# INTRODUCTION

Approximately half of all the fuel energy used in the United States is now provided by oil and natural gas. A persistent and rapid growth in energy demand during the last 3 decades has been absorbed largely by the liquid and gaseous rather than solid fuels. In 1948 the energy provided by coal was substantially the same as in 1920. Meanwhile, the use of oil and natural gas each had increased fivefold.

On a per capita basis, the change is more significant. Coal consumption has dropped from about 6 tons per person to 4-1/2 tons, while oil has increased from 4-1/3 barrels to 14-1/3, and natural gas from 7,500 cubic feet to about 35,000.

These facts would have only academic interest if the United States had unlimited supplies of all fuels. However, while the Nation's reserves of coal are adequate to meet our needs for centuries, those of oil and natural gas appear limited. It is obvious, therefore, that the security of our liquid-fuel position would be greatly enhanced if the supply could be based in an increasing degree on solid fuels, such as coal and oil shale, which make up more than 95 percent of our fuel reserves, instead of natural oil and gas. In addition, this would create new employment and help to stabilize the market for coal, which may be facing comparatively bleak prospects in the near future unless its position with respect to other fuels is improved.

## Scope of Synthetic Fuel Research

The reports on synthetic liquid fuels for 1949 deal primarily with progress in utilizing coal and oil shale as raw materials. It should be noted, however, that the program embraces very important work on the conversion of agricultural wastes into liquid fuels, together with significant research on secondary recovery from stripper oil fields and on refining processes. Notable progress has been made in each of these programs, and the results are sketched in the latter part of this summary.

## Survey of Resources for Synthetic Fuel Production

Although it is well-known that this country has enormous deposits of coal and oil shale, suitable areas for synthetic fuel plants must provide in addition water and a number of other resources and facilities. To determine the extent to which such combined requirements can be met, the Secretary of the Interior requested the Department of the Army to make a comprehensive survey of the United States and Alaska. This work is being carried out by the Corps of Engineers, and the factors under consideration include the availability of raw materials, water, power, transportation, labor, housing, and markets, as well as the problem of national defense. Sample surveys to develop techniques have been completed in portions of Colorado, Kentucky, Montana, and Texas. Two reports summarizing results of these preliminary surveys were issued during 1949.

The general survey is now under way in Alaska and the 39 States having known deposits of raw materials suitable for synthetic fuel manufacture, and reports for many of the States will be issued during 1950. The sample surveys already have shown that there will be no scarcity of raw materials or suitable locations for commercial plants. Parts of four States were found to have available deposits of raw materials that on conversion would yield 156 billion barrels of liquid fuel. These areas could support plants producing up to 7 million barrels a day of gasoline and oil, or about 20 percent more than our present consumption of all oils.

## Cost of Producing Synthetic Liquid Fuels

The technology for producing liquid and gaseous fuels from coal and oil shale was developed to a considerable degree in Europe and in some other foreign countries before World War II and has been extended rapidly in the United States both by the Government and industry since the end of the war. The question now is not - Can liquid fuels be made from solid fuels? but rather - What is the best way of doing the job?

The Government's synthetic liquid fuels research and development program is predominantly technical. However, it is essential from time to time to appraise progress in terms of product cost, which is the most important factor considered by private industry in making new investments.

So far as the cost of producing synthetic liquid fuels is concerned, it is important to point out at the outset that the Department of the Interior does not have precise cost figures. At the same time, precise estimates are not available in the United States, nor will they be available until commercial synthetic fuel plants are actually in operation.

On the other hand, the Bureau of Mines has accumulated a large fund of information regarding costs. It has operated an oil-shale demonstration mine and retorting plant for approximately 2 years and an oil-shale refinery for several months. Similarly, a coal-hydrogenation plant has completed successful initial runs. With these demonstration plants in operation and a gas-synthesis plant using coal to be completed in 1950, the synthetic fuel program is now entering its most valuable period.

