

Technical Paper Number 4

**RESEARCH AND PROGRESS
IN THE
PRODUCTION AND USE OF COAL**

By

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October 1941

This document is one of a series of technical papers supplementing the reports of the National Resources Planning Board. The contents of these papers are the sole responsibility of the authors and do not necessarily bear the endorsement of the National Resources Planning Board.

NATIONAL RESOURCES PLANNING BOARD

Contents

	Page		Page
Introduction	IV	Carbonization (cont'd)	
Mining		Future Research on Coal Carbonization	31
Review of Gains in Recovery of Coal	1	Plasticity of coal	31
Problems of mechanization	2	Expansion of coal	31
Loading devices	2	Coke-and byproduct properties of coal	31
Improvement of strip-mining methods	3	Utilization of subbituminous coals	32
Conservation of coal deposits	5	Gasification	
Reclamation of stripped areas	5	Introduction	33
Relation of Gains in Recovery		Gasification by Destructive Distillation	33
to Research Progress	6	Historical	33
Cutting	6	Fundamental research	34
Drilling	7	Recent developments	35
Breaking down coal	8	Gasification of Coal and Coke by Chemical	
Roof support	9	Reaction with Air and Steam	35
Mechanical loading devices and		General considerations	35
transportation	10	Fundamental chemistry of	
Ventilation	12	gasification reactions	36
Strip mining	13	Mechanical developments increasing	
Safety	14	efficiency in generation of producer	
Summary	14	gas and blue water gas	36
Underground mining	14	Developments in the Generation of	
Strip mining	15	Producer Gas	37
Safety	15	Historical review	37
Appraisal of Direction and Adequacy of Gov-		Stationary producers	37
ernmental Research in Production Technique	16	Mobile producers	37
Preparation		Developments in the Generation of Blue	
Gains in the Recovery of Coal	17	and Carbureted Water Gas	38
Research Progress	18	Historical review	38
Adequacy of Governmental Research	19	Developments in production technology	38
Combustion		Use of fuels in carbureted water-gas set	38
General Progress in Utilization	20	Generator fuels	39
The heating field	20	Enrichers	39
The stationary steam and power field	21	Utilization of waste heat	40
The locomotive field	23	Complete Gasification of Coal	40
The marine field	23	General considerations	40
The ceramic field	23	Recent developments	41
The metallurgical field	24	Gasification of Solid fuels with oxygen	41
Functions of Governmental Research	24	Continuous Gasification of Pulverized coal	42
Future Trends in Governmental Research	27	Gasification of Low-Rank Coals	42
Carbonization		Subbituminous coal and lignite	42
Industrial Developments	28	Peat	42
High-temperature carbonization	28	Gasification at the Mine	43
Low-temperature carbonization	29	Gases as Chemical Raw Materials	43
Medium-temperature carbonization	29	Future Research on the Gasification of Coal	43
Research on the Carbonization of Coal	29	Hydrogenation	
Coal composition	29	Introduction	45
Plasticity of coal	30	Hydrogenation of American Coal	46
Blending coals and inerts	30	Estimated Costs of Production	47
Expansion of coal during carbonization	30	Time Required to put Hydrogenation	
The BW-AGA method of experimental		on Commercial Basis	48
carbonization	30	Hydrogenation of High-Temperature Tar	48
		Suggested Program for Future Government	
		Research	48

RESEARCH AND PROGRESS IN THE PRODUCTION AND USE OF COAL

By A. C. Fieldner¹ and W. E. Rice²

Abundant supplies of high-grade coal are among the most important of the natural resources which made possible the spectacular industrial growth of the United States; it is apparent that coal will be even more important in the future. The supply of coal is not so vast that this Nation can waste it with reckless abandon. Loss and waste attend in both production and utilization. Much coal is left in mines in such condition that it never can be recovered. Some is lost in preparation. Some is wasted in utilization owing (1) to inefficient methods, and (2) to the use of high-rank coal when the more plentiful coals of lower rank could be used.

For more than 20 years the depletion rate of coal reserves has been decreased by greater use of petroleum, natural gas, and other sources of energy, and by increased efficiency of utilization. Ultimately the supplies of petroleum and natural gas will be so depleted that the uses they serve must be served by fuels produced from coal. The depletion rate of coal, therefore, will increase, and the development of more efficient methods of production and utilization through research will assume added significance.

In the following discussion, *production* is treated in two sections: (1) *mining*, and (2) *cleaning and other preparation*. In the first the term "recovery" designates the proportion of coal removed from a mine in relation to the total in the bed; in the second, "recovery" designates the proportion of the feed to a preparation plant recovered as marketable coal for shipment.

Utilization is treated in four sections:

(1) *Combustion*, (2) *carbonization*, (3) *gasification*, and (4) *hydrogenation*. Combustion, or burning to liberate heat, was the first use to which coal was put. Later the carbonization of coal to produce coke, a solid fuel in a form more suitable for the smelting of ores, particularly for the production of iron, became an important use. This was followed by various processes of gasification in which a part of the thermal energy is made available in combustible gases having greater form value than solid fuel because of the convenience with which they can be used. Early experience in carbonization and gasification by destructive distillation has resulted in the development of byproduct coke ovens; these permit the recovery of liquid and gaseous fuels and other byproducts wasted in earlier methods of carbonization. Apprehension over the possibility of depletion of petroleum has led to efforts to convert coal into liquid fuels essential for automotive, marine, and aerial transportation, and for generation of heat, light, and power in isolated places. The methods employed are direct liquefaction of coal by hydrogenation and synthesis from gases produced from coal. In the United States there has been no commercial development of either process, and research thus far has been limited to the hydrogenation process.

The Bureau of Mines is surveying the yields and quality of liquid fuels obtainable from various kinds of American coals. Preliminary tests indicate that both bituminous and lignitic coals can be liquefied. The largest yields are obtained from the higher-rank coals.

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MINING

By Albert L. Toenges¹

Review of Gains in Recovery of Coal

Progress in the technique of mining was slow until the introduction of mechanized loading. The cutting machine was a step forward but did not increase markedly the proportion of coal recovered. Output was fixed, as a rule, by the physical fitness of the loaders and the aggregate output of individuals. The miner was an independent contractor, and supervision over his working place was superficial. The increased cost of labor with consequent rise in cost of production, which resulted in the necessity for higher selling prices of the product and the inroads of other fuels, presented the problem of increasing the output of the individual and reducing the production cost per ton. In 1923 the amount of coal loaded mechanically was only 0.3 percent of the total production of bituminous mines in the United States. By 1929 this was increased to 7.4 percent, and in 1937 the amount of coal loaded mechanically was 20.2 percent of the total.²

The introduction of loading devices into mines required that they be adapted to the systems of mining in use or that systems be altered to fit the machines to give the best results. Supervision also had to be increased as output now depended upon the proper operation of the machine rather than upon the physical fitness of the individual.

Large investment is necessary to equip a mine for mechanical loading, and to reduce the fixed charges per ton, the working area should be so planned that the maximum tonnage can be obtained from a given territory. In some areas such equipment

resulted in changes in the system of mining that effected a higher recovery than was possible with hand-loading methods. Hence, the introduction of mechanical loading has been a factor in increasing the recovery in some districts.

As a rule, in mines that load coal mechanically the rate of extraction is more rapid than in those that employ hand-loading methods. Roof conditions likely will cause less trouble if extraction is rapid, as the coal usually is removed before the full effect of the roof action is operative. Many pillars that normally would be left to support the roof in working places can be withdrawn if rapid retreat from the area is possible. The room-and-pillar system of mining with some variations is the one most common in coal mines. In mines where pillars are not withdrawn the average recovery ranges from 50 to 60 percent, and in those where the coal from pillars is extracted the average recovery is 83 percent.

Mining operations in the Paris coal basin of Arkansas, in which the coal bed ranges from 18 to 34 inches in thickness, had virtually ceased in dipping beds mined by the room-and-pillar system. The introduction of a longwall system of mining, which results in approximately complete extraction of the coal bed, and the installation of mechanical loading devices have revived the industry in that field and a high-grade fuel that otherwise could not have been mined economically is now extracted.

In Wyoming the use of self-loading head conveyors has permitted the withdrawal of pillars and resulted in an increased recovery from the bed. The rate of extraction is more rapid than when the coal was loaded by hand, and the roof action is not operative until after the coal is withdrawn from the area.

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² Bureau of Mines, *Minerals Yearbook*, 1939, p. 771.

Problems of Mechanization

Mechanization has brought problems to the industry, particularly one of producing coal free from foreign impurities. In loading the coal by hand the miner can discard the impurities such as partings, bony coal, and clay veins. The mobile loading machine cannot make this separation at the face but loads the broken coal irrespective of the impurities in the bed. This practice necessitates the erection of mechanical cleaning plants at the mines. The output from these plants is not only of higher quality than the hand-cleaned coal but the coal cuttings from the cutting machines, which formerly had been discarded, are now loaded underground and cleaned mechanically. The coal-cutting machine never has been considered a factor in conservation. The cuttings contain a large proportion of fine coal and impurities from the bottom of the bed. At some mines these cuttings were shoveled aside because of their high ash content. As the undercut ranges from 4 to 6 inches or more in height, the loss from cuttings is a large proportion of the total thickness of thin beds. Thus, the necessity of cleaning mechanically the coal loaded by machine made possible the recovery of cuttings that previously had been discarded at some mines. The recovery at such properties was increased materially.

In some districts, however, principally in the Central and Midwestern States, pillar extraction is not practical because of the value of the overlying surface. The withdrawal of pillars results in subsidence of the surface and consequent decrease in the value of agricultural land. Operators who own mineral and coal rights but not surface rights have been reluctant to permit the surface to subside and thus to be subjected by the owner of the surface to costly damages.

Loading Devices

Various types of mechanical loading devices are used: mobile loading machines, either track or crawler mounted; conveyors, with or without self-loading

heads; and scrapers.

Mobile loading machines are best suited to the mining of level beds of coal or to working on the strike of pitching beds. However, they have been used to a limited extent in working places that pitch as much as 12-1/4 percent upgrade to 23 percent downgrade. Until a few years ago this type of loading machine was so constructed that it could be used only in thick beds. However, machines of high output now are being built to be used in beds as thin as 30 inches.

Conveyors are either the chain or shaking type. The coal may be loaded by mobile loading machines or by hand onto conveyors that transport it from the working place to cars placed in the entry or passageway. At some mines, the coal is loaded onto shaking conveyors by self-loading heads attached to the conveyor. Conveyors are suited particularly to mining thin beds but work satisfactorily in thick beds on heavy pitches. As conveyors can be operated in a narrow space, they can be used where the roof is not good. In the thin beds of Alabama, the Southwest, and parts of Pennsylvania, West Virginia, and other States, the use of conveyors has made possible the recovery of coal that could not be mined economically by other methods at this time.

Scraper operation is most satisfactory where the roof does not require close timbering at the face; irregular bottom or floor, however, hinders scraper work. This device also is suited to the extraction of coal from thick, pitching beds that do not permit the use of other types of equipment and has been used to advantage in driving brushed entries in low coal where roof or bottom must be excavated to obtain height for haulage equipment. Under favorable conditions (good roof, hard and smooth bottom with no excessive dips, market for smaller sizes of coal), scrapers should show a lower total cost per ton (slightly less labor cost and considerably less investment) than conveyors in beds of the same thickness. Where physical conditions permit, conveyors or scrapers are well

suitable to the extraction of coal in mines using a longwall or modified longwall system of mining.

A loading device or scow developed in the Paris field and best adapted to thin beds in which the soil separates easily from the roof, is compact, and falls without disintegration is of interest, although its application is limited. The system of operation has been described by the Bureau of Mines.³

It is believed that as the thicker beds of coal are depleted the thin beds can be mined economically by the introduction of mechanized devices for loading coal. The rapid development of loading equipment, however, has added to the complexity of mechanical mining. Careful planning is required for the return of capital before the equipment becomes obsolete. Coordination of every operation is necessary. A study of methods to coordinate transportation with loading is essential and should reveal a way to increase the output per unit and hence reduce the cost per ton.

In mechanizing mines the machinery introduced must suit certain physical conditions: Height of coal, character of roof and bottom, dip of bed, and production

³ Toenges, Albert L.: *Longwall Mining Methods in Some Mines of the Middle Western States*, Bureau of Mines, Information Circular 6893, 1936, pp. 46-55.

desired. However, the ultimate success of mechanization depends upon a thorough understanding of the problem involved and coordination of all operations—cutting, shooting, timbering, loading, and transportation. The men working with the machines should be trained properly and educated to conduct the operations safely.

Improvement of Strip-Mining Methods

In recent years progress in the technique of mining coal by the stripping method has been rapid. If the topography of the area and the depth to the coal bed favor stripping, the production of coal by this method is a large proportion of the total. The output of strip coal has increased rapidly in some States, as indicated in the accompanying table.

In the early days the overburden of coal beds that outcropped or lay at shallow depths was removed by teams and scrapers, and the coal was loaded by hand into barrows or wagons. It was impracticable to mine the coal by underground methods because of the weak overlying strata. As the overburden became thicker, this method ceased to be profitable, and the railroad-type steam shovel was introduced. Although this machine was an improvement over stripping with teams and could remove thicker overburden, its use was limited by its lack of flexibility. The revolving-type steam shovel mounted on

Production	Illinois	Indiana	Missouri	Kansas	United States
1924:					
Tons ¹	2,295,860	2,511,189	979,700	795,074	13,606,954
Percent ²	3.4	11.7	39.5	18.7	2.8
1937					
Tons ³	11,448,732	8,281,002	2,654,167	1,966,651	31,750,853
Percent	22.2	46.6	64.9	68.0	7.1

¹ Toenges, A. L., and Anderson, R. L.: *Some Aspects of Strip Mining of Bituminous Coal in Central and South Central States*, Bureau of Mines, Information Circular 6959, p. 7.

² Total State production of strip coal.

³ Bureau of Mines, *Minerals Yearbook, 1939*, p. 791.

short sections of railroad rail was the next advance in equipment. This was flexible in operation and effected economies that permitted the removal of thicker overburdens. A small shovel developed for loading coal replaced hand loading. Instead of being hauled in wagons, the coal was loaded into boxes in the pit and hoisted by a derrick to car trucks operated on a track on the high wall. Later, tracks were laid in the pit, and cars were loaded there; or if the track was laid on the high wall the cars were loaded outside the pit with a skip operated from a derrick equipped with a hoist (locally called a bank machine). The steam shovel had certain disadvantages, including the necessity of building water reservoirs and running pipe lines to the shovels. The demand for coal is greatest in the winter, and during extremely cold weather it was difficult to maintain the long water lines without which the steam shovels could not operate. The application of electricity to stripping and loading shovels mounted on crawlers was the next advance, and today virtually all large strip mines are electrically equipped. Haulage equipment kept pace with these improvements, passing through the various stages from small wooden cars to large steel cars and to motorized equipment if conditions warranted this type of haulage. Progress was gradual at first, but during the past 10 years improvements in equipment and operating technique have been rapid. Stripping shovels with a dipper capacity of 32 cubic yards and coal-loading shovels with a dipper capacity of 7 cubic yards are in use today. The capacity of mine cars ranges from 15 to 70 tons and of motorized units from 6 to 30 tons. One operator is experimenting with a unit of 80 tons capacity; this is operated with gas-electric power.

Strip mining is particularly adapted to coal beds that outcrop or lie at comparatively shallow depths. The thickness, physical and chemical characteristics, and dip of the coal bed; composition of the overburden; and the topography deter-

mine the extent of mining in strip areas. These are generally irregular and narrow, and few exceed a half mile in width. The area of strippable coal in a State usually is only a small proportion of its total area. In Illinois the area estimated to contain coal that can be mined by stripping is approximately 0.30 percent of the total area of the State. The percentage of strip acreage in the other States probably is less.

The stripping shovel, when uncovering the coal, generally works back and forth across the property and deposits the overburden in more or less parallel ridges, which vary in height according to the amount of material deposited or thickness of the overburden. Narrow valleys ranging in depth from 16 to 20 feet are formed between the ridges. The width of the final cut in an area after all minable coal has been removed varies with the depth from the surface to the coal. The coal-loading shovel follows the stripping shovel and loads the coal into large motorized haulage units or cars. In some regions the topography is rough, and the coal beds outcrop on the sides of valleys; stripping then follows the contour of the hills. Systems used in mining coal by stripping have been described by the Bureau of Mines.⁴

The proportion of coal recovered from any tract of land by strip mining depends upon physical and economic conditions, some of which follow:

1. Sometimes the cost of removing the additional overburden in local dips in the coal which involve excessive digging grades, is greater than the value of the coal recovered; the stripping shovel may pass over such grades instead of digging down to the coal, particularly in thin beds, and the coal in the dip is lost.

2. At some places the spoil banks are of such character that they slide, especially when wet, and some coal is lost in small berms left at the edge of the spoil bank.

⁴ Toenges, Albert L., and Anderson, Robert L.: *Some Aspects of Strip Mining of Bituminous Coal in Central and South Central States*, Bureau of Mines, Information Circular 8959, 1937, 87 pp.

3. In thick beds the loss of coal from the top of the bed and failure of the loading shovel to dig to the bottom will not reduce the proportion of coal recovered as much as in thin beds, that is the proportion of recovery from thick beds is usually larger than from thin beds.

4. Horsebacks or clay veins reduce the recoverable tonnage owing to difficulties presented in loading coal free from impurities. Most large strip mines are equipped with modern preparation and mechanical cleaning plants, and little or no cleaning is done in the mine. The entire bed is loaded with impurities; these later are removed mechanically in the cleaning plant.

Improvement in equipment and mining technique has reduced the losses in the forementioned classes of probable loss.

Conservation of Coal Deposits

Advances in strip mining have proved this method invaluable in the conservation of coal deposits. The recovery of coal in underground mining in the States where strip mining is important ranges from 50 to 60 percent. Strip mining recovers the maximum amount of coal from a given area, (75 to 95 percent)⁶ and prevents waste of a natural resource that cannot be replaced.

Where the coal beds lie as deep as 60 feet below the surface (at greater depths for short distances) the stratum or roof above the coal bed is generally friable and difficult to hold. Coal mined under these conditions cannot compete on an equal basis with coals from more favorably situated mines. Some of these underground mines have been abandoned or operations greatly curtailed, and others have since been developed by stripping methods, so that coal which otherwise would have been lost is now being recovered.

Thin beds of coal 14 to 24 inches thick are being mined successfully by strip-mining methods. It is doubtful whether physical and economic conditions will ever permit these beds to be mined by any

other method. In southeastern Kansas, where a bed averaging 3 feet in thickness is being mined by underground methods, it is estimated that 75 percent of the coal bed more than 2-1/2 feet thick has been depleted.⁶ Strip mining of the thinner and shallower beds will prolong the life of this field.

The coal in these areas is of relatively poor quality and for this reason must be sold at a reduced price, if at all. Underground mining is therefore not profitable, but possibly strip mining with large-capacity equipment, might pay. These areas therefore contain potential coal reserves.

Reclamation of Stripped Areas

A contrary phase to conservation in strip mining is the overturning of the land, which makes it useless for a time. The author studied extensively the reclamation of stripped areas; the findings of this investigation have been published.⁷

Erosion begins soon after the land has been turned, soil forms, and in many areas the land is restored by natural means. This process of restoration is slow, but land that was considered too poor for agricultural purposes before being stripped 20 years ago is now covered with a heavy growth of grass and timber. Some original soils will not support a heavy growth of certain grasses that grow luxuriantly in soil derived from lime-bearing shales and other rocks turned by stripping. Erosion, weathering, and natural vegetation usually will restore stripped land to use for grazing, recreational areas, forest reserves, and, in some places, agriculture. Years are required to reclaim land by these means, and it is indicated that planned reforestation will not only restore the stripped land but will prove a profitable investment in many areas.

