above 1 000° to 1 100°K, since the heating value of the product gas can then be derived only from carbon monoxide and hydrogen. Because the physical and chemical variables of an underground coal gasification system vary significantly, it is not possible to make a generalized statement about the optimum oxygen/steam ratio for all systems. Such an optimum would have to be determined individually for each system and its set of operating parameters.

Figures 14 and 15 also show that increased pressure will enhance the formation of methane. However, it is not clear that this effect can be capitalized on for underground coal gasification. The Soviet experience in UCG indicates that owing to subsidence of the overburden, which is unavoidable for a system that removes essentially all of the coal, the gasification zone is usually sufficiently porous to require that the process be carried out at the lowest possible pressure to minimize gas losses. This is a major obstacle to producing pipeline quality gas (synthetic natural gas) by UCG.

Downstream Chemistry

In underground coal gasification, as the gas progresses past the combustion zone and continues on its path to the exhaust hole, it inevitably loses heat to the surroundings and cools. The heat loss is due not only to conduction into the surrounding formations, but also due to water intruding into the hot gas stream and vaporizing. As the gas cools, there is a tendency for its composition to shift in a manner described by Figures 13 through 15. The primary reaction of concern in addition to Equations (6) and (7) is as follows:

$$2CO = CO_2 + C + 41.2 \text{ kcal/g-mole} \quad (8)$$

It can be seen that Equations (6) and (8) reduce the heating value of the product gas, while Equation (7) increases it. However, in most production systems, as the temperature decreases, the reaction rates slow down so that equilibrium compositions are not reached and the final product gas composition is determined primarily by the reaction rates rather than the equilibrium composition.

Equation (6), commonly called the water gas or carbon monoxide shift reaction, reduces the heating value of the product gas in two ways. It exchanges a hydrogen for a carbon monoxide molecule with a corresponding reduction in the heat of combustion of 9.8 kcal/g-mole. It also exchanges a carbon dioxide molecule for a water molecule. Since water is easily condensed out of the product gas and carbon dioxide is not so easily removed, this exchange further reduces the specific heating value of the product gas by diluting it with an incombustible gas.

The Soviet experience in underground coal gasification indicates that this reaction can play a major role in establishing the product gas composition (Kreinin and Revva, 1966; Skafa, 1960), possibly owing to its being catalyzed by surfaces and inorganic salts which are in abundance in underground gasification systems (Batchelder et al., 1953; Grebenshchikova, 1957). This parameter, in some situations, has limited the useful length of a gasification channel (Lavrov et al., 1971). If the channels were too long, and if there was too much water intrusion, this reaction would shift the product gas composition to an uneconomically low heating value. This factor often was the limiting factor in design of well spacing for the Soviet system.

Equation (8), commonly called Boudouard reaction, clearly reduces the heating value of the product gas by exchanging a carbon dioxide molecule for two carbon monoxide molecules. The reaction in the gas phase is sufficiently slow so that it usually does not contribute significantly to product gas composition. However, it occurs actively at 400° to 500°C in the presence of iron oxides and metallic iron such as the iron in the drill pipe casing (Skafa, 1960). The Soviets therefore felt it was important to flash cool the product gas with a water spray at the bottom of the exhaust hole to freeze the gas composition before it reached the iron casing. The spray also lowered the pipe temperature, which preserved the pipe-cement seal for the cemented casings in the access holes (Kreinin and Revva, 1966).

In contrast to Equations (6) and (8), Equation (7) would dramatically increase the heating value of the product gas if it took place to any great extent. However, evidence for Soviet operations at Podmoskovia indicates that as the gas cools in a long channel, the carbon monoxide/carbon dioxide ratio decreases as expected, but the

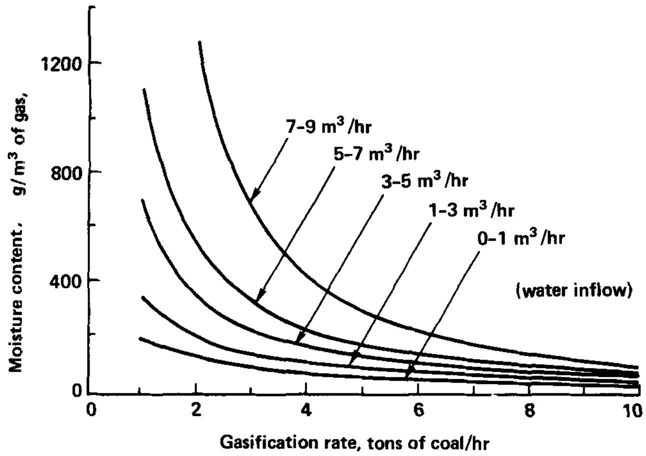


Fig. 16. Moisture content of the gas as a function of the gasification rate of the coal seam.

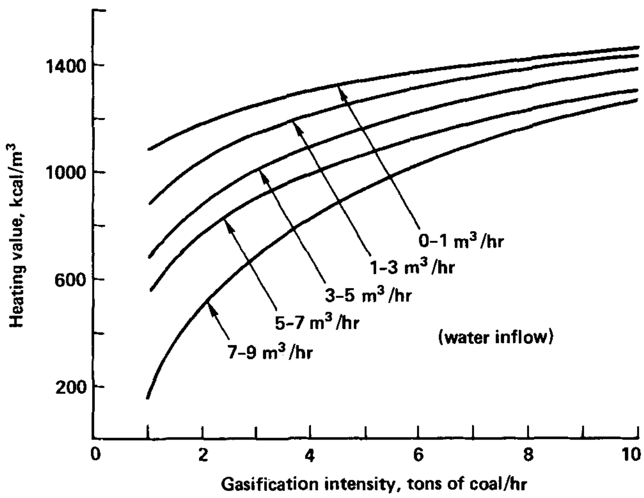


Fig. 17. Effect of gasification intensity on the calorific value of the gas at various water inflow rates into the gasification zones.

methane concentration does not increase. This indicates that the reaction rate for the formation of methane is not appreciable at low temperatures and pressures, which is consistent with experiments in surface gasifiers.

Field Results

The underground gasification of coal is a complex physicochemical process dependent upon many variables. Since the mutual interdependence of the process variables is not yet well established, and because coal is such an ill-defined and heterogeneous material, it is difficult to arrive at a rigorous scientific or engineering interpretation of the results of gasification. However, by analyzing field data, trends can be established, and a rough physicochemical interpretation can be applied. The quantitative identification and explanation of these trends is essential for establishing engineering methods to control the process and is a necessary first step that will eventually enable selection of optimum process conditions.

One Soviet paper (Antonova et al., 1967) presents a survey of laboratory and field data obtained during the period 1955 to 1966 at the Yuzhno-Abinsk station and illustrates trends in the gasification process. All the data are for gasification with air, with the product gas compositions given on a water free basis. The Soviets also did not include hydrocarbon gases higher than methane in their product gas analysis. The purpose of the study was to relate the product gas quality to three very important parameters: blast (oxidant) rate, water intrusion rate, and coal seam thickness.

The water content in the product gas is a reflection of the rate at which the water intrudes into the gasification zone from the surrounding formation. Since the water intrusion rate is determined by the permeability of the surrounding formation and the hydrostatic head for the general region, it varies very slowly with time and is essentially constant. The Soviets operated their systems so that the gasification channels in the coal were always sufficiently hot to vaporize all introducing water. This is an essential design feature, since, if the water were not removed in this manner, the water level would build up and plug the channel to gas flow. Therefore, essentially all the intruding water appeared in the product gas as water or as products of the reaction between water and coal. One would therefore expect the water concentration in the product gas to vary approximately inversely with the blast rate; that is, the water content is relative to the blast rate. This was found to be essentially true, and data illustrating this effect for different water intrusion rates are presented in Figure 16.

It is difficult to discern the actual axial distribution of water influx. This distribution is quite important in determining gas composition, since water intruding into the hot zone will participate in the gasification reactions; however, water intruding downstream after the gas has cooled may not affect the gas composition much and may only serve to lower the gas temperature further. If all of the water participates in gasification, the equilibrium compositions will be shifted as discussed previously. Figure 17 illustrates Soviet data for the effect of gasification intensity on the heating value of the product gas for various water inflow rates. The data show that the heating value increased with increased gasification intensity and reduced water inflow rate, over the ranges shown. This is consistent with the chemical equilibrium understanding of the process where, as the system cools, more carbon dioxide is produced at the expense of carbon monoxide; however, as discussed earlier, such equilibrium considerations are not applicable to additional formation of methane, since the reaction rate for methane formation appears to be too slow for it to contribute significantly.