Before presenting a brief summary of the preliminary cost estimates, it will be well to point out that the cost of producing synthetic fuels under European conditions has little or no relationship to the costs that will be experienced in the United States. This can be illustrated quite simply for the oil-shale operations. In Scotland about 1 ton of oil shale is produced per man-shift underground. In a recent 4-week test in the oil-shale mine at Rifle, Colo., production averaged 148 tons per man-shift underground. A similar comparison may be made for retorting operations. A single Pumpherston retort, as used in Scotland, produces 5 to 10 barrels of oil daily. The retorts designed for American plants based on pilot-plant work now completed will produce over 3,000 barrels of oil a day. These examples illustrate major differences in the operations. Numerous minor improvements, which are too detailed to relate here, have been incorporated throughout the mining and processing.

Material differences will also exist in the coal-hydrogenation operations in the United States and in foreign countries. As examples of these differences, the cost of coal generally is much less in the United States than in most European countries. By careful utilization of all off gases from the plant, conservation of heat by exchange between outgoing hot products and incoming raw materials and application of automatic and close control of all processing operations, the over-all heat efficiency of the plant will be increased from around 30 percent in European practice to about 50 percent.

It is therefore essential that in the United States synthetic fuel cost estimates be based not on past practices that may exist elsewhere in the world but instead on the application of the most modern technology to American conditions. It is believed that this has been done in the estimates that follow. It must be understood, however, that these are by no means final. Present cost levels are due largely to our limited knowledge of the technology. By the very nature of the research and demonstration-plant work, changes will be made constantly toward better operation, and these are confidently expected to improve the economic position of synthetic fuels.

## Production of Jet Fuel, Heating Oil, and Diesel Oil from Oil Shale

The capital investment and daily operating charges are based upon the requirements of an oil-shale plant to produce 10,000 barrels per calendar day of crude shale oil and 8,840 barrels of refined products.

The shale would be mined from the Mahogany ledge of the oil-shale formations of western Colorado. This ledge is about 72 feet thick and yields about 30 gallons of shale oil a ton. A little more than 14,000 tons of shale a day would be needed to supply the 10,000-barrel-a-day plant. From an area approximately 1 mile square, 102 million tons of shale can be mined. This amount of shale would supply a 10,000-barrel-a-day plant for 20 years.

For the purpose of cost calculations, terrain would be similar to that of the mountainous country near Rifle, Colo. The mining operations then would be at an elevation of about 8,000 feet, which is 3,000 feet above the Colorado River. The necessary processing areas would be immediately below the shale cliff. The plant site for crude-oil production would consist of three areas - the first and highest for crushing, the second for shale storage, and the third for retorting. Valleys near almost any potential retorting plant site in this area are large enough for disposal of all the spent shale during the life of the plant. The crude shale oil might be piped to a refinery near the Colorado River, or it could be partly processed to reduce the viscosity and piped to a distant point for refining.

Mining costs are based on mining shale from the Mahogany ledge in two levels. A top level, 38 feet high and 60 feet wide, would be advanced horizontally under the roofstone into the ledge. Sixty-foot-square pillars would be left in a checkerboard pattern to support the overburden. The second or bench level, 34 feet high, would follow the top-level advance similar to the bench of a quarry. The grade of the shale mined from either level averages about 30 gallons per ton. The broken oil shale would be transported by trucks to a centrally located crushing plant and thence by conveyor belt to the processing stock pile.

Costs for the retorting operations have been based on the gas-flow process developed by the Bureau of Mines. It should be understood, however, that this is by no means the only retorting process that can handle American shales on a large scale. Particular attention should be directed to a very promising retort being developed by the Union Oil Co. of California.

The refining process adopted for the cost calculations in this report consists of delayed coking of the crude shale oil followed by mild hydrogenation of the coker distillate over a catalyst. All the steps are well-known commercial operations that should offer few difficulties in application. The removal of sulfur and nitrogen is no longer a serious problem, and the crude shale oil can be processed to give a high yield of the more valuable products boiling below 725° F.