⁶ Pierce, W. G., and Courtier, W. H.; *Geology and Coal Resources of the Southeastern Kansas Coal Field*, Univ. of Kansas Bull. 24, 1937, 122 pp.

⁷ Toenges, Albert L., *Reclamation of Stripped Coal Land*, Bureau of Mines, Report of Investigations 3440, 1939, 11 pp.

⁵ *Ibid.*, p. 9.

Experiments in systematic tree planting were begun in Indiana about 1934 and in Illinois in 1930. These two States are large producers of coal by the stripping method. From 1934 (the first year for which detailed records were kept) to 1938, inclusive, 21 mine operators in Indiana planted 3,399,750 trees and 187-1/2 bushels of walnuts at a cost of \$14.50 an acre. The record of work accomplished in Illinois to 1938 and the cost are not available. In 1938 eight mine operators planted 261,500 trees on 178 acres of spoil banks at an average cost of \$22 an acre. In 1939, 14 mines planted 1,029,400 trees on 953 acres at a cost of \$10.84 an acre.

Strip mining and the application of mechanical loading devices in underground coal mines have improved technique in extraction of coal and increased recovery, thereby conserving coal deposits.

Relation of Gains in Recovery to Research Progress

The success of a mining system, whether the coal is loaded by hand or with mechanical devices, depends upon the coordination of the various steps involved in getting out the coal. If the coal is loaded by hand, the individual miner studies the conditions surrounding his working place to obtain maximum tonnage from minimum labor and supplies (usually the miner as an independent contractor furnishes his explosive and pit supplies and is paid a fixed price per ton). As machinery was introduced into other industries, methods and means were studied to apply mechanical devices to certain operations in the mine, not only to lessen hard hand labor but to increase the output per man. Many coal companies have cooperated with machinery manufacturers in research work with a view to improving safety and efficiency in coal mining. As the various mining operations became more highly mechanized it became necessary to study coordination of the operations. Coordination of every operation—cutting, breaking down the coal, timbering with the attendant problem of roof control, loading, and transportation—is highly

important in mechanized mines, and this can be accomplished best by using data collected from detailed studies of every phase of the mining cycle. Progress in mining technique followed the development and improvement of mining machinery, which in turn depends upon quality of construction materials such as alloy steels resulting from research, and upon advances in the electrical and mechanical arts.

Research and study by individuals, companies, manufacturers, government agencies, and organizations, such as the American Mining Congress, have resulted in improvements in each phase of the mining cycle, and these improvements in technique have been factors in the increased recovery of coal. Progress in some of the operations in coal mining is described briefly.

Cutting

In 1936 the underground output of bituminous coal cut by machine was 84.8 percent of the total production in the United States, as compared with 50.7 percent in 1913.⁸ The technique of mechanized cutting has progressed through various stages from the compressed-air puncher to the electric coal cutters of today. This progress has followed studies of the physical characteristics of the coal bed and surrounding strata, which have a marked effect upon the successful operation of the machine. The purpose of undercutting the bed is to facilitate the breaking down of the coal before being loaded. Cutting machines were introduced into mines to effect savings in mining costs, to reduce the proportion of fine coal that results from shooting the coal off the solid, and to increase the rate of production from a given area.

The coal puncher is operated by compressed air and is equipped with a pick-like tool attached to a reciprocating piston. The cut is made by the digging action of the pick into the face. This machine was a great improvement over the hand pick, but the rate of cutting was slow; today few coal punchers are in use

⁸ Bureau of Mines, *Minerals Yearbook*, 1939, p. 771.

in bituminous-coal mines. Continued study and research to increase the rate of cutting developed the chain cutting machine; this type includes the breast, shortwall, turret or top cutters, and shearing machines. These are almost universally operated by electricity in the United States.

The breast machine consists of a triangular cutter frame, driving motor, and gearing. The cutter frame is equipped with bits or teeth set in a sprocket-driven chain that travels on the cutter frame. The frame is moved forward in the bottom of the coal bed by a rack and pinion. The width of each cut ranges from 3-1/2 to 4 feet and the depth of the cut, 4 to 7 feet, depending upon the size of the machine. When one cut is completed the entire machine is shifted the width of the cut, and the cutting operation is repeated until the entire face has been undercut.

Further research and study evolved the shortwall machine; this has no stationary guide frame. The cutter frame and head, or cutter bar is long and rectangular. It is equipped with a bit-mounted chain driven by a sprocket on one end of the bar and passes over an idler sprocket at the other end. The machine, drawn by its own power, slides along the bottom and cuts near the bottom of the bed. The cutting operation is continuous in each place, and no time is lost resetting the machine, as with the breast machine. This machine is the most common cutting type now used in bituminous-coal mines.

The longwall cutting machine is a variation of the shortwall machine. While the machine is working along a long face the cutter bar is at right angles to the body of the machine and thus permits it to work in narrow places, approximately 32 inches between prop or packwall line and the face.

In recent years some mines have been developed in coal beds that contain dirt bands or partings. A cutting machine designed to make the cut in, above, or under the dirt band or parting and thus facilitate its removal before shooting

has been developed. It is similar to the shortwall machine but is mounted on a pivoted table, and the cutter frame swings in an arc. The machine is mounted on wheels or crawlers. Variation in design permits vertical cutting or shearing; a study of the breaking characteristics of some beds has shown this method of cutting to be advantageous. If the roof strata indicate that exposure to air causes rapid disintegration, the cut can be made in the upper part of the bed with this type of machine, leaving a thin layer of coal as a protection for the roof.

Preparation of the face so that the coal may be broken down properly is a prerequisite for maximum loading efficiency. Cutting machines remove a narrow cut or kerf from the bed, and the openings, either horizontal, vertical, or both, facilitate the breaking down of the coal by providing a freer movement of the forces of explosives. Most efficiently operated mines have studied the problems involved and planned the development to give the maximum output from the machines. The studies may indicate that all three types of machines can be used to advantage: the breast and track- or crawler-mounted turret in entries and narrow work, and the shortwall in wider places where it can be used most efficiently.

Rapid development of entries is essential in mechanized mines, and cutting machines have been a step toward the attainment of this objective. Entry-driving machines have been developed and are used to a limited extent.

Drilling

The progress in cutting has been followed by improvements in the equipment for drilling coal. Briefly, the advancement has been from the hand-operated breast auger and ratchet drill to electrically operated drills. The bits most commonly used in electric drills are the auger and a clawlike bit, sometimes called a mole-foot. The latter comprises small individual bits that can be removed and resharpened. It generally is used in drilling holes 3 inches or more in diameter.

The physical characteristics of the coal bed are important factors and must be studied to determine the proper position of the drill holes both in respect to safe and proper maintenance of the working places and to the recovery of the maximum output of larger sizes of coal from a minimum amount of drilling.

Breaking Down Coal

Much study and research have been devoted to improvement in the method of breaking down coal safely and efficiently. The Bureau of Mines has spent years of study and original research on the safe use of explosives and has assisted manufacturers in perfecting permissible explosives. The results of these investigations have aided materially in improving the technique of breaking down coal safely and efficiently; they are too numerous to mention in this report but are enumerated in the List of Publications of the Bureau of Mines.

Before 1909 black blasting powder was virtually the only explosive used for blasting coal in the United States.⁹ Its use increased with increase in the production of coal. Mine explosions occurred frequently, and many of them were caused by the use of black powder or dynamite.

As early as 1902, 7 years before the issuance of a permissible list of explosives by the United States Government, manufacturers had modified dynamites with a view to decreasing the ignition hazards attending the firing of shots in coal mines. Later study and research regarding safety, efficiency, and economical use of a large variety of explosives led to the development of what are now termed in the United States "permissible explosives."¹⁰

The proper placing of the drill hole and the confinement of the explosive are of prime importance in the efficient breaking of the coal. Demand for fine sizes of coal (minus 1-1/4-inch) has not paralleled that for larger sizes. Al-

though there is a tendency today to use smaller sizes of coal, excessive shattering of the coal bed by explosives produces an abnormal proportion of fine coal. The progress in the technique of breaking down the coal has been toward reduction of obnoxious and injurious gases from the detonation of explosives and the production of sizes larger than 1-1/4 inches.

The introduction of mechanical loading has brought to the foreground the matter of return on the increased investment in equipment. A mine is usually designed for a certain daily output; if this is large, the investment in equipment and development likewise will be large. If, however, the daily output can be produced over a period of two or three shifts, the equipment required will be reduced proportionately and should result in a small capital charge per ton. All of the operations in the cycle of mining follow each other in definite sequence and for maximum results should be continuous. One of these operations is blasting. Some State laws do not permit blasting with explosives while men are in the mine. This restriction makes difficult the operation of some mechanized systems economically, especially where conveyors are used in rooms and entries. Devices are used and improvements are being made in blasting equipment that will make it possible to break down coal safely while men are at work in the mine if proper precautions are taken to lay the dust, using water on cutter bars and to wet the face and working place thoroughly before blasting is done. Rock dust should be properly applied.

One of the devices developed is called Cardox; this has been termed permissible by the Bureau of Mines.¹¹ Briefly, it consists of a cylindrical hollow steel shell, a heating element, valve assembly, shearing disk, and discharge cap. The blasting agent is liquid carbon dioxide, which is pumped into the shell at a pres-

⁹ Tiffany, J. E.: *Coal-Mine Explosives: Their Characteristics, Selection and Safe Use*, Bureau of Mines, Information Circular 7040, 1938, 20 pp.

¹⁰ *Ibid.*

¹¹ Tiffany, J. E.: *A New Permissible Blasting Device*, Bureau of Mines, Report of Investigations 2920, 1929, 8 pp. (Improvements have been made since 1929, but the component parts of the design are essentially the same.)

sure of about 1,200 pounds per square inch, usually at a plant outside the mine. The carbon dioxide is converted from a liquid to a gaseous state by a heating element containing an electric squib. During gasification of the carbon dioxide the pressure within the shell rises rapidly until it shears the replaceable steel disk that seals one end of the shell. The coal is broken down by the rapid increase of pressure in the drill hole due to the escaping carbon dioxide.

The use of this device has increased rapidly in some districts, and breaking coal on shift has been permitted by this method in some States that prohibit the firing of explosives during the shift. The ability to advance the faces of working places more than one cut per shift greatly increases the efficiency of types of mechanical loading equipment, especially conveyors and scrapers.

Another device employed to a limited extent for breaking down coal in some mines is Airdox, which uses compressed air as the medium. Briefly, the device consists of a steel shell, discharge cap, piston, and valves. The inside of the shell is divided into two compartments, one large and the other small. After the shell is placed in the drill hole air is pumped into it through copper tubing. The air pressure varies with the physical conditions of the bed but is approximately 10,000 to 12,000 pounds per square inch. When the proper pressure has been reached

in the shell the air is released in the small chamber and the piston moves toward the small compartment. This action opens a valve, and the air is suddenly released through ports in the discharge cap of the shell. The rapid increase of pressure in the drill hole causes the coal to break down.

Roof Support

One of the major causes of accidents in the coal mines is falls of roof. The strata above coal beds vary in character, and their composition and characteristics must be considered in planning a system of mining. Much study has been devoted to roof support and control. The Bureau of Mines has made studies in many mines and has published the results of some.¹²

Wooden timbers or props most commonly are used to support the roof in working places. Entries may be timbered with single timbers or three- and four-piece sets, depending upon roof and floor. In four-piece sets a sill is placed on the bottom of the entry. Two legs are set on each end of the sill, and a cap is placed on top of the two legs and wedged securely to the roof. Where the bottom does not heave or is solid, the sill may be omitted. If the roof is likely to cave, lagging may be placed over the sets of timber.

Rooms are also timbered either with single props or with cross-bars supported by legs, depending upon the roof characteristics.

¹² Paul, J. W., and Geyer, J. N.: *Falls of Roof and Coal in Mines Operating in the Pittsburgh Coal Bed in Marion and Monongalia Counties, W. Va.*: Bureau of Mines, Technical Paper 522, 1932, 43 pp.
 Paul, J. W., and Geyer, J. N.: *Falls of Roof and Coal in Mines Operating in the Pittsburgh Coal Bed, Panhandle District, W. Va.*: Bureau of Mines, Technical Paper 534, 1932, 34 pp.
 Paul, J. W., and Plein, L. N.: *A Study of Mine Roof of the Pittsburgh Coal Bed in the Pittsburgh Mining District*: Bureau of Mines, Technical Paper 541, 1932, 97 pp.
 Paul, J. W., and Geyer, J. N.: *Falls of Roof in Mines Operating in the Pittsburgh Coal Bed, W. Va.*: Bureau of Mines, Technical Paper 547, 1933, 23 pp.
 Paul, J. W., and Calverly, J. G.: *A Study of Roof in Pennsylvania Mines Contiguous to the Monongahela River*: Bureau of Mines, Technical Paper 550, 1933, 31 pp.
 Paul, J. W., and Plein, L. N.: *A Study of Mine Roof in the Coking Districts of Western Penn-*

sylvania: Bureau of Mines, Technical Paper 563, 1935, 34 pp.
 Paul, J. W., and Plein, L. N.: *A Study of Falls of Roof and Coal in Mines in the Number 8 Field of Eastern Ohio*: Bureau of Mines, Report of Investigations 3070, 1931, 32 pp.
 Paul, J. W., and Geyer, J. N.: *A Study of Falls of Roof and Coal in Mines of Harrison County, W. Va.*: Bureau of Mines, Report of Investigations 3110, 1931, 30 pp.
 Paul, J. W.; Tomlinson, H.; and Craighead, S. J.: *Roof Support in Coal Mines in the Irwin, Greensburg, and Latrobe Basins, Westmoreland County, Pa.*: Bureau of Mines, Report of Investigations 3113, 1931, 77 pp.
 Hazen, W. F., and Christy, E. J.: *Method and Cost of Mining the Pittsburgh or No. 8 Coal Bed in a 100 percent Mechanized Mine in Eastern Ohio*: Bureau of Mines, Information Circular 6200, 1929, 21 pp.
 Paul, J. W., and Tomlinson, H.: *Method and Cost of Mining the Pittsburgh or No. 8 Coal Bed in Four Eastern Ohio Mines*: Bureau of Mines, Information Circular 6208, 1929, 21 pp.

Mechanization has introduced new problems in roof control. Mobile loading machines may require a different system of timbering than conveyors and scrapers. The special study required in each case has led to improvement in methods of timbering. In recent years steel timbering has proved successful in both entries and rooms. Long beams either of steel or alloys of steel are used at the face where mobile loading machines are employed. These machines require flexibility of movement, and the long beams that support the immediate roof without props permit an unrestricted working space for the loader.

Progress has been made in planning methods of pillar extraction following studies of roof control. No set rules can be formulated, as the strata above the coal bed in each mine or section of mine constitute a special problem. The Bureau of Mines has studied pillar extraction, timbering, and roof movements in coal mines and has published the results of some of these studies.¹³

The success of a longwall mining system depends upon control of the weight of the overburden; control has been found to be best accomplished with rock pillars and pack walls.¹⁴

Research in roof movements and control has been a decided factor in increasing the recovery of coal.

¹³ Paul, J. W., and Calverly, J. G.: *Timber Withdrawing and Devices Used for this Purpose in Some Coal Mines*, Bureau of Mines, Information Circular 6722, 1933, 15 pp.
 Geyer, J. N.: *Factors and Conditions That Aid in Alinement of Pillar-Extraction Lines in Coal Mining*, Bureau of Mines, Information Circular 6727, 1933, 15 pp.
 Paul, J. W., and Plein, L. N.: *Methods of Development and Pillar Extraction in Mining the Pittsburgh Coal Bed in Pennsylvania, West Virginia, and Ohio*, Bureau of Mines, Information Circular 6872, 1936, 31 pp.
 Greenwald, H. P.; Maize, E. R.; Hartman, Irving; and Rice, G. E.: *Studies of Roof Movement in Coal Mines. 1. Montour 10 Mine of the Pittsburgh Coal Company*, Bureau of Mines, Report of Investigations 3355, 1937, 41 pp.
 Maize, E. R., and Greenwald, H. P.; *Studies of Roof Movement in Coal Mines. 2. Crucible Mine of the Crucible Fuel Company*, Bureau of Mines, Report of Investigations 3452, 1939, 19 pp.

¹⁴ Toenges, Albert L.: *Longwall Mining Methods in Some Mines of the Middle Western States*, Bureau of Mines, Information Circular 6893, 1936, 62 pp.

Mechanical Loading Devices and Transportation

Mechanical loading and transportation should be considered together, as the success of any loading device primarily depends upon the adequate removal of the material from the working place after the coal has been loaded. Loading machines of large capacity can be built to conform to restrictions placed upon a machine, such as the necessity of operating in a restricted place, but unless some means is provided to transport the loaded coal from the machine without delay little is gained by the introduction of the loading device. These machines handle impurities with the coal, and if the bed contains a large proportion of impurities difficulties in preparation may be introduced that offset any advantages gained at the working face.

Research into the problem of mechanical loading has resulted in marked progress within the past 15 years. Physical conditions in and around the coal bed have an important bearing upon the design of loading equipment and the method of mining.

Conveyors probably were developed from the metal chutes that formerly were used in some moderately dipping beds. When a shaking motion actuated by power is applied to the chute it becomes a shaking conveyor. If an endless chain is moved along the bottom of the chute the result is a chain or drag conveyor. These devices have been used in mining thin beds of coal in European mines for many years. The economic problem of operating mines in thin beds where wage scales are high was partly solved by the application of conveyor mining to longwall or long-face mining systems. Conveyors alone, although not loading machines, should be considered under loading devices. Duck-bills or self-loading heads, however, were developed for shaking conveyors, and ultimately the conveyor became a loading machine. These conveyors have been used with marked success in thick dipping beds, such as those in Utah and Wyoming. Duck-bills also have proved efficient in thin beds. Studies were made of all factors pertaining to the bed, and mining systems were de-

signed that resulted in the successful operation of this type of loading equipment.

Various systems of mining and types of conveyor equipment used in some mines have been described.¹⁵

A loading device used extensively before the practicability of the mobile loading machine was demonstrated is the pit-car loader, which essentially is an electrically operated elevating conveyor. The coal is shoveled by hand onto the lower end of the conveyor and lifted into the car. Output per man is increased, as the elevating device eliminates the necessity of lifting the coal the height of the car by hand. The machine is mounted on two large wheels and is well balanced and, as it is light, can be moved easily in the working places. Many mines still use the pit-car loader, because it has the advantage of low first cost and simplicity of operation.

Machines that can both mine and load have been designed, but few of them are used widely in the industry. As a rule, the cost of maintaining these machines is high because of the large number of working parts. The machines are usually large and cumbersome and therefore cannot be moved readily from place to place in the mine. The McKinlay, a machine of this type, is especially adapted to driving entries and other narrow workings; it cuts, breaks down, and loads the coal and, when used with conveyor belts, approaches the ideal of continuous flow of coal from the face. This machine represents studies of most phases of the mining operation, but it is used in only a few mines at present.