An interesting process control problem is posed by the dual phenomena of water influx and gas leakage. High pressure operation can reduce water influx but exacerbates gas leakage. On the other hand, low pressure yields the opposite effects for gas and liquid flow. The only other control variable available in air gasification is the blast rate. Figure 17 illustrates how the gasification intensity, which is controlled by the blast rate, can lower the relative contribution of water influx, but higher blast rates will only be possible through higher pressure drops. The optimum combination of flow rate and pressure will, of course, be site specific but does offer some relief from gas leakage and water influx difficulties. The Soviets typically operated at gasification intensities of about 2.0 tons of coal/hr, which can yield extremely low heating values, as seen in Figure 17. Higher gasification rates, of the order of 5 tons/hr, are attainable, based on recent government testing in Wyoming (Fischer and Schrider, 1975). As seen in Figure 17, higher blast rates can yield a more satisfactory product gas heating value. However, some tests, such as Hanna II-phase 3, have found water influx to be more or less uncontrollable.

The combustion zone and product gas can be cooled not only by water intrusion but also by thermal conduction to the surrounding formations. Figure 18 illustrates how the thickness of the coal seam can affect the heating value of the product gas as a function of different water inflow rates. This figure is for a fixed gasification rate of approxi-

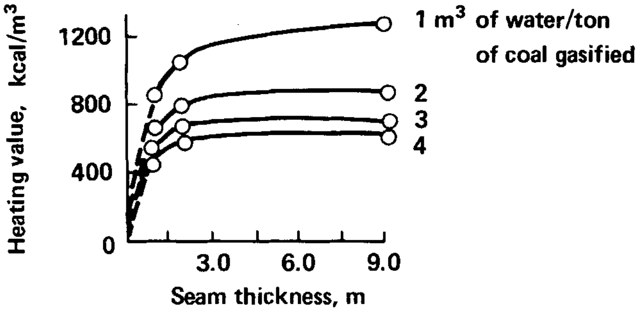


Fig. 18. Effect of seam thickness and the specific water inflow into gasification zones on the calorific value of gas obtained by underground gasification.

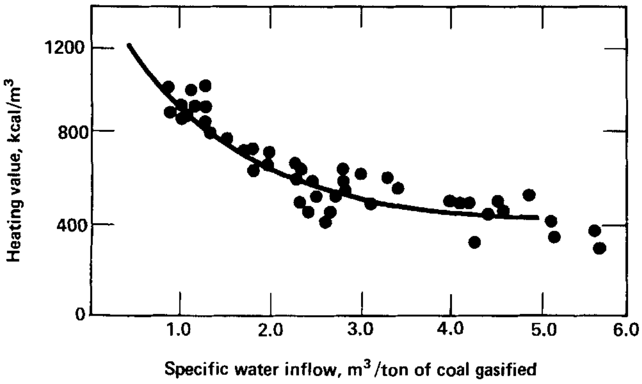


Fig. 19. Calorific value of the gas as a function of its moisture content.

mately 2 tons of coal/hr. It can be seen that the detrimental effect of the surrounding formation cooling the system becomes very significant as the seam thickness falls below 2 m. This cutoff thickness will be a function of the gasification intensity as well as the fractional oxygen concentration of the blast. Hence, for thinner seams, the heating value can be raised by increasing either of these factors. For this reason, oxygen enriched air was commonly used at the Soviet gasification station at Lisichansk where the coal seams were generally thinner than 2 m (Skafa, 1960).

Figure 19 presents water influx data in a different form. This figure shows the heating value of the product gas as a function of the water inflow per ton of coal gasified for a coal seam thicker than the apparent 2 m cutoff thickness. It can be seen that the heating value continuously improves with decreased water intrusion. However, there should be an optimum water influx, although the actual number can vary considerably among coal seams and de-

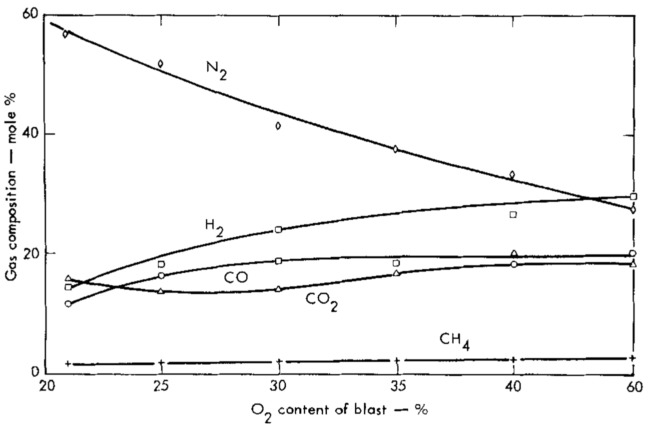


Fig. 20. Effect of oxygen content of blast on outlet gas composition.

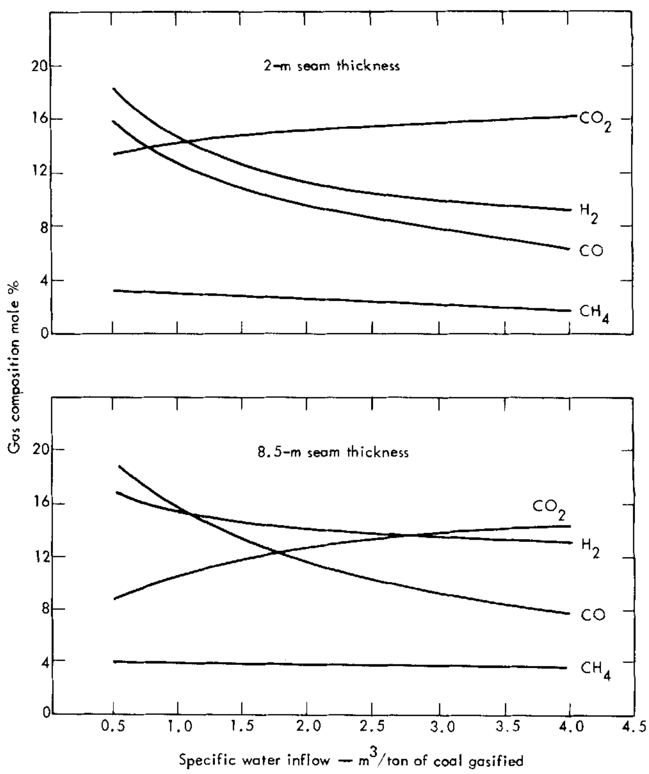
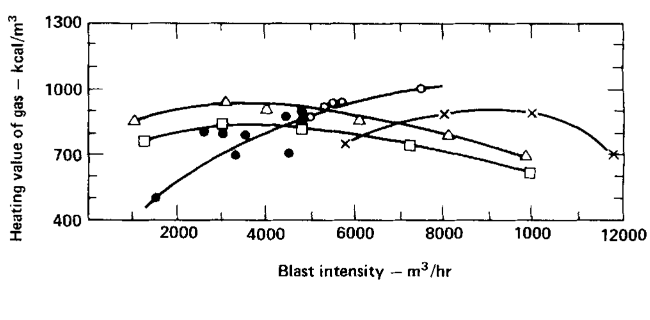


Fig. 21. Change in gas composition with seam thickness and water intrusion rate.

pends on whether the water intrusion is upstream or downstream from the combustion zone (Gunn, 1975; Bogoroditskii, 1957). The optimum is due to the trade off between sensible heat in the product gas and the production of carbon monoxide and hydrogen via the carbon-steam, Equation (5). However, as more water is added, the cooling effect of the water and the corresponding shift of the carbon monoxide/carbon dioxide equilibrium dominates and the heating value drops, yielding less than optimum thermal efficiency.

The Soviets did study oxygen/steam systems to a limited extent in the field, but they did not obtain sufficient data to establish quantitatively a similar optimum for oxygen/steam. It appears the primary incentive for the Soviet testing of oxygen enrichment was in the production of ammonia; hence data on pure oxygen gasification are scarce. Figure 20 (Skafa, 1960) shows how the product gas composition varies with oxygen content in the blast. One interesting point is that the carbon monoxide/carbon dioxide ratio did not change significantly with increasing oxygen content. Since the combustion zone temperature increases for increased oxygen concentration in the blast, one must conclude that incomplete reduction of



Key: 1—seam thickness of 14–16 m (Angren); 2—seam thickness of 5–6 m (Angren); 3—thickness of ~3 m (Yuzhno Abinsk).

Fig. 22. Effect of blast intensity on the heating value of the gas for various seam thicknesses.

carbon dioxide due to oxygen bypassing or additional water gas shift of carbon monoxide to carbon dioxide must be taking place. Stephens and Miller (1976) have concluded that the former effect is probable.