Mining-cost estimates were based on actual operations at Rifle. Estimated capital expenditures for mine development are $4,200,000 including $524,160 (12 percent) for excavations; $1,577,700 (37 percent) for installations; $1,716,500 (41 percent) for mining equipment; and $381,640 (10 percent) for contingencies. All costs were computed at prices and wage rates prevailing in 1949. Equipment estimates were based on actual quotations for delivery. Excavation costs were determined from operations at the demonstration mine. Depreciation was calculated by assigning each item of capital investment an average service life, expressed in working shifts, ranging from 2,000 for light vehicles to 15,000 for excavations and permanent structures. Calculations were made for a two-shift-a-day operation, working a 7-day week. Maintenance costs were calculated as a percentage of the equipment costs pro-rated through the life of the equipment in shifts.

Table 1 shows the product distribution. Table 2 summarizes the capital investment for the 10,000-barrel-a-day shale-oil plant, including mining, retorting, and refining. The investment amounts to $4,138 a barrel daily of crude shale oil, or $4,681 a barrel daily of finished product. It has been suggested that the capital investment for the plant should include housing for the workers. It is doubtful if this is necessary. Assuming a stable operation with reasonable promise of job security and adequate wages, the cost of housing should be carried by the employees.

As shown in table 3, the estimated operating cost of mining, crushing, and conveying the raw shale to the retort stock pile is 58.6 cents a ton. This includes management, overhead, depreciation, taxes, and insurance.

For the retorting and refining operations, equipment costs were compiled from suppliers' quotations; from published data in the form of charts and curves; or from the size, weight, and material used. Freight and erection labor have been included in the installed costs.

The estimate for utilities and general plant facilities represents a large portion of the total plant investment. Considerable effort was made to obtain reliable estimates for these facilities from such sources as the Colorado Public Service Co., Bureau of Reclamation engineers, and others who have had actual experience in this locality.

TABLE 1. - Daily production of a 10,000-barrel-a-day shale-oil plant

| | | | |
|---|---|---|---|
| Raw materials | - Oil shale.................... | tons | 14,035 |
| | Crude shale oil.............. | bbl. | 10,000 |
| Products | - Jet fuel.................... | do. | 5,150 |
| | Diesel fuel.................. | do. | 3,350 |
| | Fuel oil..................... | do. | 340 |
| | Total fuel.............. | do. | 6,840 |
| Byproducts | - Ammonia.................... | tons | 27 |
| | Coke...... .................. | do. | 62.6 |

TABLE 2. - Capital investment for 10,000-barrel-a-day shale-oil plant

| Section of plant | Capital investment [1] |
|---|---|
| Mining and crushing | $ 4,200,000 |
| Retorting | 7,458,000 |
| General facilities chargeable to crude oil | 2,280,000 |
| Utilities chargeable to crude oil | 1,989,000 |
| Total - plant items for crude-oil production | 15,937,000 |
| Operating capital (10% of plant items) | 1,594,000 |
| Total for crude-oil production | $17,531,000 |
| Refining | 15,100,000 |
| Pipe line (2 miles) | 150,000 |
| General facilities chargeable to refining | 3,435,000 |
| Utilities chargeable to refining | 2,997,000 |
| Total - refining plant items | 21,682,000 |
| Operating capital (10% of refining-plant items) | 2,168,000 |
| Total for refining | $23,850,000 |
| Total capital investment | $41,381,000 |

[1] Amounts for plant items include interest at 3 1/2 percent a year on invested capital during the construction period. Capital is assumed to be expended 10 percent in the first year, 50 percent in the second year, and 40 percent in the third year.

TABLE 3. - Summary of operating costs for producing 14,035 tons of crushed oil shale daily

| Mining: | Cost/ton |
|---|---|
| Direct supervision | $0.0171 |
| Drilling | .0475 |
| Blasting | .0848 |
| Loading | .0328 |
| Transportation | .0658 |
| Scaling | .0255 |
| Electric distribution | .0232 |
| Miscellaneous | .0162 |
| Crushing and conveying: | |
| Direct supervision | .0020 |
| Crushing | .0322 |
| Conveying | .0089 |
| Overhead: | |
| Super., eng., management | .0461 |
| Labor burden | .0339 |
| Depreciation | .1105 |
| Taxes | .0088 |
| Insurance | .0082 |
| Subtotal | 0.5535 |
| Contingencies | .0324 |
| Total cost | 0.5859 |