In recent years the greatest progress has been in the design of machines that both shovel and load. The mobile loading machine, which may be mounted on crawlers or equipped to run on a track, is a device of this kind. Briefly, these

machines comprise a loading head, which during the loading operation is kept against the broken coal; conveyors; and driving mechanism for both propulsion and loading. The loading head is equipped with devices for gathering the coal into the conveyor of the machines. Some machines employ a device that acts as a shovel and others use arms or chains equipped with picks that drag the coal onto the conveyor.

The scraper loader has been used successfully under certain favorable physical conditions of the coal bed. The loader has no complicated mechanism, and is efficient in both room and longwall work. It is used in some fields where the coal beds are thin, and a high extraction has been obtained from long faces where other systems of mining employing hand-loading methods would have been uneconomical.

The development of loading devices has been so rapid and improvements are being made so constantly that care must be taken to plan operations that will return the capital investment before the equipment becomes obsolete. Every attempt should be made to obtain the maximum extraction from an area under any system of mechanization. Mechanization has resulted in concentration of working places and, in many districts, an increase in the recovery of coal.

The rated output of mobile loading machines usually is high, and unless the transportation system is coordinated with the loading machine the efficiency of the entire program will fall. Continuous flow of coal from face to tippie, eliminating enforced idleness due to changing cars and haulage delays, is greatly desired. This can best be accomplished by the use of conveyor belts. A number of mines have adopted the conveyor-belt system.¹⁶ A combination system employing mobile loading machines in working places, chain

¹⁵ Toenges, Albert L., and Anderson, Robert L.: *Multiple-Shift Mechanical Mining in Some Bituminous-Coal Mines*, Bureau of Mines, Information Circular 7014, 1938, 56 pp.

Toenges, Albert L., and Jones, Frank A.: *Multiple-Shift Mechanical Mining in Some Bituminous-Coal Mines*, Bureau of Mines, Information Circular 7067, 1939, 58 pp.

¹⁶ Toenges, Albert L.: *Longwall Mining Methods in Some Mines of the Middle Western States*, Bureau of Mines, Information Circular 6893, 1936, 62 pp.

Toenges, Albert L., and Anderson, Robert L.: *Multiple-Shift Mechanical Mining in Some Bituminous-Coal Mines*, Bureau of Mines, Information Circular 7014, 1938, 56 pp.

conveyors from loading machines to a belt conveyor in the panel entry, rail haulage in large-capacity cars to the mine bottom, and belt conveyors from the mine bottom to the tippie on the surface is being used successfully in a mine recently opened in Illinois. Some factors favoring belt transportation are:

1. The flow of coal is steady with less interruption than with 100-percent rail haulage.

2. Heavy roof can be supported more easily and at less cost than with the wide spans necessary for rail haulage.

3. Operating costs are low, but installation cost is high; hence tonnage reserves are important in planning a belt installation.

Some unfavorable factors are:

1. A fall of rock on the belt may disrupt production from the entire mine if all the coal is transported to the mine bottom by belt. This might occur with rail haulage but probably with less serious consequences because several locomotives and trains usually are in service.

2. A projecting rock in a fall might slice the belt longitudinally and ruin it before the belt could be stopped, necessitating a large expenditure for a new belt.

Rubber-tired haulage units have been designed to serve mobile loading machines with the view of eliminating haulage delays at the face. These units comprise an electric power-driven tractor (usually storage battery) and a semitrailer holding 3 to 5 tons of coal. The trailers usually have a drop bottom, and the coal is discharged to a hopper from which it is transported to cars by a conveyor belt.

Another type of rubber-tired haulage unit is the shuttle car. These units hold 3 to 6 tons and are electrically operated (usually from storage batteries; sometimes by trailing cables); the shuttle car is a single unit. The bottom of the shuttle car is usually a drag conveyor, and the coal is conveyed to an elevating conveyor and transported to cars at the loading station in the entry.

Improvements have been made in the design of mine cars run by rail. Many mines have

replaced plain-bearing wooden cars with steel cars equipped with antifriction bearings. The capacity of the cars has been increased in some mines where mechanical loading has been installed. Large-capacity cars reduce the number of car changes and usually increase the effective loading time of the machine. The larger cars generally hold 3 to 6 tons, but some late installations hold 11 tons. Studies are being made to determine the economical size of mine cars and number of cars per trip. Many factors are involved, including size of locomotives necessary to haul the trip and added cost of track maintenance when heavier cars are transported.

Ventilation

Many mines today purchase electric power from public utility companies. When fans were driven by steam the cost of power for ventilation was seldom considered, but when electric drives to fans were installed operators realized the cost of ventilation. Fans generally are operated—and should be—24 hours a day every day in the year; unless they are operated efficiently and air passageways in the mine kept open, high power costs result. The design of fans has been changed radically from the large-diameter, slow-speed, paddle-wheel fan to the high-speed, propeller fan of today. Research on the ventilation of mines has developed highly efficient, large-capacity fans that operate at large savings in cost of power. Studies have been made in design of airways to provide low frictional resistance to passage of air. Rapid development of a mine is usually the result of mechanization, and the problem of ventilation must be planned carefully in advance. It costs less to ventilate a few concentrated areas than a large number of scattered areas.

In some areas the change in temperature of the air entering a mine has been a factor in the disintegration of the roof in entries and working places. Studies have been made of air conditioning during the summer months, when deterioration of the roof is greatest. Following these studies,

air-conditioning plants were erected at some mines and roof conditions improved.

Some systems of mechanical mining, especially where conveyors and scrapers are used, require auxiliary ventilation, and small fans have been developed to ventilate individual working places. These fans usually are placed on the entry, and the air is blown through flexible tubing to the face of the working place. State laws generally specify the minimum ratio of the volume of air passing the blowing fan to the capacity of the blower. Some mines require that the volume of air passing through the entry in which the blowing fan is installed be not less than 2-1/2 times the capacity of the blower. Bureau of Mines Mine Safety Board Decision 4 states:

"In the interest of safety the United States Bureau of Mines recommends that auxiliary fans or blowers should not be used in coal mines as a substitute for methods of regular and continuous coursing of the air to every face of the mine."

Strip Mining

Modern strip mining is a form of mechanical mining. The technique has progressed rapidly through study and perseverance by operators and engineers and the ability of manufacturers to meet the demands of the operators for equipment suited to their needs. Both stripping and loading equipment must be adaptable to the conditions known to exist in the area and efficient enough to give the desired output. The size of the units should be balanced efficiently. The mine lay-out and design of equipment should be such that maximum production can be attained when demand for coal is greatest. These requirements cannot be obtained without a study of all the factors involved. Beds of coal are being mined today with high recovery by the stripping method that could not be mined economically by other methods of mining.

One of the principle factors upon which the success of a stripping operation depends is the ability to uncover coal at a rate that will keep pace with production;

in other words, the stripping equipment must handle overburden fast enough to avoid delays in following operations. Reduction in effective working time sometimes is due to the size of pieces in the broken overburden. Studies of the character of overburden and experiments in spacing and size of drill holes and kinds and amounts of explosives have been made with the object of obtaining a degree of breaking that will result in high loading and over-all efficiency. More overburden can be removed when the material is broken into sizes that can be handled easily.

Vertical and horizontal holes have been tried; also different spacing of holes. No general rule can be established for drilling; physical conditions in each area determine the best methods for that area.

Studies have been made of the breaking characteristics of the overburden with different kinds of explosives—black powder, dynamites of various strengths, and liquid-oxygen explosives. Each of these may be used under certain physical conditions of the overburden.¹⁷ Where a thick stratum of hard rock occurs in the overlying material liquid-oxygen explosive often has been found to give the best results.

Liquid-oxygen explosives comprise a combustible absorbent saturated with liquid oxygen, which is generally manufactured at or near the mine, using air as the raw material. The explosive cartridge is usually a fabric bag filled with carbonaceous material. The diameter of the cartridge varies with the size of the drill hole and may range from 4 to 8-1/2 inches for use in strip mines. Before the cartridges are used in blasting operations they are soaked to saturation in liquid oxygen. The charged cartridges are taken to the place where they are to be used, placed in the drill holes, tamped, and then fired¹⁸ with electric detonators in

¹⁷ Toenges, Albert L., and Anderson, Robert L.: *Some Aspects of Strip Mining of Bituminous Coal in Central and South Central States*; Bureau of Mines, Information Circular 6959, 1939, 87 pp.

¹⁸ Perrott, G. St. J., and Tolch, N. A.: *Liquid-Oxygen Explosives*, Bureau of Mines, Bulletin 349, 1932, 88 pp.

much the same way as other explosives.

Advances have been made in both design of stripping and loading shovels and transportation of coal in strip mines. Motorized equipment is replacing locomotive haulage. The problem of determining economic lengths of haul by rail and motorized units in strip mines was studied by the Bureau of Mines.¹⁹

Safety

An efficient operation, whether underground or strip mine, is usually a safe operation. Improvement in the technique of mining has gone hand-in-hand with safety work in mines. The fatality rate per million tons of coal produced has declined from 4.76 in the period 1911 to 1915 to 2.92 in 1938.²⁰

One of the hazards in underground coal mines is the presence of explosive gas and coal dust. Bureau of Mines research into the causes and prevention of mine explosions has been a factor in the marked decrease in number of mine disasters. In connection with the study of explosive gas and coal dust, research has been conducted with reference to design and manufacture of electrical equipment used in mines; many coal mines now employ only electrical equipment which, under test by the Bureau of Mines, has been determined to be safe in gaseous atmospheres if it is maintained in a prescribed condition. The annual fatalities decreased from 438 for the 5-year period 1906-10 to 65 for the 5-year period 1931-35, a decrease of 85.5 percent.²¹ Thus, research has contributed largely to another form of conservation, namely, conservation of human life.

¹⁹ Toenges, Albert L., and Jones, Frank A.: *Truck vs. Rail Haulage in Bituminous-Coal Strip Mines*, Bureau of Mines, Report of Investigations 3416, 1938, 54 pp.

²⁰ Harrington, D.: *Safety Work of the Bureau of Mines and Some of Its Results*, Bureau of Mines, Information Circular 7070, 1939, p. 13.

²¹ Harrington, D., and Fene, W. J.: *Coal-Mine Explosions and Coal- and Metal-Mine Fires in the United States During the Fiscal Year Ended June 30, 1939*, Bureau of Mines, Information Circular 7092, 1939, p. 14.

Summary

Progress through research that has resulted in gains in the recovery of coal may be summarized as follows:

The need for study and planning was recognized when mechanical devices were introduced into coal mines. To obtain high efficiency from these devices, the mine should be properly designed. Carefully planned mining operations will minimize the loss of coal; thus, engineering studies to determine the most efficient plan for applying mechanical devices have been factors in increasing the recovery of coal.

Underground Mining

1. *Cutting*.—Cutting machines were introduced into mines to effect savings in the cost of mining, to reduce the proportion of fine coal that results from shooting coal off the solid and to increase the rate of production from a given area.

2. *Drilling*.—Cutting with machines resulted in the preparation of more places in the mine per shift; in order to benefit from the increased potential production so provided, devices for speedier drilling were developed.

3. *Breaking down Coal*.—The development of permissible explosives, liquid carbon dioxide, and compressed-air devices for breaking down coal and studies made to determine their proper use have been factors in conserving life and increasing the output of larger sizes of coal.

4. *Roof support*.—Much coal is lost in the mine owing to caving of the roof in working places. Study and research of methods and means for supporting the roof have increased the rate of extraction.

5. *Mechanical loading devices and transportation*.—Mechanical loading devices have contributed to a higher recovery of coal. The success of any loading device primarily depends upon adequate removal of the material from the working place after the coal is loaded, and an efficient transportation system is a necessary adjunct to mechanical loading. Research and study have developed new methods of transportation that have increased the efficiency of loading.

6. *Ventilation.*—Improvement in the design of fans has led to more efficient ventilation of mines. No coal mine can operate without a ventilating system, and research not only in design of fans but in design of airways to minimize frictional resistance to passage of air have been factors in safe extraction of coal from gassy beds.

Strip Mining

Study and research in the problems of strip mining have resulted in the extraction of coal from beds that could not be mined economically by underground methods and have increased the recovery of coal.

The reclamation of stripped coal land is being studied today, and methods and practices are being developed that ultimately will put this land to use.

Safety

Improvement in the technique of mining has gone hand in hand with safety work in mines, and research into safe mining practices has contributed to conservation of human life.

Appraisal of Direction and Adequacy of Governmental Research in Production Technique

Governmental research in relation to production technique has been directed toward safety, conservation, and increased efficiency in operation. A property that is operated efficiently usually practices conservation and safety. Efficiency generally is measured in terms of profit, and unless the mining operations are conducted with utmost safety, profits will be reduced seriously by payments of compensation and low rate of output. No operation can be considered successful if the assets of the property (the coal in the ground) are wasted.

The Bureau of Mines, since its organization in 1910, has been instrumental in promoting health and safety in coal mines. The main objective in mine safety work is the prevention of accidents to workers. Operations of mines must be regulated by law. Safety, however, cannot be promoted

by legislation alone; it must be sold to both operators and miners. Strangely, the worker must be taught and compelled to work safely. The Bureau of Mines and State safety organizations, with the cooperation of operators and miners, have taught first aid, mine rescue, and accident prevention. First-aid training has the psychological effect of bringing forcibly to the worker the effects of accidents. A man trained to render first aid to others usually is a "safe" worker. Education and supervision are the foundation for the achievement of safety in mining, and education is gained by various means: demonstrations, talks, first-aid contests, safety meets, publications, and motion pictures. The explosibility of coal dust and gases and the means of preventing explosions or limiting the extent of their destructiveness are studied at the Bureau of Mines Experimental mine. Many field and laboratory studies also have been made to prevent or limit mine explosions. These include investigations of explosives, electrical and other equipment, miners' lamps, and ventilation. Recommendations have been made to eliminate unsafe practices. Engineers investigate mine disasters to ascertain the causes and methods of prevention. The work done by the Bureau in this field has contributed to the decrease in the number of mine disasters and fatalities from explosions.²² Continued study of mine gases, dust control, respiratory apparatus and gas masks, and mine accidents is necessary if accidents in and around mines are to be eliminated.

The Technologic Branch of the Bureau of Mines conducts engineering and scientific research into the phases of producing coal safely and efficiently. Broader application of engineering principles and practices is needed in the coal industry. Relatively few coal companies are large enough or financially able to conduct studies and investigations to improve practices in this basic industry. The

²² Harrington, D.: *Safety Work of the Bureau of Mines and Some of Its Results*; Bureau of Mines, Information Circular 7070, 1939, p. 5.

studies and research in connection with the causes and prevention of mine fires, poisonous gases from explosives underground, inflammability of gases, analysis and testing of explosives for permissibility, testing of mining machinery and other equipment are well-known and have greatly increased the recovery of coal with safety. Mechanization of mines will continue to increase. Since one of the fundamental practices is breaking the coal, studies should be made to develop an explosive device or method that can be used with perfect safety while men are in the mine.

As new coal fields are opened and less-known beds developed, the reaction of the dust from these beds should be studied and the operators advised of the proper procedure to prevent explosions.

Ventilation practices of all bituminous coal mines should be investigated. Results of such studies should lead to more efficient ventilating systems. In some areas temperature and humidity apparently have an important effect upon the roof of a coal bed; this phenomenon should be studied.

Coal-mining methods (underground and strip mining) and various phases of coal mine operation (mechanical mining, underground and strip-mine haulage, and reclamation of stripped land) have been studied with the view of disseminating information concerning both efficient and some inefficient practices among the operators to give them an insight into the experiences of others.

Study and analysis of the various items that make up the cost of mining, such as power, haulage, cutting, timbering, breaking down the coal, and loading, may reveal ways and means of reducing the cost of mining; reduced costs will permit higher extraction. Each phase of the mining operation has an effect upon the recovery. Studies of these phases in a large number of mines under varying physical conditions usually point to conclusions that will benefit the industry; such studies should continue. The

number of mines using mechanical loading devices has increased rapidly in the past few years and, according to indications, will continue to increase. To obtain the maximum recovery of coal, studies of the various systems of mining and types of mechanized equipment should continue with the view of determining the most efficient method of mechanization for beds of varying physical conditions.

Fundamentally, recovery of coal may be low owing to (1) excessively thick beds, (2) excessively thin beds, and (3) properties of roof and bottom. A study of physical conditions in and surrounding the bed is necessary in planning a successful mine that will yield high recovery.

In connection with roof control, various kinds and types of roof support should be investigated, especially where mechanical loading is used. The study of the crushing strength of coal pillars should be continued, and research should be directed toward development of methods for recording the weight of overburden acting on the pillars.

As the more accessible beds are depleted, and these beds underlie or overlie other workable beds, it will be necessary to determine methods for the safe and efficient extraction of coal from these beds; this problem should be investigated.

The objective of all the studies outlined is conservation of an important natural resource and the mining of coal with safety. If methods of mining can be designed to fit particular conditions and studies of phases of mining indicate ways or means of improving efficiency of operations, it is believed a step will be made in improving some present practices. Research into these problems is not adequate because of limited personnel. The coal industry as a whole has cooperated with the Government in investigations, because it realizes the benefits derived from such studies. The publication of the results of investigations has been a factor in improving the technique of mining coal.

P R E P A R A T I O N

By H. F. Yancy¹

Gains in the Recovery of Coal

Although the term "recovery" is used here to mean the fraction of marketable coal in the feed to a preparation plant that is recovered for shipment, many coal preparation plants do not have facilities for determining their own recoveries or, conversely, for estimating their losses of marketable coal. Over the years, however, many of the larger plants have added the necessary technical skill and equipment to control the uniformity of the products shipped, so that recoveries and losses of good coal are known accurately. Obviously, appraisals of gains in recovery for the industry as a whole cannot be translated in the form of numerical values, as such information is not even obtained at many operating plants.

There are three sources of loss of coal during preparation: (1) loss with the refuse in mechanical cleaning operations; (2) loss with impurities removed from picking tables and discarded; and (3) loss resulting from the breakage of coal into finer sizes during handling in the plant; a different type of loss that affects the realization received by the operator but does not constitute an actual loss of resources. Loss of good coal in mechanical cleaning operations may be subdivided further into loss of coal in refuse and loss of fine sizes of coal as sludge.

The only pertinent information in the literature on this subject is that collected by the United States Coal Commission in the early twenties. Much of this information was not segregated to show the loss of coal during preparation activities alone. Losses during handling underground and surface preparation operations in percentage of marketable bituminous coal were found to range from

1 to 8.5 percent in the various coal-producing States, with an average unweighted loss of probably 4 percent. Special attention was given to the waste of coal in Alabama coal-washing operations. It was found that the loss ranged from 0.4 to 3 percent.²

In the Pennsylvania anthracite region the Commission's report segregated the loss in preparation and found that it ranged from a minimum of 3.7 percent in the northern field to 5.9 percent in the western middle field, an average for all fields of 4.3 percent, based on percentage of the original coal content.

If data were available on the recovery of coal during preparation or, conversely, on the losses of coal occasioned in these operations, adequate appraisal could be made of the gains resulting from the adoption of improved preparation practices. Although statistics on the cleaning of coal in the United States have been collected since 1906, first by the Geological Survey and later by the Bureau of Mines, the information requested from the operators and that published has dealt chiefly with the tonnage of raw coal handled and the amount of washed coal and refuse produced. Since 1906 the average production of refuse for the United States as a whole has not varied much from 10 percent, despite the fact that with the passage of time mechanical cleaning has been applied on an increasing scale to beds of coal naturally cleaner than those formerly treated.