Figure 21 presents some data on the gas composition as a function of water intrusion rate as well as seam thickness. Increasing the water intrusion or decreasing the seam thickness has the effect of increasing the carbon dioxide concentration at the expense of the carbon monoxide concentration. This is consistent with the equilibrium calculations which predict higher carbon dioxide concentrations at lower temperatures. In addition, the methane concentration is unaffected by the lower temperature (large water influxes) which indicates that the kinetics of formation are slow. The modest decrease of the methane concentration for the 2 m seam is not explained.

Data taken at both Angren and Yuzhno Abinsk, presented in Figure 22, show an optimum blast rate which is clearly dependent on the thickness of the coal seam (Lavrov et al., 1971*a*, *b*). The optimum blast intensity is reached at lower blast rates for thin seams than for thick seams. This could be explained in terms of the optimum water intrusion rate discussed earlier, but the location of this optimum changes depending upon the seam thickness, which affects the heat loss to the overburden. This conforms with data in Figures 17, 18, and 19.

The effect of various operating variables on the process of reverse combustion has been investigated in several locations; the results were as follows (Lavrov et al., 1968; Skafa, 1960):

1. An increase in ash content of the coal from 30 to 45% resulted in a reduction in the linking rate by a factor of 2.5.
2. As the porosity of the coal increased, the linking rate increased.
3. The migration rate of the combustion focus increased with increasing inlet oxygen concentration.
4. Reverse combustion with oxygen did not produce channels which were as permeable as for linking with air; hence air linking was almost always used, with linking rates of 1 to 3 m/day.
5. The linking rate (meters per day) was almost independent of the total linking distance.
6. There exists an optimum linking rate as a function of the total air flow.

Some explanations for these linking data have been given by Skafa (1960) and Gregg et al. (1976).

THE PLASTIC PROPERTIES OF COAL AND THEIR IMPORTANCE TO UNDERGROUND COAL GASIFICATION

A detailed treatment of the plastic properties of coal has been presented by Loison et al. (1963). However, it is useful to discuss here how the plastic properties of coal might affect an underground coal gasification system. Since there are no quantified field data showing the performance of an underground coal gasification system as a function of the plastic properties of coal, the intent of this section will be merely to outline the magnitude of these properties and how they might affect the operation of a system.

The primary plastic property of concern in UCG is the degree to which the coal swells as it is heated. Such swelling can easily plug the coal bed to gas flow if it is large enough and is not considered in the design of the system. The swelling is due to two properties: as the coal is heated, it undergoes chemical decomposition giving rise to gaseous (as well as liquid) products, and as the coal is heated, it softens and becomes more or less plastic. The end result is that heating the coal can cause it to form a bubbly mass that can swell to as much as three times its original volume if unconfined. It is easy to imagine how such swelling could plug even very large channels in the coal if the system is not designed to compensate for it.

Not all coals swell, and the degree to which swelling coals swell ranges from very little to as much as 300%. Therefore, the initial solution to the problem might be simply to select nonswelling coals for UCG. Western coals show no swelling at all but continuously shrink with increasing temperature. However, most bituminous coals do swell, and such swelling has to be taken into consideration if they are to be used in UCG. One possible design solution would consist of drilling initial gasification channels in the coal and then devolatilizing the coal and enhancing the permeability by a reverse combustion step. The resulting flow path of char must be thick enough and permeable enough to hold the channel open in the forward combustion production phase.

There have been several recent studies which attempted to quantify the flow, pressure, and temperature behavior of a number of United States coals which are of interest for UCG (Dabbous et al., 1974; Reznik, 1974; Lien et al., 1977; Thompson et al., 1977). The purpose of some of this work has been to develop relative permeability data for analyzing methane drainage of eastern coals. When coal is in the wet (virgin) state, permeabilities are quite low, even nonexistent. For shrinking western coals, as the coal is dried, matrix permeabilities can increase by a factor of 10^4 to more than 10 darcies (Thompson et al., 1977); devolatilization increases permeabilities even further. For swelling eastern coals, the permeability will also increase slightly upon drying. At devolatilization temperatures, however, the coal becomes impermeable owing to the swelling properties. But when the coal is almost completely devolatilized, its permeability begins to increase again.

How specific measurements of coal matrix permeability can be used in interpreting field performance of UCG is unclear at this time. Unfortunately, the prediction of cleat geometry probably cannot be performed in any deterministic manner, which is an obstacle to gas flow modeling. It is possible, however, that enhancement of seam permeability by reverse combustion is influenced by the drying and devolatilization of the coal matrix.

CURRENT FIELD TESTING RESULTS (UNITED STATES AND CANADA)

As of 1978 there are seven UCG field tests in progress in North America, with two more in the planning stage. All but one of these tests are being operated on western coal; all tests are utilizing the linked vertical well design. Of these tests, four are being funded by the Department of Energy (Wieber and Sikri, 1977), while the remainder are supported by private companies.

Laramie Energy Research Center

Currently, the most advanced field test in the United States is being operated by the Laramie Energy Research Center at Hanna, Wyoming, on subbituminous coal. The coal seam is approximately 6.8 m thick and varies from 90 m to 120 m deep. Site characterization has been discussed by Estep-Barnes and Kovach (1975) and Komar et al. (1973). As early as 1972, gas was produced with heating values ranging erratically from 270 to 4 300 kcal/m^3. Over a 4 mo period, an average yield of 1 170 kcal/m^3 was produced from a two-hole (inlet/outlet) system. The linked vertical well method was used, and forward burning was found unworkable without prior backward burning (Schrider and Pasini, 1973; Schrider et al., 1974; Campbell et al., 1974). Later analysis of this first test has shown that the linkage path was not performed at the bottom of the seam, which in turn gave the inconsistent product gas composition.

A second Hanna experiment, Hanna 2-phase 1, was performed in 1975 and was patterned after the Russian design, with linkage at the bottom of the seam. Over 38 days the average heating value was 1 350 kcal/m^3 (higher heating value) with very stable operation. The UCG system was operated at relatively high flow and production rates compared to previous tests; these operating conditions enhanced product gas heating value (Fischer and Schrider, 1975; Brandenburg et al., 1975; Fischer et al., 1975; King et al., 1975; Schrider and Fischer, 1975). The test was terminated before the combustion front reached the production well. One of the significant results from this test was the cold gas thermal efficiency (coal to cold low Btu gas) of about 85%, which is superior to yields of most conventional gasifiers, for example, the Lurgi gasifier. One reason the Lurgi gasifier suffers in such a comparison is the Lurgi uses excessive steam/air ratios in order to prevent slagging of the ash. Other advantages to the UCG system vs. a conventional gasifier include the natural insulation provided by the overburden, which yields lower heat losses than for the cooling system used in a conventional gasifier, and a lower outlet gas temperature (300° vs. 700°C). The process heat and sensible gas enthalpy from a Lurgi gasifier might be reused above ground, however. The fact that at Hanna only a two-hole test system was used enhanced the reported efficiency, since no significant gas leakage was experienced. Leakage problems have occurred in other tests and are more severe for a commercial scale field operation (3 to 10% of the product gas for horizontal seams). More details on the comparative energy balances have been given by Edgar (1977) and Skafa (1960).

Water influx during the 1975 Hanna experiment was estimated to be approximately 0.5 m^3/ton coal gasified. This influx rate appears to be very close to the value required to optimize the cold gas efficiency of an in situ gasifier using this particular coal, according to model calculations (Gunn, 1975). Russian data show much higher water intrusion rates (see Figure 19), but it should be remembered that gas leakage was not a problem in the Wyoming tests. Thus, water influx was more controllable.

A technique named line-drive was tested in 1975 to 76 as part of Hanna 2-phases 2 and 3 (Brandenburg et al., 1977; Brandenburg et al., 1976; Schrider et al., 1976). The goal of this field design was to link two pairs of wells and then perform a gasification sweep over a wide area between the two linkage paths, using the natural permeability of the coal. It was postulated that the gasification sweep in a direction normal to the maximum field permeability would spread out the front. The well pattern consisted of four wells located at the corners of a 60 ft square. After linking to form two parallel paths, the line-drive gasification was attempted. However, the tests showed that the natural tendency of the burning process was to channel rather than proceed over a broad front; therefore, this concept was found to be unfeasible. Instead, each set of wells was gasified more or less conventionally (although not at the same time). Various gas production rates were to be tested during phases of this test.