Daily operating costs are presented for the individual operations, - mining, retorting, and refining - in table 4. The average cost of the refined product is $3.07 a barrel or 7.3 cents a gallon. Jet fuel constitutes about 60 percent of the total product, and about two-thirds of the jet fuel is in the boiling range of gasoline, but the octane number of the gasoline fraction must be improved to meet motor fuel specifications. The octane number of the gasoline fraction can be improved and additional motor fuel can be produced from the Diesel fuel and the high-boiling fraction of the jet fuel by modifying the refining procedure to increase the hydrogenation. Further work is necessary before reliable estimates can be made for gasoline costs.

It must be clearly understood that these figures given for the shale oil and its products are costs and do not include return on investment. As such they cannot be compared directly with the selling price of petroleum products at the refinery.

Assuming a return of approximately 6 percent a year on the operating capital and the average unamortized part of the capital investment, after income taxes of 40 percent,1/ the required margin above cost is 70 cents a barrel. Adding this to the cost of $3.07 gives $3.77 a barrel, or approximately 9 cents a gallon, as the necessary refinery realization. It is not intended to suggest that this is the actual return that should be realized to attract capital, but rather to point out that oil-shale processing is not far from the point of commercial utilization.

There is one further problem that must be considered in connection with the establishment of a shale-oil industry, namely, the market for the product. The area around Rifle is sparsely populated and could not absorb the output of a 10,000-barrel-a-day plant at the present time. Construction of a pipe line of 50,000 to 100,000-barrel-a-day capacity could provide transportation to suitable consuming centers for a total cost of somewhat less than 1 cent a gallon. In this case, however, five plants of 10,000 barrels a day each would have to be built to supply the pipe line, which means a large capital outlay for both plants and pipe line at the start of commercial development.

## Production of Gasoline and Chemicals by Coal Hydrogenation

Detailed estimates have been made of the capital investment and operating costs for a 30,000-barrel-a-day coal-hydrogenation plant using Wyoming, North Dakota, Montana, Illinois, or Pittsburgh-seam coal or lignite.2/ To simplify the estimate for this summary, the costs for only one coal will be shown. This estimate is based on a modernized hydrogenation plant which takes advantage of postwar improvements. Not all of the equipment has been tested for the particular use proposed, but it is in a development stage. The demonstration plant at Louisiana, Mo., will be used to carry forward much of this development work.

These estimates represent the combined efforts of American and European engineers who are the world's recognized authorities in this field. They also worked with the engineering staffs of the companies that built the demonstration plants. In addition, the final estimates were reviewed by other industry people who are familiar with this work.

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1/ Return after 40 percent income tax is 6 percent of $3,762,000 operating capital and 3 percent of $37,619,000 initial capital investment.

2/ Hirst, L. L., and others, Estimated Plant and Operating Costs for Producing Gasoline by Coal Hydrogenation: Bureau of Mines Rept. of Investigations 4564, 1949, 83 pp.

TABLE 4. - Operating costs for 10,000-barrel-a-day shale-oil plant

Cost of crude oil

| Item | Cost/day | Cost/bbl. of crude oil |
|---|---|---|
| Costs of operation and maintenance: | | |
| Mining and crushing | $ 6,005 | $0.600 |
| Retorting | 3,056 | .306 |
| General facilities chargeable to crude oil | 822 | .082 |
| Utilities chargeable to crude oil[1] | 966 | .097 |
| Total direct cost | $10,849 | $1.085 |
| Fixed costs (depreciation,[2] taxes, insurance) | 4,125 | .412 |
| Total cost of crude shale oil | $14,974 | $1.497 |