The loss of coal with the refuse at mechanical cleaning plants varies with the efficiency of the cleaning units used, with the control exercised by the operator, and with the character of the raw coal treated. If one considers coal

¹ Supervising Engineer, Northwest Experiment Station, Bureau of Mines, U. S. Department of the Interior.

² *Report of the United States Coal Commission*, S. Doc. 195. 68th Cong., 2d sess., pt. 3, 1925, p. 1863.

as the material that has a specific gravity less than 1.60 in the feed to a bituminous-coal preparation plant, it is estimated that the minimum loss of coal with the refuse at the most carefully operated plants is probably of the order of 12 to 15 percent of the refuse. The coal in the refuse, however, always has a higher ash content than fractions of the same specific gravity in either the raw coal or the washed coal. Nevertheless the fraction of the refuse having a specific gravity under 1.60 might be included in the washed coal without significantly increasing the ash content were it possible to recover all of it in a cleaning plant. The maximum percentage of material having a specific gravity under 1.60 in the refuse in coal-cleaning plants is not known but probably reaches 40 percent in plants treating raw coals that are difficult to clean or that are poorly controlled. Expressed as a percentage of the raw coal treated, these two extremes mean that the loss of coal with the refuse of cleaning plants may range from less than 1 percent to as much as 10 percent.

As regards improvements in preparation practice, it has been observed that many of the coal-cleaning machines introduced during the last 20 years are more efficient in separating coal from impurity than those formerly used. Not all such equipment is of this type. Some actually sacrifice recovery of coal to obtain a clean product in a dry condition. In general, however, a higher recovery of coal has been obtained through the introduction of improved types of coal-washing machines and accessory apparatus. In the latter class the adoption of thickeners and filters at a few plants has increased materially the recovery of the fine sizes of coal. Recovery of fine coal from the circulating water in a wet washing plant is also facilitated by the addition of reagents to the water, which cause the fine particles to flocculate or agglomerate and therefore settle more rapidly.³

³ Yancey, H.F.; Zane, R.E.; Wood, Walter; and Cannarella, J.T.H.: *Flocculation as an Aid in the Clarification of Coal Washery Water*, Bureau of Mines, Report of Investigations 3494, 1940. 13 pp

Research Progress

For a number of years the Bureau of Mines has published reports giving the results of its investigations of coal-washing and coal-cleaning methods to bring to the attention of the coal-producing and coal-consuming public the advantages and economies of using clean, efficiently prepared coal. The work has been limited mainly to fundamental problems that could be investigated successfully by a small staff in the laboratory, such as the development of methods for evaluating the washing characteristics of typical coals and the application of these methods to various coals mined in the United States.⁴ More recently an intensive study has been made of the manner of separation between coal and refuse by certain types of coal-washing equipment.⁵ Only in isolated instances has it been possible to study the performance of mechanical cleaning equipment in actual coal-preparation plants.⁶

The research in coal preparation and coal cleaning undertaken by the Bureau of Mines has been supplemented and extended in recent years by investigations in this field conducted at the Battelle Memorial Institute for Metallurgical Research, the Mellon Institute for Industrial Research, the University of Illinois, and other universities and colleges. Examples of this work are the development of a new

⁴ Yancey, H. F., and Fraser, Thomas: *Coal-Washing Investigations; Methods and Tests*; Bureau of Mines, Bulletin 300, 1929, 259 pp.

⁵ Bird, B. M.: *Sizing Action of Coal-Washing Tables*; Bureau of Mines, Report of Investigations 2755, 1926, 8 pp. Yancey, H. F., and Fraser, Thomas: "Analysis of Performance of Coal Jig," *Trans. Am. Inst. Min. and Met. Eng.*, vol. 71, 1925, pp. 1079-1087. Yancey, H. F., and Porter, C. B.: *Pneumatic Tabling of Coal; Effect of Specific Gravity, Size, and Shape*, Bureau of Mines, Technical Paper 536, 1932, 18 pp.

⁶ Yancey, H. F., and Geer, M. R.: *Performance of a Ram-Type Coal-Washing Jig*, Bureau of Mines, Report of Investigations 3371, 1936, 18 pp. Yancey, H. F., and Shinkoskey, R. E.: *Performance of a Pulsator-Type Coal-Washing Jig*, Bureau of Mines, Report of Investigations 3372, 1936, 19 pp. A complete list of the Bureau of Mines publications on coal washing and cleaning will be found in Technical Paper 576 and in a supplement thereto which is now being prepared for publication.

coal-washing device by the Battelle Institute and the study of the process of dustproofing coal by both the Battelle and Mellon Institutes. Research in coal preparation is also conducted by several of the larger coal companies. Some of this work has been made available by publication, but many of the results have never been published.

Adequacy of Governmental Research

Considering the value of the new wealth produced each year by the coal industry, the large number of workers employed, and the present unsatisfactory economic condition of the industry, one would be forced to conclude that the few thousand dollars spent by the Federal Government for research in coal preparation each year is entirely disproportionate and inadequate, as compared with the expenditures made in behalf of other producers of national wealth. Although, as already indicated, the investigations of the Bureau of Mines in this field are carried out principally by a small staff in the laboratory, with little or no attention to the performance of operating plants, the Bureau itself does not own enough equipment to make broad studies of the fundamentals involved in the cleaning and preparation of coal. Accordingly, it is necessary to depend in part on laboratories and facilities furnished by State universities.

To improve present preparation prac-

tices, to find means for minimizing the wastage of coal at operating plants, and to develop new and more efficient methods of cleaning coal, a much broader study of the whole subject should be undertaken. Adequate laboratories should be constructed by the Federal Government, in which fundamental studies of the mechanism of separating coal and impurity could be undertaken, with the object of developing new and more efficient methods. One such coal preparation laboratory should be in the Eastern coal fields at or near Pittsburgh, Pa., and one in the Illinois-Indiana western Kentucky coal field.

Adequate, technically trained personnel should be provided for both laboratories, and the facilities and staff of the present Bureau of Mines laboratories at Tuscaloosa, Ala., and Seattle, Wash., should be increased.

In initiating a program of this nature attention should be given first to determination of efficiencies of the separation between coal and refuse being attained in representative types of preparation plants, now in operation. The performance of such plants with respect to the inclusion of worthless ash-forming impurities in the cleaned coal and the rejection of marketable coal in the refuse discarded should be evaluated by detailed studies. With this knowledge as a basis, an active program of improvement of present processes to minimize wastage of coal in preparation could be formulated wisely.

COMBUSTION

By P. Nicholls¹ and J. F. Barkley²

General Progress in Utilization

Progress in the art and practice of burning fuels for the purpose of transforming the stored energy into heat cannot be considered apart from the utilization of the heat so generated. All forms of utilization involve the absorption of the heat by some material—solid, liquid, or gaseous—and progress in the effectiveness and efficiency of absorption is a necessary complement to advancement. Again, progress both in the practice of burning and in the utilization of heat requires the use of materials that can withstand high temperatures, alone or accompanied by high strains or pressures. Thus, discovery of new materials and improvement of their qualities are bound up with progress in the utilization of fuels by burning. Such materials are refractories, insulations, steel and steel alloys for pressure vessels, and cast alloys for grates, stokers, and furnace parts.

The main fields of utilization of fuels are: Heating, stationary steam and power, locomotive power, marine transportation, ceramics, and metallurgy. Uses in other fields fall mainly in the general classification of the heating of liquids and materials in process. The burning of cements and limestones is classed in the ceramic field.

In reviewing progress in combustion, more particularly of coal or other solid fuels, each field must be discussed separately because of the material differences in the methods of burning and in the utilization of heat.

The Heating Field

The oldest method of utilizing coal for

heating rooms is by burning in open fireplaces; the heat is supplied chiefly by radiation. In America, fireplaces are used less frequently as the main source of heating, but in England much research³ has been directed toward improvement in convenience and efficiency. In America, the open fireplace early was replaced by the iron stoves, which release most of the heat into the room; moreover, a wider range of coals can be burned because of the better draft through the fuel bed. A further advance is the magazine stove, with long periods between firings; this is more satisfactory with noncoking coals. A magazine stove utilizes the principle of so feeding the fresh coal that a constant thickness of fuel bed is maintained; thus, there is the possibility of maintaining a thickness that will give good combustion.

A great many dwellings in America are equipped for central heating, with furnaces which burn all kinds of coals and cokes. Much research has been conducted both on the burning of fuels at domestic rates and in various types of furnaces. Of the many reports on domestic heating boilers, that of the Bureau of Mines for tests of coals from all parts of the country is the most comprehensive.⁴ Research at the University of Illinois has done much to improve furnaces for warm-air heating as well as to determine methods of installation for the most satisfactory operation.⁵

The household furnace has been the

¹ Supervising Engineer, Fuels Section, Bureau of Mines, United States Department of the Interior, Central Experiment Station, Pittsburgh, Pa.

² Supervising Engineer, Fuel Economy Service, Bureau of Mines, U.S. Department of the Interior.

³ Fishenden, N. W.: *The Coal Fire*, Fuel Research Board of England, Special Report No. 4, 1920.

⁴ Nicholls, P.; Flagg, S.B.; and Augustine, C.E.; *Five Hundred Tests of Various Coals in Household Heating Boilers*, Bureau of Mines, Bulletin 276, 1928, 70 pp.

⁵ Willard, A. C.; Kratz, A. P.; and Day, V. S.: *Investigations of Warm-Air Furnaces and Heating Systems*, Univ. of Illinois, Bulletins 120, 141, 188, 189, 246, 266.

worst offender in creating smoke when burning high-volatile bituminous coal. Although tests have shown that the amount of smoke may be reduced by proper firing, rarely will the householder exercise the necessary care. An important advance has been the development of small stokers for domestic furnaces which not only require little attention and give good heat regulation but also materially reduce the amount of smoke. The development of stokers has depended largely on satisfactory mechanical operation. Studies on the operation of such stokers have been made by the Anthracite Institute,⁶ Bituminous Coal Research, Inc., at the laboratory of Battelle Memorial Institute,⁷ and the Bureau of Mines.⁸

Advances in the use of coal for heating apartments and medium-size buildings have paralleled those for dwellings. The heating of factories and large buildings is based on the use of high-pressure steam, and advancement comes from progress in the steam and power field.

Stationary Steam and Power Field

The review of progress in the generation of high-pressure steam for power, heating, and processing will be restricted here to the utilization of coal. The lines of improvement have been:

1. Better knowledge and application of the principles of burning.
2. Increase in the average rate of burning.
3. Improved control and regulation of burning.
4. Increased use of preheat and higher preheat temperatures.
5. Increase in the size of furnaces

⁶ Mulcey, P. A.: "The Selection, Installation, and Performance of Domestic Anthracite Stokers," *Trans. 2nd Annual Anthracite Conference, 1939* (with bibliography)

⁷ Barnes, C. A.; *Fundamentals of Combustion in Small Underfeed Stokers*, Bituminous Coal Research Report IV, 1938 (with bibliography).

⁸ Yancey, H. F.; Johnson, K. A.; Lewis, A. A.; and Cordiner, J. B., Jr.; *Burning of Various Coals Continuously and Intermittently on a Domestic Overfeed Stoker*, Bureau of Mines, Report of Investigations 3378, 1938, 30 pp.

and total output.

6. Improved methods of handling clinker and slag.

7. Ability to use poor-grade fuels efficiently.

As previously stated, advances in furnace design and combustion must be paralleled by and depend on improvements in the steam generator, its many auxiliaries, and the constructional materials. An increase in the burning capacity of a furnace is useless unless it equips a boiler that can evaporate a correspondingly increased weight of steam.

The order of the rate of advance in boiler capacity is illustrated by the boiler, which in 1905 had a maximum rating of 30,000 pounds of steam per hour and in 1939 of 1,000,000 pounds. This rapid growth was made possible only by broad research, both in the laboratory and on full-scale operating plants; in several instances large experimental units have been built for test purposes.

Improvements have not been limited to the large units but have extended to smaller equipment for industrial plants.

As the demand for power increased, the need for a more complete technical knowledge of combustion and the properties of coals was realized. The chemistry of combustion and its physics as regards the necessity of having ample "temperature, time, and diffusion" were well understood in 1840⁹, but such knowledge was not well disseminated.

To meet the demand for more complete knowledge of the properties of American coals, the Federal Geological Survey established the United States Fuel Testing Plant at St. Louis, Mo., in 1904. Complete reports¹⁰ of the steaming and other tests that followed were published by the Federal Bureau of Mines when it was established in 1910.

⁹ Williams, C.W., *Combustion of Coal*, Liverpool, England, 1840.

¹⁰ Breckenridge, L. P.; Kreisinger, Henry; and Ray, W. T.; *Steaming Tests of Coals and Related Investigations*, September 1, 1904, to December 31, 1908; Bureau of Mines, Bulletin 23, 1912, 380 pp.

This and other Bureau of Mines publications, which were distributed widely, made data available on testing methods, chemistry of combustion, conduction and radiation of heat, and drafts; other publications contained information helpful to operators of small plants.¹¹

The successful adaptation of pulverized coal to the firing of large boilers was an important forward step in the utilization of coal. The idea of pulverizing coal was not new; the United States Navy experimented with pulverized coal in 1876.¹² It has been used successfully to fire cement kilns and to perform various metallurgical operations. Application to boilers had not been satisfactory, because the combustion chambers were too small, the flames impinged directly on refractory walls and destroyed them, and no satisfactory method had been devised either to prevent complete fusion of the coal ash or to remove it in fluid form.

In 1917 a report¹³ of the Bureau of Mines showed that a long travel of flame was required to give complete combustion unless the air and the combustible were mixed vigorously. When furnaces for pulverized-coal firing were so built they gave satisfactory performance and good efficiencies.¹⁴ The cooperative work of the Bureau of Mines and the Milwaukee Electric Railway and Light Co., resulted in the first successful application of pulverized fuel in the steamboiler field.

In the earlier designs successful removal of the ash required that the particles be deposited in a dry or unmolten state. These dry-bottom furnaces were not so successful with coals having

low-fusion ashes. The problem was solved by going to the other extreme of maintaining the ash in a liquid state and tapping it intermittently or continuously; the wet-bottom furnace was the outcome.

Operation of these furnaces depends largely on the properties of the coal ash and its slag. As relatively few data were available, the Bureau of Mines initiated in 1929 a study on the ash factor in such furnaces and the properties of coal-ash slags in general.¹⁵

The work of the Bureau of Mines on the length of travel of flames required to give complete combustion proved experimentally the importance of ample volume for the combustion chamber. By its educational effect the publication of the work was largely responsible for the practice of raising boiler settings and increasing furnace volumes in hand- and stoker-fired, as well as pulverized-coal furnaces, with resultant improvement in operation.

The size of stokers has increased rapidly, and the zoning of the air has permitted increased rates of burning in both the traveling and underfeed types. The grates of underfeed stokers have been water-cooled to chill the slag of lower-grade coals having low-fusion ash.

An outstanding development is the application of spreader-type stokers in the industrial plant. These stokers are particularly efficient in the utilization of lower-grade coals. Their application increased rapidly after the Bureau of Mines study had been made and the stoker was widely used in plants owned by the Government.

Perhaps the most accurate measurement of economy in the use of fuel is given by the records of the generation of power from coal by the public utilities. The figures available show a decrease in the average consumption of coal per kilowatt

¹¹ Kreisinger, Henry: *Hand Firing Soft Coal Under Power Plant Boilers*; Bureau of Mines, Technical Paper 80, 1916, 83 pp.

¹² *Annual Report of the U. S. Steam Engineering Bureau, 1876*, Navy Department.

¹³ Kreisinger, Henry; Augustine, C. E.; and Ovitz, F. K.: *Combustion of Coal and Design of Furnaces*; Bureau of Mines Bull. 135, 1917, 144 pp.

¹⁴ Kreisinger, Henry; Blizard, John; Augustine, C. E.; and Cross, B. J.: *An Investigation of Powdered Coal as Fuel for Power-Plant Boilers*, Bureau of Mines Bull. 223, 1923, 82 pp.

¹⁵ Nicholls, P., and Reid, W. T.: "Fluxing of Ashes and Slags as Related to the Slagging-Type Furnace", *Trans. Am. Soc. Mech. Eng., Research Papers*, vol. 54, RP-54-9, 1932, pp. 167-180; "Slags from Slag-Tap Furnaces and Their Properties," *Trans. Am. Soc. Mech. Eng.*, vol. 56, 1934, pp. 447-465.

hour from 7.05 pounds in 1899 to 3.2 pounds in 1919 and to 1.44 pounds in 1936. Since the most efficient modern stations are producing kw.-hour from 0.8 pound of coal, a further decrease in the average may be expected as new equipment replaces old.

Locomotive Field

The general principle of the design of the firebox and boiler of coal-burning locomotives has not changed materially from the earliest days. Recent advancements have followed the same lines as in stationary plants: Higher pressures, superheat, double-expansion engines, mechanical stokers, and increase in weight, capacity, and tractive power. Stokers of standard type are used widely. Pulverized coal has been tried but efficient combustion is hindered by the requirements of restricted furnace volume, high rate of combustion, ejection of all the ash from the stack, and prevention of the tendency to slag the boiler surfaces.

The decrease in coal consumed per ton-mile since 1919 has been more than 31 percent for freight and more than 18 percent for passenger service.

The Marine Field

The superior handling property of a liquid fuel for ships is so great that more than 75 percent of the ships now burn oil.

There have been great advances in marine power plants, turbines replacing reciprocating engines, higher steam pressures, and superheat. The use of stokers has been limited.

Pulverized coal has been used more or less experimentally, as has pulverized coal suspended in oil. The use of both these fuels undoubtedly would have progressed further were it not for the ample supply of fuel oil.

Most of the research work on power plants for ships has been done by naval departments of the various countries and by some of the large shipping companies.

The Bureau of Mines made a rather complete series of comparative tests in 1917

and 1918 for the Emergency Fleet Corporation. Boilers of the water-tube type were tested with hand-fired coal, stoker-fired coal, and oil. A Scotch marine boiler was tested with hand-fired coal, pulverized coal, and oil.¹⁶

The Ceramic Field

The fashioning and burning of ceramic ware is one of the oldest arts, reaching back to the earliest civilization. Until relatively recent times wood was the only fuel, and, except for the coarser ware, the artisans were reluctant to change to coal because of the effects of the smoke, sulfur, and ashes on the ware.

Although the use of coal became a necessity, the correct firing and timing were, until recent years, a matter of training and judgment. In large part they still are, because of the intermittent burning, the large mass of ware, and the inaccessibility of the ware. With the greater use of the continuous type of kiln the full advantage of instruments and controls became possible.

The ceramic industry has profited much from research carried on in America and other countries in all phases of the art. In America the heavy-ware (bricks, tiles, etc.) has been the more important. Because the plants for such ware are small and scattered and have little opportunity for coordinated research, aid has been given them by some States and the Federal Government. Many investigations¹⁷ have been made, covering different phases of the use of coal, in the main attempting to determine possible improvements in exist-

¹⁶ Kreisinger, Henry; Blizard, John; Mumford, A. R.; Cross, B. J.; Argyle, W. R.; and Sherman, R. A.; *Tests of Marine Boilers*, Bureau of Mines, Bulletin 214, 1924, 309 pp.