When the coal between the first set of two wells was gasified (phase 2), extremely high product gas heating value was obtained (1 620 kcal/m^3); the cold gas thermal efficiency averaged 89% for phase 2. A typical product gas composition is given in Table 2. The gas production was controlled from 4 800 kmole/day (1.13×10^5 Nm^3/d)

Table 2. Hanna 2, Phase 2 Product Gas (Volume %)

H_2	17.3	N_2	51.0
CO	14.7	Ar	0.6
CO_2	12.4	H_2S	0.1
CH_4	3.3	C_2-C_4	0.6

to 10 200 kmole/day, the higher number corresponding to 100 tons coal gasified/day. Approximately 1 mo later, the coal between the other two wells was gasified (phase 3). In this test, gas production reached 22 400 kmole/day with an average heating value of 1 230 kcal/m^3. The decrease in heating value vs. the earlier test was mainly due to higher rates of water influx. During the latter stages of gasification of this test, water influx rates became less controllable. Whether this was due to increased roof collapse or the fact that an adjacent cavity was created 1 mo earlier is not clear; however, these field results are different from those obtained by Russian field tests which show that increased flow rate should improve heating value.

There have been various estimates of coal consumption or contact efficiency (fraction of coal gasified) for the Hanna tests. However, the tests performed so far do not provide conclusive data on contact efficiency, owing to several analytical difficulties:

1. Lack of knowledge about the scale-up of a two-well system to a multiwell system and the lack of a suitable sweep efficiency model based on chemistry and physics of UCG.

2. The inability to close the material balance for a UCG system due to an independent water influx measurement, which affects the hydrogen and oxygen balances; a direct measurement of the fraction of coal remaining underground which is carbonized and not gasified (although this should be rather small); measurement of the time-temperature environment underground, which affects the carbonization products.

A discussion of the above material balance calculations has been given by Schrider et al. (1974).

The Hanna 2 tests were the best instrumented UCG tests ever performed. Sandia Corporation has used elaborate instrumentation for monitoring physical test variables (Stoller, 1975; Northrop and Stoller, 1975). Two types of measurement techniques were used: diagnostic (thermal, in-seam gas sampling, pressure, overburden tilt, and displacement) and remote monitoring techniques (electrical, passive acoustic, and induced seismic). The usefulness of these techniques and an analysis of the field results have been given by Northrop et al. (1977). The thermal data have been the most informative, with details on formation of the reverse combustion link near the bottom of the seam, outward and upward progress of the forward gasification process, and the transient reaction of the coal between the two wells. One interesting result was that the reverse combustion link was not a single path but rather consisted of a partially developed link which terminated between the wells and a completely developed link which wandered in an elliptical path between the two wells. The size of the reverse combustion link was found to be about 1 m in width, which confirms a previous analysis. The combustion front during forward gasification was found to be narrow (about 0.6 m), with heating rates on the order of 3 to 5°C/min; no extensive pyrolysis zone was observed. It should be mentioned that the chromel-alumel thermocouples were consumed by the combustion front, so there is no data on maximum combustion temperatures (above 1 100°C).

Future tests at the Hanna site will be oriented towards optimizing well spacing (wider spacings will be used) and determining the effects of subsidence, gas leakage, and water influx for operation of the effects of subsidence, gas leakage, and water influx for operation of the several holes in parallel.

Lawrence Livermore Laboratory

The Lawrence Livermore Laboratory project, also sponsored by the Department of Energy, was originally based upon placing an array of chemical explosives within a thick coal seam greater than 15 m (Higgins, 1972; Stephens, 1974). Using explosive fracturing, a vertical rubbleized zone would be formed, yielding in effect a packed-bed reactor. Steam and oxygen would be pumped into the bed at high pressure to produce a product with a high percentage of methane. The intermediate Btu gas would then be collected through vertical wells and upgraded on the surface to synthetic natural gas or other products at costs competitive with conventionally produced synthetic fuels (Stephens, 1973; Stephens, 1974; Pasternak, 1973).

The site used in initial testing of the explosive fracturing concept was in the Powder River Basin (Hoe Creek #1; see Hill and Thorsness, 1977; Stephens et al., 1976). This coal is quite different than that at Hanna. Although both are nominally subbituminous, the Hanna coal is higher in rank and less reactive. The Hoe Creek coal is also wetter than the Hanna coal, both in terms of natural moisture content (30 vs. 10%) and groundwater flow. The seam tested was 38 m deep with a thickness of 7.6 m. A linked vertical well design rather than a vertical packed bed, as originally postulated by Higgins (1972), was used; explosive charges were employed to create the linkage path.

Two explosive charges were detonated at the bottom of the seam, causing extensive fracturing. Permeability tests (air and water flow) showed permeability roughly increased by a factor of 10. However, later tests showed that the permeability at the bottom of the seam was lower than for the upper part of the seam; the explanation for this result was that the large amounts of coal fines produced obstructed the flow through cracks in the coal seam, causing more permeable paths to exist near the top of the seam. Subsequent gasification tests provided further evidence that the linkage was inadequate. Override of the combustion front created a situation which was conducive to oxygen bypassing and burning from the top down. The gas composition, as reported by Hill et al. (1977), was quite erratic, varying as much as 500 kcal/m^3 over the space of several days. The heating value averaged 1 200 kcal/m^3 for the first 8 days and then decreased to essentially zero. The resource extraction was less than 20% of the fractured region, which was another outcome from the override of the combustion zone. Of the coal consumed, 73% was recovered as heating value in the gas. Seven percent of the product was lost through leakage to other parts of the seam. The explosive fracturing concept has been abandoned in favor of testing of the linked vertical well concept, using countercurrent combustion for linking and periodic injection of steam and oxygen.

A second field test, Hoe Creek #2, was operated in late 1977 in another coal seam, although at essentially the same depth and thickness conditions of Hoe Creek #1. This test was heavily instrumented for temperatures, pressures, and gas sampling, the latter especially for determining the distribution of gasification induced contaminants. Measurements of cavity size and burn front location were performed using high frequency electromagnetic transmission techniques (Spataro, 1977). Test objectives included investigation of reverse combustion in a wet seam (path, linkage rates, specific air consumption, gas quality, water influx); determination of forward air gasification sweep width, efficiency, gas composition, water influx, gas losses, and pressure and temperature gradients; operation of a 3 day steam-oxygen burn; and measurement of air and water quality parameters.

Fourteen days were used to produce the reverse burn link over the 18 m well spacing. This rate of linking is comparable to that obtained at Hanna. Thermocouple measurements indicated that multiple paths formed through the highly developed cleat system in the coal. The rate of advance of the link was as fast as for the Hanna coal. Following this phase, forward gasification using air was initiated and lasted 58 days. The product gas for forward gasification varied from 900 to 1 350 kcal/m^3. During a 2 day period in the middle of the test, oxygen and steam were injected in place of air, yielding a medium Btu gas of 2 250 to 2 700 kcal/m^3. While the data analysis is incomplete at this time, several conclusions are apparent (Stephens, 1978):

1. Override of the coal seam by the combustion front occurred, causing wild fluctuations in the heating value, more severe than in Hoe Creek #1. The gradual decline in heating value over time, similar to other field tests which exhibited override, was due to oxygen bypassing and channeling through the rubble zone. The reason for the override was due to a well casing failure near the top of the seam, which caused gas flow to that point rather than to the bottom of the seam. Owing to financial limitations, another well was not drilled. The override of the coal seam resulted in excessive leakage, as much as 30%, into overlying strata.

2. The control of water influx gave rather surprising results. Whereas Russian experience showed that total water influx has a large effect on heating value (see Figure 19) and the amount of water influx can be controlled by system backpressure, gas heating values for the Hoe Creek test tended to be more or less independent of the total water influx. One explanation for this result is that only a fraction of the water actually entered the reaction zone, and the excess water cooled down the gases (and did not promote the water gas shift reaction). Material balance data indicated that the reacting water was roughly equal to water bound in the coal (about 25% by weight).

3. Oxygen injection was handled successfully, and expected heating values were obtained, although channeling of the gas did produce oxygen breakthrough after several days. Somewhat surprisingly, the oxygen burn tended to reduce gas losses; it also attained higher temperatures and gave better resource utilization.

In conjunction with field operations, extensive work on the structural properties of Wyoming coals and explosive fracturing have been performed (Bonner and Abey, 1973; Leach, 1975; Wong, 1975; Stone and Snoeberger, 1976) by personnel at Lawrence Livermore Laboratory. Successful models for calculating fracture extent, as measured by compressive shear failure, are available; these models along with coal mechanical properties were used to design the Hoe Creek #1 fracturing program. However, as mentioned earlier, it was found that permeability is not a simple function of the degree of fracturing. Chemical properties of the coal have also been determined (Campbell, 1976; Pasternak et al., 1973; Stephens, 1972; Stephens and Miller, 1976*a*, 1976*b*). Analyses of potential in situ reactor design and operating problems have been performed by Gregg (1974*a*, *b*, *c*, 1977), Homsy and Sherwood (1976), Sherwood (1972), and Thorsness (1976). Analysis of potential pollution of groundwater has been performed by Campbell and Washington (1976), and groundwater quality field data on Hoe Creek #1 has been reported by Mead et al. (1977).