Cost of refined products

| Item | Cost/day | Cost/bbl. of refined products |
|---|---|---|
| Refining operation and maintenance: | | |
| Refining | $ 6,705 | $0.758 |
| Pipe lines | 54 | .006 |
| General facilities chargeable to refining | 1,231 | .139 |
| Utilities chargeable to refining[1] | 1,890 | .215 |
| Total direct refining costs | $ 9,880 | $1.118 |
| Refining fixed costs (depreciation,[2] taxes, insurance) | 4,477 | .506 |
| Gross cost of refining | $14,357 | $1.624 |
| Cost of crude shale oil | 14,974 | 1.694 |
| Gross cost of refined products (average of 7.90 cents/gallon) | $29,331 | $3.318 |
| Less byproduct credits: | | |
| Ammonia at $75/ton | 2,025 | 0.229 |
| Coke at $3/ton | 188 | .021 |
| Net cost of refined products (average of 7.30 cents/gallon) | $27,118 | $3.068 |

[1] Includes water, steam, and electricity at prices adequate to cover cost of maintenance and operation, depreciation, taxes, and insurance on utilities.

[2] Based on expected life of individual units of mining and crushing equipment, giving average depreciation of 13.5 percent/year, and 15-year payout (6 2/3 percent/year) for other plant items, except utilities.

The estimated capital investment for a 30,000-barrel-a-day plant is shown in table 5. As it is assumed that the coal will be purchased, the investment in the coal mine is not included. The initial cost amounts to $8,227 per barrel day of product, or nearly 247 million dollars for the plant.

TABLE 5. - Capital investment for 30,000-barrel-a-day coal hydrogenation plant

| Section of plant | Cost |
|---|---|
| Hydrogenation | $ 99,625,000 |
| Gas production | 53,204,000 |
| General and auxiliary plants and facilities | 93,974,000 |
| | $246,803,000 |
| Dollars/barrel/day | 6,227 |

Coal requirements of the plant and the output of products are shown in table 6. The gasoline is a high-octane automotive gasoline low in sulfur (below 0.01 percent) and higher in aromatics and B.t.u. per gallon than gasoline obtained from petroleum. The phenols are carbolic acid, cresols, and xylenols.

Operating costs are shown in table 7 and for gasoline amount to nearly 11 cents a gallon. As in the oil-shale estimates, these are costs and do not include return on the investment. This item must be added to determine a selling price. It should be noted, however, that all other items, such as insurance, property taxes, social security, general administration, etc., are included. The plant is amortized over a 15-year period. Adequate provision has been made for maintenance and supervision.

TABLE 6. - Coal consumption and final products

| | |
|---|---|
| Bituminous coal, tons/day: | |
| Run-of-mine coal | 13,117 |
| Moisture ash-free coal | 10,089 |
| Production, bbl./day: | |
| Gasoline | 21,630 |
| Liquefied petroleum gases | 7,140 |
| Phenols | 1,230 (450,000 lb.) |
| Total | 30,000 |

TABLE 7. - Daily operating costs for 30,000-barrel plant

| | |
|---|---|
| Coal, $3.12 per ton | $ 40,925 |
| Other materials | 17,443 |
| Other direct costs | 28,636 |
| Indirect costs | 18,136 |
| Fixed costs (15 years amortization) | 56,072 |
| Total | $161,212 |
| Credits: | |
| Phenols at $0.10/lb. | $ 45,000 |
| Liquefied petroleum gases at $0.06/gallon | 17,993 |
| Total credits | $ 62,993 |
| Cost of gasoline | 98,219 |
| Cost of gasoline, cents/gallon | 10.8 |

At present, it is doubtful that a coal-hydrogenation plant producing motor gasoline primarily would be an attractive commercial investment. For example, if it is assumed that approximately a 6-percent return after income taxes is required on the average unamortized part of the capital investment (5 percent on the initial investment, of which 3 percent is for return and 2 percent for taxes), the net realization to the plant for the gasoline must be 14.5 cents a gallon. Comparable grades of motor gasoline now are selling for about 10 to 15 cents at wholesale.

Coal-hydrogenation plants offer wide flexibility with regard to quality of product, and commercial possibilities are somewhat more promising if the plant is operated to produce aviation gasoline. For example, the product distribution readily can be changed to that shown in table 8.