¹⁷ *Special Summary Report No. 86 on the Kiln Investigations*, Mellon Inst. of Ind. Research, 1928; *The Burning Problems of Industrial Kilns*, 1924, Bureau of Mines and the Heavy Clay Products Associations; *Problems in the Firing of Refractories*, Bureau of Mines, 1927, 197 pp.; *Tests on Brick Kilns Fired with a Stoker*, Bureau of Mines, Report of Investigations 3122, 1931, 20 pp.; *Burning of Coal in Down-Draft Ceramic Kilns and Burning Characteristics of Some Ohio Coals*, Bureau of Mines Technical Paper 598, 1939, 34 pp.

ing types of plants rather than to evolve new types of kilns, the construction of which would require large investments.

The Metallurgical Field

The use of heat in the procurement and adaptation of metals for the use of man is also an ancient art; as in the pottery industry, for centuries wood was the only fuel available. This restriction, since the ash of wood is relatively free of materials that affect adversely the qualities of metals, resulted in the production of such high-grade material as the famed Damascus steel.

The principal methods of using fuel in practical operations are:

1. The admixture of the solid fuel with the ore, as in blast furnaces for the production of pig iron, or with the metal, as in foundry cupolas for melting cast iron. Although hard, non-caking coals can be used, high-temperature coke is usually the more economical fuel.

2. The exposure of the metal to the flames in furnaces in which the metal is not in contact with solid fuels, as in reverberatory, reheating, and many other types of furnaces. Gas is the fuel usually preferred, but pulverized coal now has extended use.

3. The melting of the metal in crucibles. Gas is the common fuel, but pulverized coal has been substituted in some instances.

Thus, the use of raw coal in metallurgical operations is rather limited to its pulverized form, the burning being equivalent to that of gas. The largest use is as coke in blast furnaces; many investigations¹⁸ have been made to determine the relation between the properties of the coke and the quantity required per ton of iron. Considerable raw coal is used in gas producers for making gas for metallurgical furnaces.

¹⁸ Perrott, G. St. J., and Sherman, Ralph A.: "Reactivity of Coke in Relation to Blast-Furnace Operation," *Proc. Eng. Soc. West. Pennsylvania*, vol. 39, 1924, pp. 351-360. Royster, P. H., and Joseph, T. L.: "Effect of Coke Combustibility on Stock Descent in Blast Furnaces," *Trans. Am. Inst. Min. and Met. Engrs.*, vol. 70, 1924, pp. 224-233.

Progress in the efficient use of fuels has accompanied and, to a large extent, has depended on improvement and increase in size of furnaces.

Functions of Government Research

The foregoing short reviews of progress relating to the combustion of coal illustrate to some extent the type of aid which the Federal Government has given to the individual citizen and to industry. Except for the work which the Navy Department has done, no Federal Agency other than the Bureau of Mines has been required to conduct researches related to the burning of coal or its derivative, coke.

The investigations conducted in the past have not been selected according to a pre-arranged schedule or from a charted set of relationships. Rather, the choice has been guided largely by the needs at the time, and help has been given where it seemed to be most required. Nevertheless, the investigations fall into certain groups and indicate trends in the policies on which the selection of subjects for investigation was based. Two important contributing factors that should be recognized are the state of knowledge and the training of engineers in subjects related to the combustion of coal.

When investigations were begun under Government auspices in 1904 the dispersion of knowledge on coal and its combustion was limited, and little attempt had been made to train the engineers of plants or educate the firemen. Of course, coal was burned for the purposes needed, but on combustion much less information was available than on steam engines, for example. College courses included only the most meager instructions on fuels and their combustion; in fact, the terms "combustion" and "fuel engineer" did not appear until about 1925.

The main types of research on coal as a fuel and brief discussions of each follow. References to publications in each group are restricted to a few for illustration.

1. *Investigations made at the request of or for other Governmental departments.*—The Bureau has rendered continuous

service as fuel and combustion engineer for all Government-owned heating and power plants. Special investigations are made for departments on request, for example, the study made for the Emergency Fleet Corporation¹⁹ and that for the War Department²⁰ to determine the values in fuel equivalents of coals purchased by the various Army Posts.

2. *Investigations on fundamentals of combustion, fuel beds, and furnaces.*—The conduct of investigations on fundamentals and principles should not be restricted by lack of facilities or by limitations of time. Because generally no direct or immediate return can be realized, and because the results should be given wide publicity, such work is particularly the province of a Governmental institution.

The fundamental investigations²¹ of the Bureau of Mines have received wide approval both in America and abroad. They have been of great value both educationally and in industry.

3. *Investigations resulting in publications of an educational nature to those concerned with the operation of furnaces.*—Although all publications may be classed as educational, publications of the Bureau of Mines, especially those issued in earlier years, have been of great benefit not because of the technical data presented but because of the wide interest aroused in the operation, attendance, and care of furnaces and boilers. The fact that the publications were free or their cost low facilitated their missionary effectiveness.²²

4. *Investigations on the properties of*

¹⁹ See footnote 16.

²⁰ See footnote 4.

²¹ Kreisinger, Henry; Ovitz, F. K.; and Augustine, C. E.; *Combustion in the Fuel Bed of Hand-Fired Furnaces*; Bureau of Mines, Technical Paper 137, 1916, 76 pp.
Nicholls, P.: *Underfeed Combustion, Effect of Preheat, and Distribution of Ash in Fuel Beds*; Bureau of Mines, Bulletin 378, 1934, 76 pp.
See also footnote 16.

²² Barkley, J. F.: *Questions and Answers for the Coal Fireman*; Bureau of Mines Handbook, 1930, 17 pp; *Questions and Answers for the Home Fireman*; Bureau of Mines Handbook, 1936, 24 pp.

American coals and cokes and results obtained when they are burned under various conditions.—Many investigations made by the Bureau of Mines are of this survey type. They are appropriate governmental work, because they include coals from all States and do not favor any particular type of furnace or boiler. The two most comprehensive investigations of this group are those covering combustion of coals under small industrial boilers²³ and in household-heating boilers.²⁴

5. *Investigations to determine the burning characteristics of coals and cokes.*—In this class of investigation the conditions under which the fuels burn are under close control, so that results are highly accurate and are independent of other factors.²⁵

6. *Investigations on properties of clinkers and slags and their relation to the burning of fuel.*—The compositions of coal ash vary over a wide range, and the relation between composition and properties of clinkers and slags is complex, as is that between the burning of the fuel and clinker and slag formations.²⁶ These investigations are of wide interest, they should include all kinds of coal, and, because of the time required, should be continued until completed. These requirements are fulfilled under governmental auspices.

7. *Investigations to determine the justification for claims made for classes of proprietary products or devices to be used in connection with the burning of fuels.*—Government departments frequently receive requests from inventors and others that they make tests of their devices or ideas. If the sale and the use of some

²³ See footnote 11.

²⁴ See footnote 4.

²⁵ Nicholls, P., and Landry, B. A.; *Coke as a Domestic Heating Fuel*; Bureau of Mines Report of Investigations 2960, 1929, 18 pp.

²⁶ Nicholls, P., and Selvig, W. A.; *Clinker Formation as Related to the Fusibility of Coal Ash*; Bureau of Mines Bulletin, 364, 1932, 71 pp.
Nicholls, P., and Reid, W. T.; "Viscosity of Coal-Ash Slags," *Trans. Am. Soc. Mech. Eng.*, vol. 62, 1940, pp. 141-153.

class of product becomes general and if the truth of the claims made is questionable, an investigation may be desirable, especially if the product is sold to householders. Such investigations have been made by the Bureau of Mines.²⁷

8. *Investigations conducted in cooperation with an association of an industry, a technical society representing an industry, or a combination of manufactures.*—The purpose of such an investigation is to assist in studies of problems common to an industry or to aid in the testing of some new development. The Bureau of Mines has conducted a number of such cooperative investigations.²⁸

9. *Investigations to obtain data required in the preparation of specifications or codes.*—This type of work is done for, or in cooperation with, committees of technical societies,²⁹ appointed to formulate specifications or codes to standardize methods of test or measurement or to fix definitions for qualities. These activities are important and are a public service; the greater part of the experimental work required is done in governmental laboratories. Cooperation of this type can be expected to increase in the future.

10. *Investigations relative to smoke abatement.*—The production of smoke and soot is one of the factors observed in all studies on combustion of coal.³⁰ The

Bureau of Mines has developed methods of test for atmospheric pollution; at the request of cities it also has cooperated³¹ in making surveys to determine degrees of pollution and in attempts to abate the nuisance. The power to enact laws governing atmospheric pollution belongs to the States; the customary practice has been for the State to transfer the responsibility to each city or community by empowering it to issue ordinances should it so decide.

The subject is so important and standardization and unification so logical that the Bureau of Mines continually receives calls for help. The Bureau has issued many publications on smoke-abatement work.³²

The foregoing list does not include the "selection of coals" for specified services or the chemical analysis of the ash and its fusion properties; nor does it include the relation between the burning characteristics and the chemical and physical properties of coals, such as chemical analyses, caking and coking properties, ignition characteristics, and size. One of the main objects of all investigations on burning is to correlate results with other properties so that coals may be selected for specified uses and fulfill specified requirements of adaption and efficiency.

An important function of the Bureau of Mines—and one of its most useful contributions to industry—has been that of making data available on the properties of coals from all fields. For this function the first requirement is the development of methods of test for each property and the standardization of definitions and test specifications through cooperation

²⁷ Nicholls, P., and Staples, C. W., *Removal of Soot from Furnaces and Flues by the Use of Salts or Compounds*: Bureau of Mines, Bulletin 360, 1932, 76 pp.
Nicholls, P.; Rice, W. E.; Landry, B. A.; and Reid, W. T.; *Burning of Coal and Coke Treated with Small Quantities of Chemicals*: Bureau of Mines, Bulletin 404, 1937, 158 pp.

²⁸ Sherman, Ralph A., *A Study of Refractories Service Conditions in Boiler Furnaces*; Bureau of Mines, Bulletin 334, 1931, 144 pp.
Kreisinger, Henry; Argyle, W. R.; and Rice, W. E., *Fuel-Efficiency Tests on Batch Oil Still*, Bureau of Mines, Bulletin 302, 1929, 84 pp.

²⁹ American Society for Testing Materials: Sectional Committee on Classification of Coals; Committee D-5 on Coal and Coke.

³⁰ Randall, D. T., and Weeks, H. W., *The Smokeless Combustion of Coal in Boiler Furnaces, with a Chapter on Central Heating Plants*: Bureau of Mines Bulletin 40, 1912, 188 pp.

³¹ Monnett, Osborn; Perrott, G. St. J.; and Clark, H. W., *Smoke-Abatement Investigation at Salt Lake City, Utah*: Bureau of Mines Bulletin 254, 1926, 98 pp.

³² Barkley, J. F., *Smoke Abatement—Selections from Papers by O. P. Hood*: Bureau of Mines, Information Circular 7016, 1938, 19 pp.; *Some Fundamentals of Smoke Abatement*: Bureau of Mines, Information Circular 7090, 1939, 59 pp.; *Reduction of Fly-Ash Emission from Chimneys*: Bureau of Mines, Report of Investigations 3472, 1939, 10 pp.

with committees of national societies. Based on these specifications, tests are required of thousands of samples of coals from all districts; moreover, these must be kept up to date. The initiation and maintenance of this work is definitely a governmental responsibility. It requires reliability, assurance of continuation, independence, lack of bias in the selection of coals to be tested, and distribution of publications at low cost.

For the future it is desirable that the number of properties standardized shall increase until complete data on all coals are available. A knowledge of the relation of the combustion characteristics to qualities of coal will permit intelligent selection for each type of use.

Future Trends in Governmental Research

The preceding discussion has shown that the selection of the types of investigation relating to the combustion of fuel carried out by the Bureau of Mines was not fixed by definite rules or sequences but that decisions were guided by requirements and conditions at the time when new projects were started. This approach should continue in the future. A Federal agency is particularly fitted to work on projects that require contact with many people or require considerable cooperation. The findings of a Federal laboratory are not looked upon as being prejudiced from any commercial interest, as are findings by commercially controlled laboratories. A commercial laboratory frequently asks the Bureau to repeat a research problem it has performed so that the findings will be more acceptable to the trade.

More work should be done on fundamentals and principles and on subjects of very broad scope, such as on properties common to all coals. Investigations of this type should be conducted in the most thorough manner and above all, once they have been started, should be carried to completion. These requirements are fulfilled with more certainty when investigations are undertaken by established Government bureaus.

A number of known research problems

could be undertaken if funds were available. These problems are not only laboratory problems but also research problems of a nature that could be solved only by large-scale operations in the field. The lack of funds for these large-scale studies in the field prevents the Bureau from obtaining the solution of many important problems.

Research studies should be started on the sizing of coal, since the size composition has a marked influence on characteristics in burning; the ignitibility and reactivity of coal; coking, agglutinating, and swelling properties of coal; nature of the volatile matter in coal; the ash, its fusion and its slag-producing characteristics; and many details in connection with the control and operation, as well as the design of virtually all modern equipment. Much more knowledge is needed on the grindability of the various coals. Another property that also affects pulverization is the abrasive nature of coal, about which little is known. Many inquiries have come to the Bureau concerning the improved fuel efficiency to be expected from the installation of thermostatic control of hand-fired domestic heaters; these can not be answered at present. Research is needed to determine the proper setting heights of medium-size boilers. This problem has confronted manufacturers, operators, and smoke-abatement engineers for many years. It is a commercial laboratory and field problem that would save manufacturers and users much expense if it were properly solved. Much remains to be done on studies of fly-ash elimination in medium-size boiler equipment. This, again, is a problem having immediate economic results.

Further study is desirable on small domestic stokers as to tuyere shape and agitation of the fuel bed. Considerable work is yet to be done on the utilization of anthracite, especially in the smaller units.

Coal producers see the great need for research on coal but for economic reasons have been unable to expend the amounts they desire on such work.

CARBONIZATION

By D. A. Reynolds¹

Many of the natural resources of the United States have been seriously depleted. Virgin forests are nearly exhausted, many of the rich beds of ore are exhausted, and the proven reserves of petroleum are estimated to last only 10 to 20 years. In contrast, the wealth of coal has been reduced but slightly if considered on a basis of tonnage. Only 0.5 to 2 percent of the original supply of bituminous coals has been consumed; the estimated reserves are more than 3 trillion tons of coal of all ranks, including lignite.² These reserves are enough to supply the needs of this country for several thousand years at the present rate of consumption.

Although a small proportion of the reserves is coking coals, usable in modern byproduct ovens (singly or in blends), such coal constitutes a large proportion of the total coal mined in this country. As the quantity of coal carbonized in the United States in any normal year equals 16 percent of all the coal used, it is evident that much coking coal is consumed outside the carbonization industry. Conservation of valuable coking coals is necessary. It may be accomplished by using a greater proportion of less valuable noncoking coals for heating and steam raising, and by extending the range of coals adaptable to coke making.

Industrial Developments

High-Temperature Carbonization

Coke was made in Germany as early as 1584. The beehive oven was patented in England in 1620 but was not used extensively until about 1735. Scientific coal carbonization started with the development of the byproduct oven during the

latter part of the last century. Although tar, ammonia, and benzol were recovered in early types of ovens, the value of the excess gas was not generally realized until after the end of the World War. At that time synthetic ammonia displaced ammonia from the list of profitable byproducts, and gas became important because of economic necessity. The use of blast-furnace gas of low heating value for heating coke ovens, a process developed in Europe, was an important development, because it enabled operators to dispose of the richer coal gas advantageously. Attention was also directed to the quality of byproduct coke, which, according to blast-furnace operators, had never equaled beehive coke; larger ovens heated more uniformly came into use, and both the quality and uniformity of the coke improved. Narrow ovens were found to produce coke of more uniform cell structure and to give higher yields of byproducts.

Recent modifications of commercial byproduct ovens permit better control of the composition of the volatile products. The Still method minimizes cracking to increase the yield of paraffin hydrocarbons, whereas the Goldschmidt method does the reverse to obtain high yields of aromatic hydrocarbons. The Koppers method permits the operator to control the heating of the volatile products and thereby vary the yields of paraffin or aromatic hydrocarbons.

Although the American byproduct industry is only about 40 years old, it substantially has relegated the old beehive type of oven to marginal production. Its magnitude can be realized from the statistics of 1929, when maximum production was reached: Coke, 53 million tons; gas, 843 billion cubic feet; tar, 681 million gallons; ammonium sulfate, 856,214 tons; crude light oil, 201 million gallons.³

¹ Associate Chemist, Central Experiment Station, Bureau of Mines, Pittsburgh, Pennsylvania.

² National Resources Committee, *Energy Resources and National Policy*: Document 160, 76th Congress, 1st Session, 1939, 435 pp.

³ Bureau of Mines, *Mineral Resources of the United States*, 1929, Part II, p. 574

Low-Temperature Carbonization

Low-temperature carbonization processes are designed to decrease the smoke nuisance, to increase the efficiency of fuel utilization, and to provide raw materials for other industries. Although early investigations of this subject were made in the United States, the work has been extended largely in countries with limited petroleum resources, which recognized that liquid fuels could be synthesized from their coal deposits.

During a recent 10 year period the production of low-temperature tar in Germany multiplied about fivefold—from 200,000 tons in 1929 to 1,000,000 tons in 1938.⁴ This growth resulted from a demand for: (1) Low-temperature coke to be used as a fuel; (2) coke as a source of hydrogen for hydrogenation processes; and (3) primary tar for conversion into liquid fuels. The fact that Germany has met about 50 percent of her peacetime needs of gasoline proves that coal processing has succeeded in supplying materials necessary to the synthetic oil and gasoline processes. Blends of coking and noncoking coals are carbonized at low temperatures in Germany to conserve valuable supplies of coking coal; 20 to 30 percent higher yields of oil are thus obtained. England has the world's largest low-temperature carbonization plant for bituminous coal with a daily capacity of 500 tons. This is one of four plants producing "Coalite," which have a combined daily capacity of 2,000 tons.⁵ Important byproducts of this process are petrol, diesel oil, and tar for conversion by hydrogenation.

In the United States, where there is no immediate need for obtaining liquid fuels from coal, low-temperature developments have been designed to use certain fuels more efficiently. Washed screenings or dust from a plant cleaning Pittsburgh bed coal are converted into Disco; a high-grade smokeless fuel, by the modified

Wisner process. This plant has a daily capacity of 325 tons of screenings; tar and oil products are marketed.⁶ A plant at Dickinson, N. D., converts lignite into smokeless briquettes (60,000-70,000 tons of briquettes annually) by the Lurgi process.

The diversity of methods developed in various countries for the low-temperature carbonization of coal is owing partly to the wide variations in composition and properties of coal suitable for this treatment. A standardization of practice comparable with that attained in high-temperature carbonization is not likely to be reached.

Medium-Temperature Carbonization

The Curran-Knowles sole-flue oven process produces a coke that is more combustible than high-temperature coke and therefore is more satisfactory for domestic use. The chief advantages of this process are that any coal may be carbonized without damage to the oven and the capacity is greater than that of many low-temperature processes. Two plants using this process operate near St. Louis, Missouri, with daily capacities exceeding 300 tons of coal and two Canadian plants have a combined annual capacity of 50,000 tons.

Research on the Carbonization of Coal

Coal Composition

Of all factors affecting the carbonization of coal, none is as important as the constitution of the coal itself and the fact that so much about this subject is unknown affords ample proof of its complexity. Formulas have been derived whereby the yields of carbonization products may be calculated from the proximate analysis of the coal and the composition of byproducts has been related to the chemical composition of the coal. Investigations of the macroscopic constituents of coal indicate that the quality of coke is modified by the type of coal carbon-

⁴ *Iron and Coal Trades Review*, "German Low-Temperature Tar Production," vol. 139, 1939, p. 285.