Other Institutions and Companies

The Morgantown Energy Research Center, under Department of Energy sponsorship, is concentrating on UCG of Eastern Bituminous coal, which is a swelling coal as opposed to the Western shrinking coals. This experiment was originally based on using an approach called the longwall generator, in which two parallel horizontal holes are directionally drilled (up to 200 m) and then linked; the intent with this method is to provide an aerial gasification sweep over a wide area. The economic trade off in this case is between directional holes and a larger number of vertical holes. The Soviet thermal permeability enhancement approach works best on shrinking coals; hence drilling or explosives appear to be the best alternatives for swelling coals. However, as with the line-drive technique tested at Hanna, a broad front sweep is difficult to attain for any erosive, chemical process (Dinsmoor et al., 1976). Much of the technology development at this location has been devoted to directional drilling (Shuck et al., 1976; Shuck and Fasching, 1975). One horizontal hole was directionally drilled in 1976, but it has not been used for gasification. Morgantown ERC plans instead to use the linked vertical well process with reverse combustion (which will be quite difficult). Three possible linking distances will be used: 12, 18, or 30 m. If reverse combustion does not succeed, hydraulic fracturing will be used for linkage. Testing is to begin in 1978. If this test is successful, the longwall generator approach will be attempted. Test personnel conjecture that the swelling properties of the coal may stabilize the broad reaction front and prevent channeling.

There are several other field tests underway or in the design stage. The only government sponsored project in this group involves gasification of steeply dipping beds. The lead companies in this project are Gulf Research and Development and TRW. Gulf R&D has previously conducted a limited UCG field test in Kentucky in 1969 (Raimondi et al., 1975). The other five tests are privately sponsored, will employ the linked vertical well design and include Texas Utilities (Texas lignite), Texas A&M (Texas lignite), Alberta Research Council (Alberta subbituminous coal), Atlantic Richfield (Wyoming subbituminous coal), and a New Mexico consortium (New Mexico subbituminous coal). Rather incomplete information is available on these tests either because of their proprietary nature or because only preliminary results have been obtained.

The Texas Utilities project is based on a license of the Russian technology. One linking test was performed in 1976, and current plans are to gasify a 2 m thick seam in the Wilcox formation 80 m below the surface. About 15 000 tons/yr will be consumed the first year, increasing to 50 000 tons/yr thereafter (until 1982). Details on their water quality monitoring program have been provided by Itz and Oliver (1977). Environmental analyses of water samples from this field test have been reported by Humenick and Mattox (1977). The Texas A&M project is operating in the Yegua formation at a depth of 100 m with a seam thickness less than 1.6 m. The objectives of this test have been described by Jennings et al. (1977). These two tests should provide field data for thinner seams which are hydrologically active, and some evidence on subsidence should be available from the Texas Utilities test.

The Alberta Research Council carried out a field test in 1976 on a 3.6 m seam approximately 20 m deep (Roehl et al., 1977). The site was near a strip mine, which will afford the opportunity for post test excavation. Four holes were drilled at the corners of a 9 × 18 m rectangle. The drying, linking, and gasification of the first channel went smoothly, with gas heating values ranging from 990 to 1 350 kcal/m^3. However, a successful link was not obtained in the second channel. When a line-drive from the unsuccessful link to the gasified channel was attempted, gas leakage was too severe (note the shallowness of the seam). At this point, the test was abandoned.

MODELING OF UNDERGROUND COAL GASIFICATION

A number of specific models are needed to describe quantitatively and control an underground coal gasification process. A model is needed to predict the chemical composition of the product gas as a function of the injected gas composition and rate as well as how it might vary with coal type, seam thickness, and water intrusion rate. There is a need to be able to predict the fraction of coal that will be recovered with a particular well pattern, which would require a multidimensional model possibly coupled with the chemical composition model. There are numerous other predictive models needed to quantify the particular linking process used, the environmental effects, such as subsidence and aquifier contamination, and many additional details associated with the final system design. These physical and chemical models will have to be eventually coupled with economics so that parameterized calculations can be made for the purpose of designing an economically optimized system.

Very little mathematical modeling was undertaken by the Soviets; it is rumored that the Soviet UCG modelers fell out of favor, mainly owing to erroneous predictions. Significant modeling efforts have recently been initiated in the United States; some success has been achieved with one-dimensional chemical models, which will be reported here.

System Identification

The identification of appropriate models for an in situ gasifier is not a trivial problem; it requires the definition of the gas generator and its boundaries and must concern itself with time varying phenomena (expanding reaction zone, propagating reaction zone, variable gas flow direction, geometry, boundaries, etc.). The operation of the gasification system is essentially a batch operation, and the gasifier undergoes irreversible and dynamic transformations during gasification. Merging of two or more individual gasifiers can occur (Galland and Edgar, 1973).

The coal seam contains three phases (solid, liquid, gas), and the solid phase is continuous. The pattern of contact among the three phases is important for the analysis of UCG. The porous medium (coal) can be a coherent material or be formed by the juxtaposition of many mechanically independent blocks, as in a packed or rubbleized bed. Since the gasification reaction generates much heat, fracturing and reaction occur concomitantly, although plastic deformations are possible (Sawyer and Shuck, 1976).

The reactor geometry is dependent upon design of the field (inlet and outlet borehole spacing), the seam thickness, and the point in the seam where linking is performed. If the boreholes are linked at the top of the seam, a void space is formed at the top of the seam after gasification, and reaction occurs generally in a downward direction. The reaction movement downward would be inhibited by liquid flows of slag, water, and oils. On the other hand, if the seam is linked at the bottom, there will exist a regime of operation when, depending upon the thermal characteristics of the coal, the reaction zone will be spreading along the axis of gas flow as well as normal to the flow direction. Assuming isotropic linear rates of combustion, there will be no inert fill material from roof collapse affecting the reaction until the reaction zone has propagated a distance equivalent to the seam thickness. The length of time in this fixed-bed regime is mainly a function of seam thickness. However, the next regime of operation consists of a mixed system, namely, a channel reactor in series with a fixed-bed gasifier. The length of time in this regime is mainly a function of the borehole spacing.

The gasification patterns which evolve during roof collapse are a function of the nature of the rock. The collapse of the roof can lead to the formation of channels bypassing the gasification area. In addition, communication can be established with highly permeable or water bearing strata, which can lead to considerably higher losses of blast and gas from the in situ generator, or to a higher influx of ground water. Estimates of the magnitude of these effects based on different roof collapse patterns have been given by Campbell (1975).

According to Skafa (1960), three types of changes in the state of the roof rock are distinguished. The first type is represented by a sagging of the roof rocks without any substantial break in continuity. The gasified space is thus filled in, maintaining an approximately constant specific reaction surface of the coal in the gasification channel. This helps keep the characteristics of the blast and gas flow constant (Figure 23). The second type is represented by collapse of the roof rocks with partial filling of the gasified space, due to the fragmentation and/or swelling the roof rocks during their collapse. As a result, part of the gasified space is filled with rock rubble which diverts the gas flow. This may have a favorable effect on the course of the gasification process, as in the case of the sagging roof (Figure 24), since the fragmentation of the rock yields an effective increase in volume of this material. The third type is represented by a collapse and shrinkage of the roof rocks in which the specific reaction surface of the coal in the gasification channel is not kept at an approximately constant value. This gives rise to bypass channels for blast and gas (Figure 25) when a successively larger surface area of overburden is exposed to the hot gas.

In practice, one type of roof collapse can develop into another, and different types of deformation and collapse

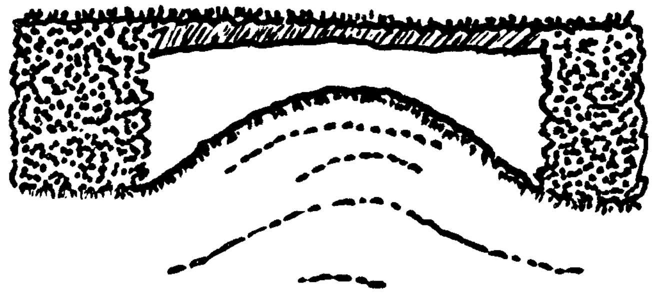


Fig. 23. Character of the filling of the gasified space due to sagging of the roof rocks.