⁵ Thau, A., "Status of Coal Carbonization," *Gas u. Wasserfach*, vol. 81, 1938, pp. 902-905.

⁶ Leshar, C.E., *Production of Low-Temperature Coke by the Disco Process*: Am. Inst. Min. & Met. Engrs., Technical Publication 1176, 30 pp. 1940.

ized; bright coals have stronger swelling and agglutinating properties than associated splint coals. Fusain, a coal constituent occurring in variable amounts, increases the strength of coke from certain coals when present in amounts up to 10 percent of the coal charge.

Plasticity of Coal

The characteristics of coal in the plastic state have been studied widely in the past twenty years. Results of Bureau of Mines investigations, which have dominated this phase of coal research in this country, may be summarized as follows: An accepted modern concept of coal plasticity has been established. A new instrument for measuring the plastic properties of coal has been devised which has proved to be superior in certain respects to other types. Investigations of various methods for determining plastic properties show that the most complete information is given by the Agde-Damm dilatometer for the pre-plastic range and by the Davis plastometer for the plastic range, and that the Gieseler plastometer affords a better index of the fluidity of coal. Application of these methods to a large number of coals showed that: (1) Splint coals are less fusible than bright coals; (2) the fluidity of extremely fluid coals is reduced by moderate oxidation which may improve their coke-making property; (3) the low fluidity of high rank coals is reduced enough by slight oxidation to destroy their coking properties.

Results of European investigations indicate that pressure applied to the charge during the carbonization of poorly coking coals modifies the plastic coal, thereby improving the strength of coke. Carbonization under pressure may, therefore, be a means of extending the range of coking coals.

Blending Coals and Inerts

Because most coking coals yield better coke when blended with other coals, blending is of prime importance in coal carbonization. Not only are blends of coking coals carbonized but non-coking coals,

anthracite, pitch, and pulverized coke have been used. Important factors in the carbonization of blends are particle size, mixing, plastic and miscellaneous properties of the constituents. A large number of carbonization tests have shown that the properties of coke from blends are not always an average of those of the constituent coals. Each coal must be considered as a separate blending problem; there is no fixed proportion of low-volatile coal which will give optimum results with different high-volatile coals. Certain European coals are blended with coke breeze or oxidized coal to reduce swelling and to improve the quality of coke.

Expansion of Coal During Carbonization

Coals that develop unsafe pressures can not be used in byproduct ovens without risk of serious damage to the oven walls; therefore, the measurement of such pressures experimentally is important to operators. Various methods of measurement have been devised but none of these has been accepted as standard. The Bureau of Mines has studied this problem using two electrically heated test ovens and has found that the contraction of the charge in the pre-plastic range and of the coke are practically constant factors for different coking coals and therefore concluded that the expanding properties of coal are determined by its behavior while plastic. The vertical slot oven, developed by the Bureau to carbonize 400-pound charges with two-sided heating, affords a satisfactory means of determining the expanding properties of coals.

The BM-AGA Method of Experimental Carbonization

A large number of assays for determining the coke- and byproduct-making properties of coal have been developed but these methods give little information concerning the quality of products because of the small amount of sample carbonized. In 1929 the Bureau of Mines, in cooperation with the American Gas Association, developed a carbonization test using charges

weighing up to 200 pounds. The yields of coke and byproducts from this test are large enough to be tested by standard methods, thereby affording more complete data than are obtainable from tests on a smaller scale. Forty-eight coals have been carbonized by this method at high, medium, and low temperatures, and the qualities of the cokes and byproducts determined. Petrographic, agglutinating, plastic, expanding, friability, slacking, and oxidizing properties of these coals have been studied also. The comparison of test results and plant data (available for some coals) is an important part of this work and the agreement has been close enough fully to justify confidence in the method of test. Referring to the results of these investigations, Mulcahy wrote:⁷ "Although much work on coal has been regarded as too fundamental or theoretical to be of practical value, the work of the Bureau of Mines in this respect is of tremendous value in indicating the trends we can expect under different carbonizing conditions."

Future Research on Coal Carbonization

In the interests of conservation, research on carbonization of coal should be continued in the high-temperature, medium-temperature and low-temperature fields. High-temperature coke must be improved both in uniformity and quality to meet the more exacting demands of future metallurgical processes. The operation of byproduct ovens must be modified so that a broader range of coals may be used for the production of metallurgical coke. Research on low- and medium-temperature carbonization should be directed toward more efficient utilization of all ranks of coal and lignite as fuels and toward the elimination of the smoke nuisance. All research on carbonization of coal should anticipate that this industry may be called upon to supply materials for

the production of synthetic liquid and gaseous fuels as the natural supply of these decreases.

Plasticity of Coal

Although the plastic properties of coals have received much attention both in this country and abroad, there is need for standardization of methods and definitions. More attention should be given to the plastic properties of blends in order to conserve the supply of the best coking coals. Knowledge of the plastic properties of lower grade coals will accelerate the development of processes for their utilization as fuel and as constituents of blends for coke-making.

Expansion of Coal

Investigation of the expansion of coal has been confined largely to the development of apparatus and the study of fundamental factors. Future studies should deal with the influence of density of charge, width of oven, rate of heating, and content of moisture, size and composition of the coal.

Coke- and Byproduct-Making Properties of Coal

In the carbonization laboratory of the Bureau of Mines, the government has facilities for determining the yields of coke and byproducts obtainable from coal at various temperatures; the tar and coke testing laboratories provide for testing the products of carbonization. Many of the coking coals of the United States have been tested in these laboratories. The following factors should be investigated in relation to coal carbonization: density of charging, moisture content of coal, particle size, ash composition, effects of washing, and composition of coal. Attention should be given to the improvement of coke for both metallurgical and domestic use through the blending of coal with other coal and with inert materials. The production of metallurgical coke from some of the coals of the Pacific Northwest should be investigated in view of the desirability of a steel

⁷ Mulcahy, B. P., *Foundry Coke. An Interpretive Discussion*: American Gas Association Production Conference, New York, N. Y., May 23, 24, and 25, 1938, 14 pp.

industry in that region. More accurate methods of measuring the strength and burning characteristics of coke should be developed.

Utilization of Sub-bituminous Coals

In 1937 the Bureau of Mines extended its studies on the utilization of American coals to include further investigations on the utilization of sub-bituminous coals and lignites. A field station was established at Golden, Colorado, and

Production and Use of Coal

equipped to develop improvements in the utilization of lower-rank Colorado coals for power production and domestic heating. Experimental investigations were made at the Central Experiment Station on certain physical and chemical properties of these coals.

Carbonization processes which have been used on low-rank European coals should be investigated to determine their applicability to American coals.

G A S I F I C A T I O N

By Martin.A. Elliott¹

Introduction

Coal may be gasified at elevated temperatures by two fundamental processes, namely, destructive distillation in the absence of air, or chemical reaction with air, steam, or certain other gases. In the destructive distillation of coal a solid residue of coke remains after the gas, light oil, and tar are volatilized. This coke is also a solid fuel and can be gasified by chemical reaction with air and steam just as the coal from which it was derived. Therefore, as coke and coal are so closely related, all processes in which either fuel is gasified should be considered.

Coal or coke may be gasified in conjunction with the gasification or chemical transformation of other fuels. For example, in the carbureted water gas process, coal and oil may be gasified in a single apparatus. Similarly in the reforming of natural or refinery gas in the fuel bed of a water gas generator, coke is gasified and hydrocarbon gases are cracked.

This report reviews developments and progress in the technology of gasifying coal or coke either in fundamental gasification processes or in combinations and modifications of these processes. The report points out the relation between progress and research whenever this is indicated.

Gasification by Destructive Distillation Historical

The gasification of coal by distillation in a retort was reported as early as 1688 by John Clayton, a clergyman of Yorkshire. However, no practical use was made of this discovery until 100 years later when William Murdoch, also an Englishman, lighted one room of his

home with gas obtained by distilling coal in an iron retort. In the 100 years following Murdoch's demonstration that gas could be generated from coal and stored for future use, the cast iron retort was replaced by the fireclay retort which eventually was replaced in the United States by the modern byproduct coke oven. Some of the more important developments affecting this transition in production technology will be discussed.

In the early days of the gas industry the primary objective in distilling coal was to produce a rich gas that would burn with a luminous flame. However, when the incandescent gas mantle was developed between 1885 and 1893 by Carl Auer von Welsbach, the production of a gas having a high illumination power was no longer required. This development affected production technology because it permitted the use of gasification processes and techniques yielding gas of a lower heating value. Thus, for the first time, laboratory research which started originally in the field of pure chemistry had a profound influence on the technology of coal distillation for the production of gas, and in fact was one factor responsible for the ultimate use of the byproduct coke oven by the gas industry. Although the incandescent mantle was responsible for the change from the production of a rich gas to the production of a leaner gas, this change was accelerated by the increasing use of electricity for lighting.

The invention of the atmospheric gas burner in 1855 by Robert Wilhelm Bunsen was another development attributable to research that contributed indirectly to progress in the gasification of coal. The importance of Bunsen's contribution is apparent when it is realized that he made available a simple, inexpensive, easily controllable device for burning gas with a smokeless flame.

⁶ Gas Engineer, Explosives Division, Bureau of Mines, U. S. Department of the Interior.

The contributions of applied research to progress in the gasification of coal frequently are reflected in increased operating efficiency. It is of interest therefore to show the progress made for a period of one century in the efficiency of gasifying coal in retorts. This is shown in Table 1, applying to equipment used in England where the gas retort still is used extensively. In the United States the use of the gas retort has declined in recent years.

Fundamental Research

Fundamental research on coal carbonization and gasification lagged considerably behind the technology of production and it was not until 1902 that the mechanism of coal carbonization accepted today was first postulated. From that time fundamental research has contributed to progress in coal carbonization, particularly in the production of coke. As this has been considered in the section on coal carbonization, it will not be discussed here except to emphasize the contributions made by studies in heat transfer; in the properties of refractories; in fundamental chemistry and physics; and finally the important cooperative research of the Bureau of Mines and the American Gas

Association which is supplying data on the gas, coke-, and byproduct-making properties of American coals.

Prior to the investigation of the Bureau of Mines and American Gas Association no fundamental data were available on the gas-, coke-, and byproduct-making properties of American coals carbonized at various temperatures under standardized conditions. The results obtained in this investigation are of practical and economic value because they permit the preliminary selection of a coal or the blending of coals to achieve a desired result and thus reduce the number of expensive large-scale tests required for a final decision. The investigation has progressed to such a point that it is not possible to estimate some of the gas-, coke-, and byproduct-making properties of coals from data obtained in a chemical analysis of the coal. The data made available by this investigation serve those interested in carbonizing coal for the production of coke as well as those interested in distilling coal for the production of gas. It is singularly significant that this investigation was carried out in cooperation with the gas industry which in its early days had no particular interest in the quality of coke produced.

Table 1.— A Century's Progress in the Gasification of Coal in Retorts¹

Year or period	Type of retort	Approximate carbonizing temperature, °F.	Gas Yield, cubic foot per ton of coal	Heating Value of gas, B.t.u. per cubic foot	Coke consumed for heating retorts, pounds per ton of coal carbonized	Thermal yield in gas, million B.t.u. per ton of coal
1820 to 1830	Horizontal iron	1,100	6,000-7,000	700-750	500	4.7
1860	Horizontal iron fireclay	1,000	6,000	720	300	4.3
		1,500	8,000	660	400	5.3
1910	Horizontal fireclay	1,800	12,000	550	300	6.6
1930	Horizontal Vertical (steamed)	2,000	19,800	530	250	7.3
		2,000	16,000	500	200	8.0

¹ This is a modification of a similar table given in, *Coal-Its Constitution and Uses*, W. A. Bone and G. W. Himus, Longmans Green Company, 1936.

Recent Developments

Recent modifications of byproduct ovens permitting greater control of the composition of the volatile products have been referred to in the section on carbonization. However, it is important to emphasize that these are the results of applied research because they are practical applications of fundamental principles discovered in studies of the mechanism of coal carbonization and gasification.

As the foregoing indicates, the byproduct coke oven is still developing, although the changes are of a more or less minor nature. However, if the comparatively recent proposal to generate gas by distilling coal in an electrically heated retort is used commercially, radical changes in the design of carbonizing equipment will follow. That the use of electricity for this purpose is feasible and possibly economical when cheap off-peak power is available has been claimed in recent publications.^{2 3} Up to the present time (1940) this process has not been used commercially.

The overall thermal efficiency of the modern byproduct oven is high as shown by the results of heat balances on two types of oven which indicated efficiencies of 87⁴ and 89⁵ percent. This efficiency is a measure of the overall performance of the byproduct oven and is the efficiency of converting the energy in the coal charged and in the gas used for heating or underfiring into useful energy in coke, gas, light oil and tar. Considering only the energy in the coal charged, the results of the heat balances referred to in the foregoing indicate respectively that 94 and 98 percent of the energy in the coal is obtained as coke, gas, light oil

and tar. If the ovens are heated or underfired by gas produced in carbonizing the coal, the net yield of energy from the coal will be decreased by the energy in the gas used for underfiring, which according to the forementioned heat balances is approximately 8 to 10 percent of the energy in the coal. Inasmuch as approximately 35 to 45 percent of the gas produced in byproduct ovens would be required for underfiring, the present tendency is to underfire coke ovens with lower grade gases and thus release the higher grade coke-oven gas for other uses.

It is therefore apparent that the modern byproduct coke oven is already an efficient unit, and although further improvement is possible the maximum economic efficiency is being approached rapidly. Further improvement in the coke oven will be obtained at progressively higher equipment cost. Consequently progress in this field will not result in marked gains in the over-all efficiency of utilizing coal. This fact must be considered in formulating a long-range research program.

Gasification of Coal and Coke by Chemical Reaction with Air and Steam General Considerations

All processes in which coal and coke are gasified by reaction with air and steam are based on fundamental chemical reactions of carbon. Three of these reactions, important in generating producer gas and blue water gas, are:

(1) Reaction of carbon with oxygen to form carbon dioxide; (2) reaction of carbon dioxide with carbon to form carbon monoxide; and (3) reaction of steam or water vapor with carbon to form carbon monoxide and hydrogen.

Producer gas is formed when air containing some steam is passed through an incandescent fuel bed. Heat is liberated in the fuel bed by the reaction of carbon with oxygen from the air and this sensible heat is then changed to potential heat in the gas by the reaction of carbon with both carbon dioxide formed in combustion and steam accompanying the air. These

² Curtis, Harry A., Stitzer, Ralph B.; and Darby, Wilbur J., "Fuel Gas Generator, A Development Using Electrical Energy as a Source of Heat;" *Ind. and Eng. Chem.*, Vol. 32, 1940, pp. 757-762.

³ Walker, H. S., "The Carbonization of coal with Electricity," *Gas Age Record*, Vol. 70, 1932, pp. 27-30.

⁴ Wilson, D. W.; Forest, H. O.; and Herty, C. H., *Ind. and Eng. Chem.*, Vol. 15, 1923, pp. 261-264.

⁵ Munster, J. K., *Blast Furnace and Steel Plant*, Vol. 11, 1923, pp. 389-392.

latter reactions absorb heat and therefore by suitable control of the air-steam ratio the fuel bed is maintained at a high temperature. In this process the gas is generated continuously and the coal or coke is gasified completely. However, because of the diluent effect of the nitrogen from the air a gas of low heating value is produced.

Blue water gas is formed when steam reacts with incandescent carbon, consequently this gas is present in producer gas because the air supplied to the process contains some steam. Blue water gas itself may be generated in an intermittent process in which the heating of the fuel bed by an air blast is alternated with steaming to convert most of the stored heat into potential energy in blue water gas. The gas generated in the steaming period is collected; it consists essentially of carbon monoxide and hydrogen and some carbon dioxide from undesirable gasification reactions. Hydrocarbons may also be present in low concentrations when the gas is generated from bituminous coal. In the generation of blue water gas all of the solid fuel is gasified, but only that portion gasified in the steaming period is stored for later use. Thus, the heating value of blue water gas is greater than that of producer gas because water gas is not diluted by nitrogen from the air.

The discussion of the progress in the gasification of coal and coke by chemical reactions yielding producer gas and blue water gas will cover: (1) Contributions of research to the fundamental chemistry of the gasification reactions; (2) mechanical developments leading to increased efficiency and economy; and (3) progress made in the design and operation of gas producers and of equipment for generating blue water gas alone or in combination with either the gasification of oil or the cracking of hydrocarbon gases.

Fundamental Chemistry of Gasification Reactions

Research on the theoretical aspects of the gasification of coal and coke by chemical reaction with air and steam has

yielded valuable data on the thermodynamics and kinetics of the reactions of carbon with oxygen, carbon dioxide, and steam; stoichiometry of these reactions; of fuels; effect of ash and catalysts on the gasification reactions; and the course of the gasification reactions in fuel beds of producers and water-gas generators. These theoretical studies have made information available on the fundamentals of the gasification reactions; this information has been used in establishing the fundamental variables to be controlled in carrying out these reactions on a commercial scale. Without this knowledge progress in production technology would have been greatly retarded and could have been accomplished only by the needless expenditure of effort, money, and material.

An outstanding example of fundamental research leading to increased efficiency of gasification of coal and coke is the work of the Bureau of Mines on the essential factors in the formation of producer gas. This study furnished data on the kinetics of the reactions of anthracite, coke, and charcoal with carbon dioxide and steam. The results showed the importance of temperature, time of contact, and character of fuel, all of which are subject to control in large-scale gasification undertakings.

Many investigators, including the Bureau of Mines, have studied the reactivity or combustibility of coke extensively. Such research has prompted investigations to determine the effect on the velocity of gasification reactions of adding catalysts to coal and coke. The results have indicated that the reaction of either steam or carbon dioxide with carbon is accelerated when comparatively small proportions of sodium or potassium carbonate are present. At the present time (1940) this work has not been applied commercially. However, as pointed out, catalysis of steam-carbon reactions may be applicable to certain gasification processes.

Mechanical Developments Increasing Efficiency in Generation of Producer Gas and Blue Water Gas

Research on fundamental gasification

reactions, applied to the generation of producer gas and blue water gas in the fuel beds of large-scale equipment, indicated the importance of maintaining uniform operating conditions. Variations in such factors as condition and depth of fuel bed, rate of admission of air and steam, and duration of the blast and run or steaming period in the generation of blue water gas can cause both operating difficulties and significant losses in efficiency.

The control of many operating variables has been made possible by the development of automatic equipment for charging fuel, removing ash, controlling air and steam, and operating valves. Such equipment has contributed greatly to increased efficiency and economy in the generation of producer gas, blue water gas, and carbureted water gas and is a result of research and developments in metallurgy, mechanical engineering, and instrumentation.

Developments in the Generation of Producer Gas

Historical Review⁶

When fuel is burned in deep beds secondary combustion of gases similar to producer gas is completed in the space above the top of the bed. Thus, producer-gas reactions have been applied ever since fuel was burned on grates. However, the true producer principle of burning gases generated in deep fuel beds at some place away from the fuel bed was not applied until 1832 when Faur built a gas producer. This was not used widely until the Siemens brothers applied it in connection with their invention of the open-hearth furnace in 1861. The use of producer gas increased until at one time it was an important fuel for heating furnaces, but, in recent years its use for this purpose has declined.