TABLE 3. TYPICAL FEATURES OF PACKED BED AND CHANNEL MODELS

	Packed bed	Channel
1. Oxidation zone	Narrow, < 1 m.	Long, > 20 m.
2. Product gas heating value	> 130 Btu/SCF	< 100 Btu/Scf (higher CO_2 content)
3. Maximum gas temperature, °C	1 300°	1 700°
4. Outlet gas temperature, °C	300°	1 000°
5. Velocity dependence	Insensitive	Very sensitive

Fig. 24. Character of the filling of the gasified space by the collapse of the roof rocks.

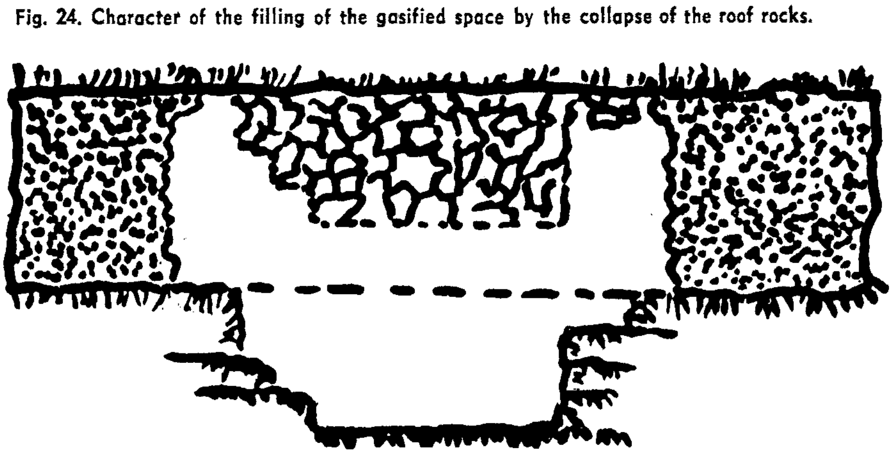


Fig. 25. Scheme of the collapse of the roof rocks into the gasified space without considerable breakdown of these rocks.

of the enclosing rocks may occur in different sections of the same channel.

Chemical Composition Models

Two basic approaches to modeling the chemistry of underground coal gasification systems have been explored, the packed-bed model and the channel model. The packed-bed model is the same as that for a fixed-bed gasifier; the channel model assumes that coal is gasified only at the perimeter of the channel. Both models probably describe the process reasonably accurately in different locations and at different times, as discussed earlier. Yet the predicted gas composition for the two models, given a common set of input parameters, differs significantly. These differences have been highlighted in a paper by Edgar et al. (1976) and are summarized in Table 3. As mentioned earlier, the UCG system is purposely designed so that at some point in the gasification channel there is a zone that can best be described as a packed bed with a large amount of surface area available for reactions. When such a zone exists, it will favorably dominate the outcome of the reactions. However, there are quite a number of field tests which have exhibited bypassing of reactors (England, Alabama, Hoe Creek), so the channel model is helpful in understanding the behavior of these tests. The most productive approach to modeling the product composition from a successfully operating underground coal gasification system is to consider the reaction zone as a packed bed. Hence the models developed for UCG will be generally analogous to those for conventional moving bed gasifiers (Yoon et al., 1977). This approach will help one describe product gas composition from a properly designed system, although the channel model is more useful for analyzing sweep efficiency.

The modeling of in situ gasification as a permeation or packed-bed process by Gunn and Whitman (1976) and Kotowski and Gunn (1976) has met with success, since recent government laboratory field test data from Hanna, Wyoming, have shown excellent agreement with their model. The only parameter fitted in their model was the water influx, which permitted closure of the hydrogen balance. While these models are only one dimensional (spatial) in nature, they provide a very good reaction product model for the Wyoming field test data. Thorsness and Rosza (1976) have developed a more extensive reaction model for a packed-bed gasifier, which consists of a larger set of differential equations.

Both the Gunn and Thorsness/Rosza models are transient models and take into account the moving reaction zone, but in different ways. The Gunn model assumes a constant front velocity (v) to convert the set of pde's (which are functions of x and t) into a set of ode's in a new variable ($\eta = x - vt$). The Livermore model assumes quasi steady state; that is, the unsteady state problem can be solved as a series of steady state problems in x.

Both models treat gasification and pyrolysis, although the pyrolysis models have only been developed for shrinking Western coals (swelling coals would create some difficulties in modeling pyrolysis under flow conditions, as discussed by Sawyer and Shuck, 1976). The Thorsness/Rosza model considers fitted kinetic models for pyrolysis data developed by Campbell (1975), while Gunn's model considers pyrolysis products from Wyoming coal to be additive with gasification of the char. This assumption is also used in modeling surface gasifiers, as discussed by von Fredersdorff and Elliott (1963). In other words, pyrolysis is much more rapid than gasification, and thus gasification occurs after pyrolysis is complete up to some arbitrary temperature. Gunn's model considers seven mass species (carbon monoxide, carbon dioxide, hydrogen, nitrogen, oxygen, water, methane) and two Equations, (1) and (2). His model in effect burns all oxygen to carbon dioxide; the heat produced then drives the endothermic carbon-steam reaction. No carbon dioxide reduction or water gas shift reaction is included. Methane is produced solely through pyrolysis. The Thorsness/Rosza model considers, in addition to the seven gas species, mobile water, fixed, water, and tar, giving a total of ten mass species. It contains eleven reactions: five char-gas reactions: (1), (4), (5), (6), and (7), coal pyrolysis, coal drying, steam condensation/vaporization, and three gas phase oxidation reactions (of carbon monoxide, hydrogen, methane).

The main equations used in both models are:

Gas phase mass balance (plug flow)

$$\frac{dC_i}{dx} = \frac{1}{v}\left[-C_i \frac{dv}{dx} + \sum_j a_{ij} R_j \right] \tag{9}$$

where the summation term involves reaction rates and stoichiometry. In Gunn's model, η rather than x is used.

Gas phase energy balance

$$\frac{dT}{dx} = -\frac{1}{vC_g}\left[h_T(T - T_s) + H_g\right] \tag{10}$$

Gas phase velocity: Gunn's model assumes constant gas velocity, while the Thorsness/Rosza model changes the velocity according to

$$\frac{dv}{dx} = \frac{-v}{P}\frac{dP}{dx} + \frac{v}{T}\frac{dT}{dx} + \frac{RT}{P}\left[\sum_i\sum_j a_{ij}R_j\right] \tag{11}$$

The Livermore model distinguishes solid temperature from gas temperature; hence, it is a heterogeneous model, which allows independent calculation of the combustion front velocity through a solid phase pde for temperature. Gunn's model, on the other hand, is homogeneous and assumes a constant combustion front velocity, which is calculated iteratively. Seventeen nonlinear equations must be solved in the Thorsness/Rosza model, while Gunn's model requires solution of eleven nonlinear ode's. It should be mentioned that the calculations of Thorsness and Rosza show that the assumption of constant velocity is very good after an initial start-up period. Gunn's model assumes kinetic control (since it is not heterogeneous), while the Thorsness/Rosza accurately uses diffusion controlled kinetics. Kinetic data based on similar coals were obtained from the literature in original testing of both models, although recent research at Argonne National Laboratory (Young et al., 1976, 1977) is aimed at developing kinetic data for Wyoming coals under conditions of underground coal gasification.

As mentioned earlier, Gunn's model gives excellent agreement with the Wyoming field test, although they have found that the product composition is not very sensitive to the kinetic parameters assumed. They have compared test data for a wide range of air injection and water influx rates and have found good agreement. Thorsness and Rosza (1976) have shown that their model gives satisfactory agreement with combustion tube data.

While excellent agreement between test data and model is encouraging, it certainly does not indicate that the models developed to date are sufficient for predicting all aspects of gasification behavior. The lack of sensitivity of Gunn's model to kinetic parameters has been noted above. The reason behind this is that the char-steam Equation (5) goes to completion, with very little conversion of carbon monoxide to carbon dioxide via the water-gas shift Equation (6). Thus there are no kinetic or mass transfer limitations. The heat produced in the oxidation zone is used to drive the endothermic char-steam equation. Other heat sinks include the heat loss to overburden and underburden and the sensible heat of the product gas and ash left behind. In Gunn's model, the amount of carbon dioxide is predetermined by the fixed carbon content of the coal and is, in a sense, diluted by the production of carbon monoxide and hydrogen. Low water/air ratios, such as experienced in some of the Hanna tests, would be conducive to little or no water gas shift reaction.

On the other hand, recent test data from the Hoe Creek tests have shown that the total water flux does not participate in a chemical reaction sense. A large amount can intrude outside of the reaction zone, is vaporized, and recovered as steam. In this case, the reaction products can be adequately predicted using algebraic (material and energy balance) equations. Batchelder and Steinberg (1950) have proposed such an approach for modeling gas composition for fixed-bed producers. These equations require selection of the water gas shift equilibrium constant (at some properly chosen temperature). An equivalent approach is to assume that in the oxidation zone some mixture of carbon monoxide and carbon dioxide is formed (rather than all carbon dioxide); Jennings et al. (1977) have compared such an algebraic method with combustion tube data and found it satisfactory.