Stationary Producers

Probably the most important development in producer-gas operation was the use of

steam in conjunction with the air blast because it increased the cold-gas efficiency and quality of gas and permitted continuous operation by reducing clinker formation. Other developments in producer operation generally resulted from the adaptation of the producer principle to a specific application and led to the down-draft producer, up-draft producer, suction producer, and pressure producer. In addition, mechanical developments led to variations in the method of feeding and poking and in the method of removing ash. The advances in gas-producer operation attributable to mechanization are shown in Table 2, which was published in a comparatively recent article on gas-producer practice.⁷ Many modifications in producer design have been made in an effort to utilize inferior fuels⁸ efficiently.

Table 2.—Advances in Gas Producer Operation

Kind of gas producer	Year	Coal gasification per —	
		Producer day	Square foot producer area per hour
Hand worked	1910	Tons 5 to 10	Pounds 6.6 to 15.0
Early mechanical	1920	20 to 30	30.0 to 40.0
Modern mechanical	1930	40 to 90	50.0 to 95.5

Mobile Producers

The mobile or portable gas producer for supplying fuel for internal-combustion engines used for road and rail transport and for ship propulsion has been investigated intensively⁹ and applied commercially¹⁰ in Europe because of the deficiency

⁷ Windett, V. A., "A Review of Certain Gas-Producer Practice," *Iron and Steel Inst. Yearbook*, 1931, pp. 218-293.

⁸ *Blast Furnace and Steel Plant*, "New Producer Gasifies Inferior Coal," vol. 27, March 1939, pp. 269-270.

⁹ Institution of Mechanical Engineers, "Coal as Fuel for Internal-Combustion Engines," *Proceedings*; vol. 141, 1939, pp. 363-428. Marais, J. K., "Producer Gas as a Fuel for Internal-Combustion Engines," *Jour. South African Inst. Eng.*, vol. 37, November 1938, pp. 74-111; Fuel Research Inst. (South Africa), Bull. 15, 1938, 70 pp.

¹⁰ Goldman, B., and Jones, N. C., "The Modern Portable Gas Producer." Theory, Design, Fuels, Performance, Utilization, and Economics," *Jour. Inst. Fuel*, vol. 12, February 1939, pp. 103-140

⁶ Haslam, R. T., and Russel, R. P.: *Fuels and Their Combustion*, McGraw-Hill Book Co., Inc., 1926, 809 pp.

of liquid fuels. The use of producer gas from lignite as a fuel for tractors has been investigated in the United States by the University of Minnesota.

Developments in the Generation of Blue and Carbureted Water Gas

Historical Review

In 1780 Fontana discovered blue gas when he passed steam over incandescent carbon and obtained a combustible gas that burned with a nonluminous blue flame. This discovery antedated by 12 years Murdoch's utilization of coal gas for lighting purposes. However, blue water gas was only a theoretical possibility in the early history of the gas industry, although the period 1823 to 1859 was marked by pioneering and experimental work that led to the development, between 1859 and 1875, of retort processes for producing blue water gas or carbureted water gas.¹¹ Much of this work was directed to the development of a process in which blue gas could be enriched with light oils or rosin so that its illuminating power would be comparable to that of coal gas. However, no successful process was available until 1875 when Lowe introduced an apparatus in which the blast gases from the blue-gas generator were burned with secondary air in a chamber adjacent to the generator. The heat thus stored in this chamber was used during the steaming period for cracking oil and "fixing" the oil gas used to enrich the blue gas produced in the generator. Lowe's principle of carbureting blue gas was fundamentally sound; although some minor modifications have been made, it is the basic principle underlying the modern carbureted water-gas set.

Today carbureted water gas is generated in an apparatus consisting of three refractory-lined, cylindrical steel shells known as the generator, carburetor, and superheater. The generator contains a thick fuel bed of coke or sometimes of bituminous coal, which is alternately

bituminous coal, which is alternately blasted with air and then steamed when the air is shut off. During the blasting period a gas of low calorific value similar to air-blown producer gas is generated, and the blast or blow gases are burned with secondary air in the carburetor and superheater. The superheater contains checkerbrick, and the carburetor may or may not be checkered. After the blow or blast period the fuel bed is steamed and the blue water gas thus generated passes into the carburetor into which gas oil is admitted to be cracked. The mixture of blue water gas and products of oil cracking pass through the superheater, where the cracking reactions are continued. The gas, which consists of blue water gas and hydrocarbon gases, is then cooled and purified to remove tar, light oils, and impurities. Although there are many other details and modifications in the generation of carbureted water gas, the essential principles are those outlined here.¹²

Developments in Production Technology

Progress in the technology of producing blue water gas and carbureted water gas is marked by increased thermal efficiency, decreased labor costs, improved control, and greater flexibility in the use of fuels. The following discussion will consider developments in utilizing different fuels in the carbureted water-gas process and in utilizing waste heat. No further reference will be made to the influence of mechanization, as this has already been discussed.

Use of Fuels in the Carbureted Water-Gas Set

Modern carbureted water-gas sets can utilize as raw materials a variety of solid, liquid, and gaseous fuels including coke, anthracite, bituminous coal, gas oil, heavy residuum oil, natural gas, and

¹¹ Stone, T. W., *History of Water Gas*, presented at the 1926 Convention of the Canadian Gas Association.

¹² A comprehensive review of recent developments in water-gas manufacture emphasizes and reviews progress in this field and in related gasification processes. Logan Lloyd, "Water-Gas Manufacture," *Proc. Am. Gas Assoc.*, 1932, pp. 976-1015.

oil-refinery gas. This flexibility in fuel utilization, which was made possible by applied research, enhances the inherent flexibility of the carbureted water-gas process and therefore represents an important advance in production technology.

A discussion of the fuels used in the carbureted water-gas process can be divided conveniently into the solid fuels used in the generator for making blue gas and the liquid and gaseous fuels used for enriching the blue gas or for imparting special properties to the finished gas.

Generator Fuels

Anthracite and coke.—Anthracite was used extensively as a generator fuel in the early days of the water-gas industry. However, when water-gas equipment was used more widely anthracite was not always economical, because the cost of shipping it to more distant places was high. Consequently byproduct coke and retort coke, available locally, were used and today have replaced anthracite as a generator fuel for carbureted water-gas manufacture.

Bituminous coal.—In the winter of 1917-18 the demand for coke by the war industries and the restrictions of the Fuel Administration on the shipment of coke from the eastern States made it virtually impossible for many water-gas plants in the central States to obtain coke. In consequence, some plants, particularly in Illinois, were forced to use bituminous coal as a generator fuel. Although bituminous coal had been used to a limited extent,¹³ no data had been published on the operating problems, of which there were many, as the experience in Illinois indicated. Therefore, to obtain fundamental data needed to solve operating difficulties, the Federal Bureau of Mines, the University of Illinois, and the Illinois Geological Survey Division undertook a cooperative study of the operation of water-gas sets using bituminous coal from the central district as

generator fuel. The results of this study were valuable in solving operating difficulties; in fact, even after the shortage of coke ceased to be a factor bituminous coal was used as a generator fuel in some plants because it was more economical than coke.

Enrichers

Historical review.—In the early attempts to carburet blue water gas such enrichers as resin, cannel coal, and naphtha were gasified in externally heated chambers or retorts. Shortly before the invention of the Lowe process, petroleum derivatives were used extensively by the gas industry. Until recently gas oil was the principle material used for enriching blue water gas. However, other liquids and gaseous hydrocarbons now are also used for this purpose.

Heavy oil.—Before 1920 gas oil was used extensively for enriching blue gas in the carbureted water-gas process. At that time increases in the price of gas oil were feared, and new operating procedures were developed to permit the use of less expensive heavy oils. Since that time the use of heavy oil in the manufacture of carbureted water-gas has become general in the larger gas plants on the eastern seaboard. This development is of interest chiefly because it indicates the effect of economic considerations on the technology of fuel utilization. At present prices of coke and heavy oil (1940) the manufactured-gas industry on the eastern seaboard finds it economical to replace coke by heavy oil. To accomplish this some of the heavy oil is sprayed into the fuel bed of the generator, and the carbon from the cracking of this oil becomes available for making blue gas or for combustion during the blow.

Refinery and natural gas.—Oil-refinery and natural gas have been used extensively in recent years by the manufactured-gas industry. The proportion of these gases that can be utilized without increasing existing heating-value standards is limited by the characteristics of the manufactured gas for which the gas appliances in the system were designed originally.

¹³ Fulweiler, W. H., "Utilization of Bituminous Coal in the Manufacture of Water Gas," *Proc. Internat. Conference on Bituminous Coal*, 1926, pp. 472-513.

To permit the utilization of higher proportions of these hydrocarbon gases without changing heating-value standards or readjusting appliances, operating procedures were developed to re-form or change the characteristics of the hydrocarbons. In the re-forming process natural or refinery gas is cracked by passing it through the incandescent fuel bed of a water-gas set. Carbon, a product of cracking, is deposited in the fuel bed and consequently reduces the use of coke in the process. The hydrogen formed in cracking permits a further reduction, because this gas replaces blue gas which would otherwise be generated from coke.

In the early stages of developing processes for re-forming natural gas the Bureau of Mines cooperated with many operating companies to obtain fundamental data on this process. This applied research assisted greatly in the extension and future development of processes for re-forming natural and refinery gases.

Tar.—Much of the water-gas tar produced from heavy oils is used as boiler fuel because of the lack of any other extensive market. To realize a higher utilization value from this product, some study has been given to the use of various tars as carbureting agents. However, most of the published data apply to European conditions.

Utilization of Waste Heat

The first real progress in the effective utilization of waste heat in generating blue water-gas was the introduction of Lowe's principle of heating the "fixing" chamber internally by burning the blast gases from the generator. Since that time heat losses have been reduced by the use of waste-heat boilers and by modifications in the methods of introducing air and steam. Applied research has been an important factor in this progress.

Waste-Heat Boilers.—The application of the waste-heat boiler to blue and carbureted water-gas sets has reduced greatly the heat carried away by the blast gases and thereby has increased the thermal efficiency of the process. This development is particularly important in

the generation of straight blue gas; otherwise the potential heat in the blast gas would be wasted because in the generation of blue gas no use is made of this potential heat. The carbureted water-gas process uses it to heat the checkerbrick in the carburetor and superheater. However, even in carbureted water-gas operation waste-heat boilers recover some of the sensible heat in the blast gases.

Methods of Introducing Air and Steam.—Critical study of the methods of introducing air and steam into the carbureted water-gas set have led to the development of the backrun, the Chrisman downrun, and the reversed air blast, each of which reduces waste-heat losses. These developments are the result of applied research, supplemented by earlier advances in the knowledge of the carbureted water-gas process and in the fundamentals of heat transfer.

Complete Gasification of Coal

General Considerations

The fundamental objective of complete gasification processes is to convert in one operation a large proportion of the energy in a single fuel—coal—into energy in a gaseous fuel of reasonably high quality, leaving only ash as a solid residue from the process. This objective defines the restrictions imposed on the ideal complete gasification process. However, if only the ultimate result is considered, it will be found that coal is being gasified completely in the United States today by three methods: (1) In water-gas plants using bituminous coal as generator fuel; (2) in gas producers using coal as fuel; and (3) in water-gas plants operated in conjunction with and using coke from coke ovens or gas retorts. None of these methods satisfies all of the requirements of so-called complete gasification, either because the gas produced is not of reasonably high quality, as in the case of producer gas, or because the process is not carried out in a single operation. The closest approach to a complete gasification process in the United States is the use of bituminous

coal as generator fuel, but even this application does not fulfill all of the requirements, because oil also is frequently a raw material.

Recent Developments

In the United States the so-called complete gasification process has not passed beyond the experimental stage. Although various systems for complete gasification have been operated successfully in Europe for many years, yet in 1926, according to Fulweiler, many of these had little advantage over the utilization of bituminous coal in existing apparatus.¹⁴

Recent developments have been more promising; these will be discussed briefly. However, no attempt will be made to consider all processes for the complete gasification of coal, because many of these are not adapted to the production of city or industrial gases. Such processes, as well as those discussed in the following section have been reviewed in recent articles.¹⁵

Most recent research on complete gasification processes has been directed toward development of methods for producing continuously a gas of high quality. Such research has led to the gasification of coal with oxygen and steam under pressure and to the use of externally heated retorts or tubes in which pulverized coal is gasified.

Gasification of Solid Fuels with Oxygen

Significant progress in the attainment of an ideal complete gasification process

¹⁴ Fulweiler, W. H., "Utilization of Coal in the Manufacture of Water Gas," *Proc. Internat. Conference on Bituminous Coal*, 1926, pp. 472-513.

¹⁵ Logan, Lloyd, "Water-Gas Manufacture," *Proc. Am. Gas Assoc.*, 1932, pp. 976-1015.

Fieldner, A. C., "Recent Developments in Coal Utilization," Bureau of Mines *Minerals Yearbook*, 1932-33, pp. 433-450; "Recent Developments in Coal Preparation and Utilization," Bureau of Mines *Minerals Yearbook*, 1934, pp. 627-643; 1935, pp. 601-709; 1936, pp. 625-643; 1937, pp. 935-954.

Fieldner, A. C., *Developments in Coal Research and Technology in 1937 and 1938*, Bureau of Mines, Tech. Paper 813, 1940, 95 pp.

Gwosdz, J., "The Complete Gasification of Coal," *Proc. Third Internat. Conference on Bituminous Coal*, vol. 1, 1931, pp. 809-839.

Barnes, C. A., *Possibilities of Research in the Gasification of Coal*, Bituminous Coal Research, Inc., Tech. Report V, June 1939, 36 pp.

is evident from the results obtained in the operation of the Lurgi plant¹⁶ at Zittau, Germany. The research of Lurgi Gesellschaft für Wärmetechnik have resulted in the development of a continuous process for gasifying brown coal with oxygen and superheated steam at a pressure of 20 atmospheres (300 pounds per square inch). The coal is completely gasified and yields a gas having a heating value of about 500 B.t.u. This process, which is carried out in one stage, meets all the technical requirements of a complete gasification process. Present fuel prices (1940) are so low that the high cost of oxygen imposes economic restrictions on the widespread adoption of the process. In Russia¹⁷ the Lurgi process has been applied successfully to the gasification of anthracite, bituminous coal, brown coal, and peat.

The gasification of coal with oxygen and steam at atmospheric pressure has received considerable attention. However, according to Gwosdz,¹⁸ the results have not been encouraging, because the quality of the gas, thermal efficiency of gasification, and capacity of the units studied were all below expectations. Recent experiments of the Hydro-Electric Power Commission¹⁹ of Ontario in which coal and coke were completely gasified by electrolytic oxygen and steam at atmospheric

¹⁶ Drawe, R., "Results of Pressure Gasification with Oxygen," *Arch. Warmewirt.*, vol. 19, No. 8, 1938, pp. 201-203.

Danulat, F., "The Gasification of Solid Fuels with Oxygen under Pressure," *Mitt. Metallges.*, No. 13, 1938, pp. 14-22.

See also Sieden, R., "The Gasification of Solid Fuels by Oxygen under Pressure," *Ind. and Eng. Chem., News Ed.*, vol. 16, No. 19, 1938, p. 535; *Periodic Review of the Metallgesellschaft*, No. 13, April 1938, pp. 13-21 (in English).

¹⁷ Kagan, G. B., and Litvin, M. Z., "Gasification of Low-Grade Fuels with a Steam-Oxygen Mixture," *Khim. Tverdogo Topliva*, Vol. 8, 1937, pp. 1155-1165.

Nedelcovic, N., "Gasification of Coal with Pure Oxygen Instead of Air," *Szenkiserleteti Közlemenyek*, vol. 3, 1937, pp. 94-107.

¹⁸ Gwosdz, J., "The Complete Gasification of Coal," *Proc. Third Internat. Conference on Bituminous Coal*, vol. 1, 1931, pp. 809-839.

¹⁹ Stuart, A. T., "Electrolytic Hydrogen and Oxygen in Industrial Gas Production" (Complete Gasification of Coal with Oxygen), *Canadian Chem. Met.*, vol. 21, 1937, pp. 283-286.

pressure indicated that this process might be economical if off-peak power were used for producing the oxygen and if a commercial outlet could be found for the by-product hydrogen. The economic aspects of complete gasification of coal with oxygen and steam in a water-gas set have been discussed by Willien.²⁰

Continuous Gasification of Pulverized Coal

Experimental plants built in Germany for the continuous gasification of pulverized coal show the feasibility of the process. Both the Heller process²¹ and Herzberg process²² utilize externally heated chambers for gasifying the pulverized fuel with steam. Processes of this type have the advantage of being continuous and of utilizing low-grade fuels. However, Barnes²³ points out that economy is assured only when heat transfer is satisfactory and when the loss of combustible in the ash is the minimum. He also states that the process in which pulverized coal is gasified in externally heated metal tubes offers the most promising possibilities for future development. Other processes for the continuous gasification of pulverized coal use mixtures of oxygen and steam²⁴ or gasify the coal under pressure.²⁵

²⁰ Willien, L. J., "Future Gas Production Cost Potentialities," *Gas Age*, vol. 84, November 9, 1939, pp. 21-23, 36-37.

²¹ Thau, A., "Producing Water Gas from Powdered Fuel by the Heller Process," *Proc. Third Internat. Conference on Bituminous Coal*, vol. 1, 1931, pp. 788-808.

²² Gwosdz, J., "The Complete Gasification of Coal," *Proc. Third Internat. Conference on Bituminous Coal*, vol. 1, 1931, pp. 809-839.

²³ Barnes, C. A., *Possibilities of Research in the Gasification of Coal*, Bituminous Coal Research Ind., Tech. Report V, June 1939, 36 pp.

²⁴ Humphrey, H. A. (to Atmospheric Nitrogen Corp.), *Combustible Gas Containing Hydrogen and Carbon Monoxide*, U. S. Patent 1,794,232, February 24, 1931.

²⁵ Szikla, G., and Rosinek, A., "Development of the Szikla-Rosinek System of Firing," *Feuerungstechnik*, vol. 26, April 15, 1936, pp. 97-102. Haken, von Kurd, "Pressure Distillation of Coal in Powdered Form," *Brennstoff u. Warmewirt.*, vol. 21, 1939, pp. 117-118.

Gasification of Low-Rank Coals Sub-bituminous Coal and Lignite

Lavine²⁶ in reviewing the progress in the utilization of American sub-bituminous coals and lignites points out that these fuels have been used to a limited extent in carbonizing apparatus²⁷ and in the generation of producer gas. Until recently these fuels had not been investigated in the United States as raw materials for other gasification processes. However, laboratory studies²⁸ of the production of high-hydrogen water-gas directly from sub-bituminous coals and lignites have led to the construction of a pilot plant for continuous gasification of these fuels at the University of Minnesota.

In Europe the gasification of lower-rank coals has been studied intensively. For example, as pointed out previously, brown coal is used in the Lurgi process in Germany.

Peat

The possibilities of utilizing peat commercially have been considered.²⁹ However, in the United States comparatively little work has been done on problems relating to the gasification of peat. At present (1940) the production of gas from partly dried peat containing 18 percent moisture is the objective of a cooperative investigation of the University of Minnesota and the Works Progress Administration.³⁰

²⁶ Lavine, I., *Progress in Low-Rank Coals, Ind. and Eng. Chem.*, vol. 26, 1934, pp. 154-164.

²⁷ Hood, O. P., and Odell, W. W., *Investigations of the Preparation and Use of Lignite*, 1918-1925, Bureau of Mines Bull. 255, 1926, 204pp.