Gunn et al. (1976) have also compared their fixed-bed model with Russian field data in order to evaluate the effects of air injection rate, oxygen enrichment, water intrusion, coal ash content, coal seam thickness, and pressure. While only semiquantitative comparison was possible owing to incomplete information on coal characteristics and water influx, the composition model did give the right trends in most cases.

The models described above also do not attempt to predict detailed pyrolysis behavior of a given coal during UCG. If the one-dimensional model is indeed valid as an approximation, pyrolysis products are additive with char gasification. However, the total amount of tars and oils produced at the Hanna site is only about 5% of the total energy content of the coal reacted; the weight of tars and oils is only a fraction of the Fischer assay of the Hanna coal. This means that the one-dimensional zoned model (Figure 12) may be inadequate for predicting gas composition, especially for methane, ethane, and other hydrocarbons produced by thermal cracking of tars and oils. Similar conclusions for conventional moving-bed gasifiers have been reached by Yoon et al. (1977). Two explanations for this occurrence can be proposed; one involves pyrolysis of the coal (at slow heating rates) and then deposition of the tars and oils as they cool further downstream. These materials then are repyrolyzed and/or combusted. An alternative concept is embodied in an earlier discussion in this paper. The existence of lateral reaction zones as well as axial ones is proposed there; namely, at a burning coal face, zones of oxidation, pyrolysis, and drying are set up in an outward direction into the virgin coal. Owing to the pressure gradient around the reactor (assuming that the in situ gasifier operates at a pressure lower than the hydraulic pressure underground), steam and pyrolysis products must pass into the burned-out region. In so doing, they pass through the oxidation zone of the burning coal face and are cracked to lower molecular weight components. Steam produced in the drying zone can also react with hot char. Forrester (1976, 1977) has performed block pyrolysis experiments on 16 cm diameter cylinders of Western subbituminous coal at heating rates from 1° to 3°C/min. When the products of pyrolysis are compared with those for small particles (Campbell, 1976*a*), it is evident that measurable char and tar gasification takes place for pyrolysis temperatures over 600°C, due to the formation of steam inside the cylinder. Further laboratory experimentation such as that by Young et al. (1977) needs to be performed to quantify the interaction of oxidation, reduction, pyrolysis, and drying zones at a burning coal face.

Another unanswered question in the modeling activities is how one should combine a product composition model with a sweep efficiency model. It does not appear that the two models can be completely decoupled, mainly because both models are strongly affected by the energy balance, which in turn depends upon the reaction products. More details on sweep efficiency modeling are given later.

Modeling of channels was first performed to explain anomalous behavior of surface gasifiers. The physicochemical behavior of a gasification channel has been discussed by Frank-Kamenetskii (1955) and Thring and Essenhigh (1963). The latter authors have presented a simple model for a turbulent channel surrounded by carbon with constant radius. Assuming a surface reaction which is first order in oxygen concentration and unaffected by temperature, they obtain an exponentially decreasing oxygen concentration, or

$$C = C_o \exp\{-f\, k_1 x / v\pi\} \tag{11}$$

The exponentially decreasing oxygen profile is essentially the same as that obtained by Magnani and Farouq Ali (1975), Stewart and Wall (1976), and Dinsmoor et al. (1976) for more complicated nonlinear models. However, these three models include many of the pertinent UCG phenomena, such as water influx and heat transfer to the overburden.

The reaction rate from Equation (11) averaged over the length of the tube is proportional to

$$v\,[1 - \exp\{-f\, k_1\, L/v\pi\}]$$

Therefore, with this model it could be concluded that as the velocity of the channel increases, the overall rate of reaction can decrease owing to the decreased residence time in the tube, thus reducing the yield of products and increasing the oxygen content of the exiting gas.

On the other hand, one can argue that near the laminar/turbulent transition point, the rate of reaction is diffusion controlled and can increase markedly with increases in the velocity. Thus, for a channel operating under such heterogeneous reaction conditions, there will be an optimum velocity (blast rate) which maximizes the rate of reaction, due to combined effects of residence time and mass transfer rates. Such an optimum blast velocity was observed for the Newman-Spinney trial (Gibb, 1964), where horizontal boreholes were drilled for linking purposes.

However, in a channel, the occurrence of gas phase oxidation of carbon monoxide to carbon dioxide becomes much more significant relative to the heterogeneous reactions, owing to the limited amount of surface area. In order to better define the dominant mode of carbon monoxide generation in a channel, Szekely and Maroudas (1966) have analyzed the three zone theory of Thring. Using a classical transport phenomenon approach to treat the diffusion of carbon monoxide from the reacting surface into the gas phase, they performed an analogue reactor simulation for the expected range of diffusion and reaction rate coefficients. These data led Szekeley and Maroudas to conclude that in the presence of gas phase oxidation, the production of carbon monoxide in a channel could only proceed by reduction of carbon dioxide to carbon monoxide on the hot carbon surfaces, rather than by primary formation of carbon monoxide at the reaction surface and escape of carbon monoxide from gas phase oxidation.

Gasification channel simulations by Dinsmoor et al. (1976) have also demonstrated the unimportance of primary carbon monoxide production on product gas yields, since all carbon monoxide formed in the oxidation zone is rapidly oxidized to carbon dioxide in the gas phase.

Other evidence for gas phase oxidation of gaseous species (carbon monoxide, hydrogen) is due to Derman et al. (1963). In this laboratory study, the gas phase temperature rose above the solid phase temperature at some intermediate point axially. This profile is in disagreement with those developed by Magnani and Farouq Ali (1975*a*, *b*), which show the gas phase temperature asymptotically approaching but not exceeding the solid temperature, due to the omission of gas phase reactions in their model.

The effect of moisture, ash, and volatile content of the coal and the oxygen content and flow rate of the blast on the quality of the product gas and rate of displacement of the reaction zone have been investigated on laboratory scale systems by Lavrov (1957), Derman et al. (1963), Kreinin (1962*a*, *b*), Yanagimoto et al. (1967, 1968*a*, *b*), Ishikura (1965), Pitin et al. (1963), and Dziunikowsky (1960) and are as follows:

1. The velocity of the fire front is proportional to oxygen concentration in the blast stream and inversely proportional to the coal moisture content.
2. The combustion temperature increases with oxygen concentration in the blast stream and reaches a maximum of 30 to 35% oxygen, after which it declines.
3. The combustion temperature is inversely proportional to the moisture content.
4. For each coal rank, there is a minimum oxygen concentration in order for the combustion front to advance; below this value there is no movement.
5. For each coal type, there is an upper bound on allowable moisture content, above which the combustion front does not move for air injection.

These studies are reminiscent of similar research on moving reaction zones in packed-bed catalytic reactors, for example, Vortmayer and Jahnel (1972), and on heavy oil recovery (Berry and Parrish, 1960). Hokao (1962, 1964, 1965) has presented a set of theoretical models for movement of the fire front along the wall of a gasification borehole and in a coal bed, but these models are based on simplifying assumptions which are somewhat unrealistic. Krantz and Gunn (1977) have recently performed a stability analysis for reverse combustion, which allows them to calculate finger size. Such an analysis would allow a priori design of linking compressors.

Heat Transfer and Channel Growth During In Situ Gasification

For a model of heat transfer in the solid phases, particularly the coal, Loison (1953), Warner et al. (1962), and Wang (1969) have investigated the distribution of temperature around a gasification system assuming an isotropic medium of constant effective conductivity: their calculations confirm experimental observations. For example, Loison (1953) and Stewart and Wall (1976) have calculated that heat effects around the reaction zone of a unit are limited to a narrow layer (1 to 2 m) in the solid close to the reaction surface.

The calculation of the heat transfer by conduction into the virgin coal requires the consideration of a moving (burning) coal surface at some reaction temperature T_w in a porous medium initially at T_∞. The solution to the general moving boundary problem for heat conduction in a semiinfinite medium is well known; Wong (1975) has recently considered its application in UCG, allowing for convective effects of pyrolysis products and water vapor into the void space (at $x = 0$). For rectangular coordinates, the solution for standard simplifying conditions is

$$x \leq x_w \quad T = T_w + \{\exp[V/\alpha(x_w - x)] - 1\} \left[\frac{\epsilon_w \rho_w h_{fg}}{C} + T_w - T_\infty\right] \tag{12}$$

$$x > x_w \quad T = T_\infty + (T_w - T)\exp[-V/\alpha\,(x - x_w)] \tag{13}$$

x_w is given by

$$x_w = \alpha/V \ln\left[1 + \frac{T_\infty - T_w}{(\epsilon_w \rho_w h_{fg}/C) + (T_w - T_\infty)}\right] \tag{14}$$

For the above heating rate, the heated zone (where water is vaporized) spans approximately 30 mm. This indicates that not much heat is lost to the surrounding strata. If one assumes that the water vapor produced moves the opposite direction to the combustion front, creating a transpiration effect, the heated zone is calculated to be even smaller. This calculation indicates why a conduction driven phenomenon such as backward burning does not provide much sweep efficiency; that is, it creates narrow channels. On the other hand, forward burning proceeds by convective mechanisms and hence is not subject to the restrictions mentioned above.