²⁸ Brewer, R. E., and Ryerson, L. H., "Production of High-Hydrogen Water Gas from Younger Coke Coals: Steam-Carbon Reactions," *Ind. and Eng. Chem.*, vol. 26, 1934, pp. 734-740; "Effect of Carbon Dioxide upon Cokes," *Ind. and Eng. Chem.*, vol. 26, 1934, pp. 1002-1008; "Effects of Catalysts," *Ind. and Eng. Chem.*, vol. 27, 1935, pp. 1047-1053.

²⁹ Odell, W. W., and Hood, O. P., "Possibilities for the Commercial Utilization of Peat," Bureau of Mines Bulletin 253, 1926, 160 pp.

³⁰ "Research in Peat-Gas Production at the University of Minnesota," *Gas-Age*, vol. 83, 1939, p. 26.

Gasification at the Mine

The carbonization of coal at the mine mouth and the distribution of gas over long distances is practiced extensively in Germany.³¹ It has been suggested that this practice be extended to include carbonization or complete gasification of the entire output at the colliery.

The gasification of coal underground is being studied in Russia, but the published results furnish no convincing evidence of the practicability of the scheme.

Gases as Chemical Raw Materials

Developments in the utilization of blue water gas and coke-oven gas as raw materials for the synthesis of ammonia, alcohols, and hydrocarbons are outstanding examples of progress attributable to fundamental research. A review or discussion of these developments is outside the scope of this report; however, it is important that, as these developments assume greater commercial importance, the use of coal will increase and doubtless further progress in the gasification of coal will result.

Future Research on Gasification of Coal

A broad program of research on the gasification of coal should cover technical and economic aspects of the production of gas from all types of coals and also related problems in distribution and utilization. Such a broad scheme is essential, because studies in production technology may be influenced greatly by considerations in distributing and utilizing the gas produced, as evidenced by past experience in the gasification of coal; for example, the use of the Welsbach mantle obviated the necessity for production of gas high in illuminating and calorific value.

The justification for recommending a broad outlook becomes apparent when one realizes that production technology and

economics are influenced greatly by the properties of the gas required by the consumer or imposed by economic considerations of gas distribution. These three aspects must be considered in relation to one another for a sound technical and economic solution of future gasification problems.

The fundamental objective of a long-range research program on the gasification of coal should be the development of efficient and economical methods for producing gas of a satisfactory composition, using only coal as the primary fuel. Such an aim is inevitable. Ultimately gas manufactured from coal alone will be substituted for natural gas and for gas produced from petroleum derivatives. Meanwhile, progress in the fundamental objective of research on coal gasification may assist in conserving natural gas and oil, provided that these sources of gas can be replaced economically by gas made from coal.

A review of processes for the complete gasification of coal alone discloses that the production of gases having relative high heating value is accomplished only in complex processes and at high operating costs. For example, the gasification of coal by oxygen and steam under pressure yields a gas having a heating value of about 500 B.t.u. per cubic foot. However, this process is much more expensive and complex than the gasification of bituminous coal in a water-gas set, which yields a gas whose heating value is considerably less—about 330 B.t.u. per cubic foot. In view of the possible difficulty and cost of producing gases of high calorific value from coal alone the advisability of distributing gases of lower heating value should be considered.

The importance of studying heating-value standards to determine rational standards is evident when one realizes that existing standards of heating value have not been determined by the technical and economic aspects of production, distribution, and utilization but probably have their origin in the now obsolete illuminating-gas standard. Barnes³² recently pointed out the importance of modifying heating-value standards.

³¹ *Transactions of the Third World Power Conference, "Organization of the Production, Transportation, and Distribution of Natural and Manufactured Gas,"* vol. IV, 1936, pp. 279-523.

³² Barnes, C. A., *Possibilities of Research in the Gasification of Coal*, Bituminous Coal Research, Inc., Tech. Report V, June 1939, 36pp.

The desirability of distributing low heating-value gas has been pointed out frequently.³³ Furthermore, the effect of heating value on utilization value has been considered.³⁴

In a study of heating-value standards consideration should be given also to the specific gravity of the gas because this property must be considered in production, distribution, and utilization.

The decision as to the emphasis to be placed on specific problems in an extended investigation of the gasification of coal will be determined chiefly by economic considerations. For example, the process of gasification that gives a satisfactory gas at the lowest over-all production and distribution cost consistent with high efficiency of conversion should be investigated most intensively. However, a particular process should not be investigated to the exclusion of all others because these may be more economical under some conditions.

In reviewing the possibilities of research in the gasification of coal, Barnes³⁵ gives the following general outline for conducting research that might prove profitable:

1. *Preparation of gaseous enrichers using coal as a source of raw material.*— Consideration should be given to (a) the direct synthesis of methane from carbon monoxide and hydrogen or to (b) the synthesis of methane by the hydrogenation of coal under pressure using blue water gas as the source of hydrogen.

2. *Complete gasification of coal with the production of low B. t. u. water gas.*— The development of a continuous process

for producing uncarbureted water gas from pulverized coal in metal tubes heated externally has possibilities. However, the application of such a process will be limited to the generation of gas for industrial purposes, because "there is little chance in the near future of distributing generally a gas of much lower B. t. u. than the present standards."

3. *Complete gasification of coal with the production of a high B. t. u. gas.*— One variation of this is high-pressure hydrogenation referred to in 1 (b), and another variation is the gasification of coal with oxygen and steam under high pressure.

4. *Coal-gas processes.*—"The carbonization of coal under pressure for the purpose of producing a more reactive coke and a higher B. t. u. gas to be used as an enricher for water gas may have possibilities."

In addition to these proposals of Barnes, the possible application of off-peak power for heating gas-generating equipment should be studied further, as should proposed processes for gasifying pulverized coal with oxygen and steam under pressure. In the latter process the effect of alkali catalysts should be more thoroughly investigated.

No mention has been made of the importance of investigating problems in the fundamental chemistry of the gasification reactions or of the importance of studying present practices and processes. The possible developments from fundamental research are manifold, as experience in the past has indicated. In the field of applied research, much remains to be learned about the technology of large-scale gasification processes. In addition to studies in production, the problem of purifying the gas produced should receive more study, particularly in relation to sulfur compounds, as these will assume greater importance as it becomes necessary to utilize fuels high in sulfur. Thus, continued progress in the gasification of coal depends not only on the development of new technique but also on the improvement of existing technique.

³³ Field, E. B., "Advantages and Disadvantages in the Production and Distribution of a Low-Quality Gas," *Gas Journal* (London), vol. 224, 1938, pp. 903-905.

Perry, J. A. "Types of Plants and Quality of Gas Best Suited for the Development of the Gas Industry," *Proc. Am. Gas Assoc.*, 1924 pp. 818-824.

³⁴ Weaver, E. R., *Relation Between Heating Value of Gas and Its Usefulness to the Consumer*, Nat. Bureau of Standards, Technol. Paper 290, 1925.

³⁵ Barnes, C. A., *Possibilities of Research in the Gasification of Coal*, Bituminous Coal Research, Inc., Tech. Report V, June 1939, 36 pp.

HYDROGENATION

By H. H. Storch¹

Introduction

The chemical combination of a relatively small proportion of hydrogen with certain types of coal results in an oil similar to crude petroleum. This combination of coal and hydrogen is effected under high pressures (3,000 to 15,000 pounds per square inch) and at temperatures of 850° to 950° F. In Germany the process for producing gasoline from coal has been developed rapidly during the past decade; the production of German coal-hydrogenation plants in 1938 has been estimated as 900,000 metric tons of gasoline. At Billingham, England, 150,000 tons of gasoline is produced annually from coal by hydrogenation. The National Resources Committee² gives a more detailed historical and statistical review of coal hydrogenation. In the United States the first continuous experimental coal-hydrogenation plant has been erected by the Bureau of Mines at its Central Experiment Station in Pittsburgh, Pa. This plant is designed to hydrogenate about 6 pounds of coal an hour. It includes apparatus for the production of hydrogen from steam and natural gas, compressors for producing the desired pressure of hydrogen, and alloy-steel converters for conducting the reaction between coal and hydrogen.

The main object of the Bureau of Mines in conducting the work of the coal-hydrogenation laboratory is to furnish information concerning the characteristics of American coals for hydrogenation purposes. Such information is considered a desirable preparation for the time when the United States finds it necessary to provide additional sources of motor fuel, lubricating oils, and bulk organic chemicals

for the plastics, explosives, lacquer, solvent, and other industries.

A second objective of the Bureau's research is to study the influence of such important factors as temperature, pressure, rank and type of coal, contact time, and catalysts on the products obtained by hydrogenation of coal. Except for a relatively small amount of research published by the British Fuel Research Laboratory, little information on the fundamentals of coal hydrogenation is available, despite the voluminous patent literature, which is often more confusing than informative. Unquestionably much more is known by industrial interests, particularly in Germany and Great Britain, than appears in print. However, a study of the development of coal hydrogenation in these countries reveals that the intensive drive made during the past decade to achieve large-scale production has left little, if any, time and funds for fundamental research. This point perhaps may be amplified by a review of the experience with the high-pressure synthesis of ammonia in the United States. For about two decades after the introduction of this process on an industrial scale it was found desirable to study (in the Fixed Nitrogen Research Laboratory in Washington, D. C.) the fundamental factors involved. The benefits of this research to industry are apparent to chemical engineers engaged in high-pressure work. A single example of such benefits is the rapidity with which the synthesis of methyl alcohol developed on a large scale owing to the fundamental work done in high-pressure research in connection with the synthesis of ammonia.

The scientific and engineering problems involved in coal-hydrogenation procedures are much more difficult to solve than those involved in the synthesis of ammonia and methanol. In the latter processes only

¹ Principal Physical Chemist, Central Experiment Station, Bureau of Mines, Pittsburgh, Pa.

² National Resources Committee, *Energy Resources and National Policy*, 1939, pp. 317-323.

gaseous materials are pumped into a high-pressure vessel, but in the hydrogenation of coal not only gas but also a suspension of a gritty solid in oil must be pumped. Instead of one catalyst as in the synthesis of ammonia or methanol, several are necessary in coal hydrogenation; instead of a single step in which a gas is passed over a catalyst, both a liquid and a vapor phase, each requiring special temperature, pressure, and catalyst, are employed. This complexity indicates that at least as much time should be devoted to fundamental research in coal hydrogenation as was found desirable by the Federal Government for the synthesis of ammonia.

Hydrogenation of American Coals

The assay made in the Bureau of Mines Plant consists in determining the maximum quantity of an oil containing 20 percent of gasoline and 80 percent of oils boiling below 650° F., which can be produced in a single pass through one converter. Table 1 contains the assay data on seven coals ranging in rank from a medium volatile bituminous coal to lignite.

Several interesting conclusions may be drawn from these data. Excepting the Mary Lee coal and the lignite the yields of oil do not change much with rank, when the comparison is made for the dry coals. For the coals as mined it should be stated that the low rank coals which comprise 50 percent of the national coal reserves, contain large amount of water and this explains the rapid decrease in oil yield with decreasing rank of coal. The hydrogen consumed on a dry, ash-free basis does not show any with rank of coal and is the same (within 10 percent of its value) for all of the coals. This fact is explained by the progressively larger amounts of oxygen eliminated as carbon dioxide with decreasing rank. The yields of tar acids and tar bases are about 100 times those obtained in carbonization. The tar acids (phenol, cresols, xylenols) are of commercial value as raw materials for the plastics industries, and the tar bases serve as raw materials in several organic chemical processes. Most of the oils obtained in the coal assay are aromatic in nature and could be utilized as solvents and as

Table 1.—Hydrogenation assay of some United States coals

Coal Bed	State	Rank	Total oil yields, percent of			Hydrogen consumption percent of m. a. f. coal	Tar acids, yield in percent of m. a. f. coal	Tar bases, yield in percent of m. a. f. coal
			Moisture - and ash free coal	Dry coal	Coal as mined			
Mary Lee	Alabama	Bituminous, M. V. "A"	59.8	54.1	51.7	8.5	7.4	2.3
Pittsburgh	Pennsylvania	Bituminous, H. V. "A"	70.5	65.2	65.1	9.0	11.1	2.8
No. 6	Illinois	Bituminous, H. V. "B"	70.5	65.4	60.4	8.5	11.4	1.6
McKay	Washington	Bituminous, H. V. "C"	68.5	65.7	59.3	7.6	13.0	3.2
Puritan Mine	Colorado	Sub-bituminous "A"	63.0	59.3	48.9	9.7	12.2	2.6
Monarch No. 45	Wyoming	Sub-bituminous "B"	66.5	63.1	48.5	8.5	14.5	2.9
Fort Union	North Dakota	Lignite	54.0	47.0	29.0	8.0	11.4	1.3

Note.—M. V. = medium volatile; H. V. = high volatile;
 "A," "B," "C," are classifications of rank in decreasing series.

raw material for the production of benzene and toluene for manufacture of explosives. The possibilities of coal hydrogenation as a source of organic chemicals is apparent, and the demand for such chemicals is large, particularly in the rapidly growing plastics industry. The average selling price of these raw materials should be about 20 cents per gallon (or about 2 cents per pound). The cost of production should be lower than that of gasoline because the second stage of hydrogenation is not needed.

Careful appraisal of the present technical and economic status of processes for obtaining gasoline and Diesel fuel from coal leads to the conclusion that the coal-hydrogenation process is available for large-scale development under American conditions to supplement any future diminishing of the supply of petroleum fuels that may occur. Neither high-nor low-temperature carbonization of coal can be expanded enough in capacity to furnish any large contribution of liquid fuel. The light oils and tars from these processes are by-products, and total plant capacity is determined by the demand for the main products, coke and gas.

At present this process is operating on a large scale in Germany, and the cost is said to be approximately 18 cents per United States gallon. This cost is far above the present American cost of petroleum gasoline at the refinery. There is little doubt that when the time comes for the production of gasoline from coal, American costs may be as low as 12 cents per gallon if the program of research and development applied to this problem is as intensive as that conducted on the manufacture of gasoline from petroleum. However, that cost is more than twice the present price of gasoline at the refinery. The labor and equipment required for making gasoline from coal greatly exceed those necessary for manufacture of gasoline from petroleum and, what is more important, much energy is lost in the process of conversion. In round numbers, 4 to 5 tons of coal are consumed in making one ton of gasoline and only 40 to 45

percent of the original heat units in the coal used remains in the resulting motor fuels.

The United States does have large resources of coal. The reserves of coal, exclusive of anthracite, are estimated at $3\frac{1}{2}$ trillion tons. It is believed that $1\frac{1}{3}$ times our present annual production of coal would be needed to yield our present annual requirements of gasoline. Such increase of consumption of coal would no doubt solve the immediate problem of the coal industry, but at the expense of a greater consumption of national fuel resources. A forward-looking national fuel policy would seek to delay the day of making gasoline from coal as long as possible by reserving the higher-value fuels, natural gas and petroleum, for those uses that cannot be met so efficiently by the direct combustion of coal.

Estimated Costs Of Production

The best available estimates on the cost of production of synthetic gasoline by coal hydrogenation are given in the reports³ of the Committee of Imperial Defense of Great Britain and the Labor Party of England.

The estimated total costs of production discussed in these reports range from 12 to 25 cents per United States gallon, the spread being due principally to various rates of amortization of the plant and secondarily to the cost of the coal. The Imperial Defense Committee concludes that the cost for a new plant would range from 15.6 cents to 19 cents per United States gallon. (Conversion figures to United States units taken from Egloff's article.)⁴ The corresponding estimate of the British Labor Party is 18 cents per United States gallon. Egloff⁴ concludes

³ *Subcommittee on Oil from Coal* (Viscount Falmouth, chairman), Committee of Imperial Defense. H. M. S. Office, London, February 1938, 71 pp.
Labor's Plan for Oil from Coal. Published by the Labor Party (London) June 1938. (Both reports are reviewed by Gustav Egloff, see reference 4.)

⁴ Egloff, Gustav, "Motor Fuel Economy of Europe," *Ind. Eng. Chem.*, vol. 30, 1938, pp. 1091-1104.

that, on the basis of all sources of information, the cost per United States gallon of motor fuel produced by coal hydrogenation is about 18 cents, and that for American conditions with lower cost of coal and improvement of manufacturing technique the cost would be less than 16 cents per gallon.

Time Required To Put Hydrogenation On A Commercial Basis

It must be emphasized that the industrial plants obtaining gasoline from coal in England, France, Japan, and Germany are not, in a strict sense, on a commercial basis. Large subsidies in the form of tariffs or excise taxes on petroleum or gasoline from petroleum are required to make their operation commercially possible. None of these countries has any important home sources of petroleum, but they do have extensive deposits of coal. In case of war and blockade, the production of motor fuel from coal would be of the greatest importance to these countries. The large internal petroleum resources of the United States, if properly conserved, will defer this war need of converting coal, certainly for one and possibly three or more decades.

Large-scale hydrogenation of coal in the United States would require an extended period of research on our particular coals to determine which coals would give the best yields and which locations would prove most economically desirable.

Hydrogenation of High-Temperature Tar

At the request of Jones and Laughlin Steel Corporation some cooperative research was done during the year ended July 1, 1939, in the coal hydrogenation plant on the hydrogenation of high-temperature byproduct Koppers retort tar. Three months operation with Jones and Laughlin tar in the continuous hydrogenation plant indicated that solvents can be produced from high-temperature byproduct coke-oven tar by hydrogenation. These compare with similar materials produced from petroleum and sold as lacquer solvents and plasticizing oils. With residual (topped) tar

at 4 cents a gallon and coke-oven gas (for the production of hydrogen) at 10 cents a thousand cubic feet, the cost of production of the solvents has been estimated to be about 17 cents a gallon. This includes charges of 10 percent for maintenance and 20 percent for obsolescence of a plant costing approximately \$2,000,000 and producing about 50,000 tons annually.

Suggested Program For Further Government Research

This outline of the work of the Bureau of Mines on hydrogenation of coal and tar should be supplemented by notes concerning the interest exhibited by industrial companies in the work. Details of construction of the experimental plant and results of assays have been supplied upon request to representatives of the Carbon & Carbide Co., Battelle Memorial Institute, Koppers Co., Colorado Fuel & Iron Corp., New Mexico School of Mines, Canadian Bureau of Mines, Gulf Research Corporation, Illinois Geologic Survey, American Cyanamide Co., General Electric Co., Lever Bros., Hooker Electrochemical Co., and the Goodrich Rubber Co. During the presentation of papers on hydrogenation of coal at meetings of the American Chemical Society the representatives of leading chemical and oil companies have exhibited sustained interest in the results of the Bureau's coal-hydrogenation work.

The present facilities will permit only about one-tenth of the necessary fundamental research on the mechanism of coal-hydrogenation reactions. Extensive work is necessary on the chemical composition and physical properties of the hydrogenated coal at various stages of hydrogenation, as influenced by temperature, pressure, time of contact, turbulence, catalysts, pasting vehicle, and rank of coal. Fundamental research in the field of the Bureau's coal-hydrogenation work should be extended. Such research will supply the necessary tools for the most efficient chemical utilization of coal by hydrogenation, and the byproducts of this research unquestionably will hasten the development of the whole field

Hydrogenation

of the chemistry of coal, so that new processes, which cannot now be foreseen, will be developed for the chemical utilization of coal. The coal reserves of this country are so large that efficient utilization of coal will be a perennial

problem for many decades; and it is therefore a conservation measure to engage in "long term" fundamental research on a scale commensurate with the importance of coal in industrial activities.