The enlargement of the combustion channel is basically controlled by heat transfer phenomena. As the channel expands, the local reaction rate is reduced owing to a drop in the linear gas velocity (the combustion reaction is mass transfer controlled). Once the combustion focus reaches the top of the seam, the roof strata become exposed to the hot gases. Further combustion causes progressively more of the roof strata to be exposed to the combustion gas, while the reaction surface remains roughly the same.

The heat transfer to the overburden is complicated by the fact that the actual heat transfer area is unknown. Thermal fracturing of the coal or overburden creates a much enlarged effective surface area due to cracks and fissures. The final shape and size of the reactor will always be site dependent. Therefore, this term may be one that must be estimated in the field, since there is some uncertainty regarding the thermal diffusivity and composition of the overburden, especially at high temperatures. Hence it may be convenient in practice to lump these effects into a single term.

As discussed earlier (Figure 18), heat losses by conduction become relatively more important as the seam thickness decreases. Simulation runs for a growing channel have shown this effect (Dinsmoor et al., 1976), but a simple model is just as instructive. Consider a rectangular channel of width W and height H, where the hot gases transfer heat over the rectangular faces (proportional to $W + H$) and heat is generated by the surface reaction, which is proportional to H. For thin seams ($W >> H$), the relative amount of heat losses is thus proportional to W/H. As H decreases for thinner seams, the relative heat losses increase.

Warner and Szekely (1965) have considered a simple heat transfer model for enlargement of the channel. As the cavity enlarges, more surface area is exposed; the maximum width of the combustion channel is reached when the heat generated by the reaction zone equals the heat losses. Rather than using the moving boundary solution discussed earlier, they assumed the solution of unsteady state conduction in a semiinfinite slab with heat losses to the overburden only (area equal to $2W$). The solution for the heat flux in this case is

$$q = k(T_w - T_\infty)/\sqrt{\pi\alpha t'} \tag{15}$$

The rate of heat generation is given by

$$Q = V H \rho_c h_c \tag{16}$$

The velocity of the combustion zone is not constant in this model but is assumed to decrease as the cavity size grows (this step utilizes an empirican constant K'); this accounts for possible diffusion limitations. The derivation developed by Warner and Szekely erroneously used $\sinh^{-1}$ instead of $\sin^{-1}$, as pointed out by Young (1974), and the final corrected equation for the maximum half width Y is

$$Y = \frac{\rho_c h_c H}{2k(T_w - T_\infty)\, 1.5708} \sqrt{\frac{\pi \alpha V_o}{2K'}} - \frac{0.5708}{1.5708\, K'} \tag{17}$$

Therefore, this model predicts that the maximum half width is proportional to the seam thickness (H), coal calorific value (h_c), and to the square root of the initial burn velocity (V_o). It is inversely proportional to the heat loss, as given by $T_w - T_x$. This model also assumes that a vertical coal face is maintained during the cavity expansion. More details on the thermal fracturing and disintegration of a coal face might provide a more realistic estimate of cavity growth. Corlett and Carson (1977) have discussed several approaches to analyzing this problem in terms of crack and fissure formation.

Another interpretation of channel growth has been advanced by the model simulations of Dinsmoor et al. (1976) and Edgar et al. (1977). Their analysis indicates that the channel width stabilizes (ceases growth) at a point where the flow approaches the laminar flow regime. At this stage, the reaction zone does not expand but propagates, as a consequence of the diffusion controlled reaction. As discussed by Edgar et al. (1977), the growth of the channel depends upon the relative balance of heat generation (due to reaction) and heat losses (convection and radiation to the gas stream, evaporation of intruding water, and conduction into the virgin coal and overburden). Galland and Edgar (1973) have calculated that radiation is the predominant mode of energy transfer between the solid surfaces and the gas phase in the reaction zone for channels of the size of 1 m. For smaller channel sizes, convective heat transfer becomes progressively more important. The actual exchange is a function of the gas composition; in general, the nonoptically thin gas phase screens a part of the radiative exchange.

The above mathematical model, which initially assumes a cylindrical channel in a bed of coke, consists of gas species balances (including gas phase oxidation) and gas and solid energy balances, and employs the pseudo steady state assumption to simulate channel growth. As the gas velocity is reduced owing to growth of the channel, the diffusion controlled oxidation rate is reduced. Ultimately, heat losses overcome heat generation, and loss of ignition results. Oxygen bypassing becomes progressively more severe during the cooling down of the coal face, and the oxidation zone extends over most of the channel length. A gradual increase in flow rate as the channel grows in size might overcome these negative effects, but no test of such a strategy has been performed.

Other models proposed to model sweep efficiency have been advanced by Jennings et al. (1976) and Thorsness et al. (1977). The first model completely decouples the flow and chemical reaction/energy problem and assumes that the flame-front moves at a rate which is directly proportional to the air flow rate. The progression of the reaction is determined by finite-difference solution of the pressure flow grid network. The authors claim that the limited Hanna field data agree with their model predictions. However, this model suffers from ignoring the heat transfer/reaction characteristics and thus does not predict the effects of gasification intensity, seam thickness, coal rank, and oxygen concentration. Hence, it is of limited utility. Thorsness et al. have attempted to apply existing fluid flow and heat transfer codes to the expansion of a gasification cavity. An overall gasification/pyrolysis reaction was used, rather than a series of species equations. The model consisted of energy balances for the solid and gas and a mass balance incorporating Darcy's law and the ideal gas law. While qualitative trends were correct, further testing of the model is required. Features to be added to the model include a means of distributing water influx to the seam and diffusive transport of reactants to the burning coal face.

THE FUTURE OF UNDERGROUND COAL GASIFICATION

The commercialization of UCG in the United States will certainly occur in the next 15 yr. Successful field tests on the linked vertical well process prior to 1980 can only accelerate the use of this technology. Early applications of the technology will probably occur in Wyoming owing to the favorable seam thicknesses and other geological conditions, and in Texas, where there is a tremendous demand for low and medium Btu gas. The locations of current field tests conform with this prediction. As mentioned previously, the chief technological questions center around the extrapolation of previous field results, especially in Russia, to specific sites in North America. Of course, while the economics of UCG are presently attractive, use of in situ gasification, as with other synfuel processes, is dependent upon the price of primary fuels such as natural gas and oil. Economic studies for producing low, medium, and high Btu gas via UCG have been performed by Buder et al. (1976), Garon (1976), Moll (1976), Bidlack and Arscott (1976), and Mason and Hall (1976).

The major technical challenges for UCG currently recognized include optimization of the basic process design variables (for example, well spacing, production pressure), determination of the best methods for seam preparation for a variety of coals, development of cost-effective instrumentation, use of oxygen/steam for gasification, a better definition of the geological factors in water influx and gas leakage, analysis and minimization of groundwater pollution by organic and inorganic materials, and determination of subsidence effects. These technical problems will require both field and laboratory research in order to realize their solution; undoubtedly chemical engineers can play a major role in this research and development effort.

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NOTATION

a_{ij} = stoichiometric reaction coefficient
C = solid specific heat
C_g = gas phase specific heat
C_i = concentration of i^{th} species
C_o = initial concentration of oxygen
f = constant
H = seam thickness
h_c = coal heat of combustion
h_{fg} = latent heat of vaporization (water)

H_g = energy input to gas phase by chemical reaction
h_T = heat transfer coefficient
k = thermal conductivity
k_1 = rate constant for oxygen disappearance
k' = constant
L = channel length
P = pressure
q = heat flux due to conduction
Q = heat generation rate
R = gas constant
R_j = reaction rate expression
t, t' = time
T = gas temperature
T_s = solid temperature
T_w = wall temperature
T_∞ = virgin coal temperature
v = gas velocity
V = coal linear burning velocity
V_o = initial linear burning velocity
W = width of cavity
x = spatial coordinate
x_w = location of drying front

Greek Letters

α = thermal diffusivity
ϵ_w = water volume fraction
η = transformation variable
ρ_c = coal density
ρ_w = water density

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