TABLE 8. - Product distribution in making aviation gasoline

| | Bbl./day |
|---|---|
| Gasoline, 91 octane | 12,210 |
| Aviation gasoline, 100 octane (100/130 grade) | 11,910 |
| Liquefied petroleum gas | 2,580 |
| Phenols | 1,230 |
| Total | 27,930 |

The total product from the plant would decrease from 30,000 to 27,930 barrels a day, primarily because of the lower output of liquefied petroleum gas that results in part from use of this material to make alkylate.

The average realization of the plant for aviation gasoline (to earn approximately 6-percent return after income taxes on the average unamortized part of the investment) must then be 16.6 cents a gallon instead of the 14.5 cents a gallon for automotive gasoline. The 100/130 grade in the coal regions is quoted at 16 to 18 cents a gallon and the 91 octane at about 15 to 16 cents. In this case, the plant would have a better chance of making a profit. These costs, however, are by no means final. There is reasonable promise that they can be reduced in the near future.

An analysis of the cost of the coal-hydrogenation products shows the following:

| | Percent of product cost |
|---|---|
| Coal | 25 |
| Other operating costs | 40 |
| Fixed costs (15 years amortization) | 35 |
| Total | 100 |

It is estimated that successful application of the new continuous coal-mining machines in a mine specifically developed for their use will make it possible to produce coal in underground mines at less than $2.00 a ton. More important, however, are prospective reductions in the cost of conversion. New catalysts are under development that should permit material reduction in the 10,000-pound-a-square-inch operating pressure. This could result in a substantial reduction in fixed costs and some reduction in operating costs. Success in these two changes alone could reduce the cost of the product by 15 to 20 percent.

Some further attention should be directed to the byproduct credits in these estimates. The use of liquefied petroleum gas is growing in most areas, and the demand should be adequate. A plant close to a good market but distant from a source of natural L.P.G. (liquefied petroleum gases) should be able to realize 6 cents a gallon for this product. Phenols, in general, are worth more than 10 cents a pound, and this credit appears conservative for a few plants. However, a large number of hydrogenation plants might tend to create an oversupply of phenols unless new uses were developed.

Operation of a limited number of coal-hydrogenation plants to produce chemicals as a major part of the products may be very attractive. In addition to phenols, coal-hydrogenation plants can produce important quantities of benzene, toluene, xylene, naphthalene, and tar bases, all of which have market prices considerably higher than liquid fuels. Several of these chemicals are important to national defense and may be in short supply in case of war. Even in peacetime the demand in some cases is likely to outstrip our present capacity to produce.

It is clear from this discussion that a coal-hydrogenation plant is not yet in as favorable a position as an oil-shale plant so far as conversion costs are concerned. On the other hand, because coal supplies are available over a wide area, the coal plants have greater opportunities for realizing lower product-transportation costs, selecting favorable markets, and producing high-quality products that will bring a premium price. A suitable combination of coal supply, plant location products, and market can go a long way in neutralizing differences in conversion costs.

So far, only the surface has been scratched in the development of synthetic fuel processes. Costs that now appear in or near the competitive range can be reduced still further. New developments in the processes for coal are in the laboratory. More effective catalysts, which permit operation at lower pressures, are in sight. Dry coal hydrogenation, permitting the use of lower operating pressures, elimination of paste preparation, and greater plant throughput has made steady progress during 1949. In addition, perusal of the detailed reports will illustrate the sturdy foundation of productive science, the skill and understanding, that are being built up in the laboratory programs. These developments lead toward simpler and cheaper synthetic fuel processes.

## Gas-Synthesis Plants

The Bureau of Mines is also completing a gas-synthesis demonstration plant at Louisiana, Mo. It is anticipated that the final units will be placed in operation during 1950. Two sections of the plant, the oxygen unit and the coal gasifier, are now completed and have been operated successfully for several months.

Cost calculations for commercial gas-synthesis operations using coal will be based on the demonstration tests, but it will be a year before these estimates can be made.

A commercial plant producing mainly motor gasoline from natural gas is being constructed by the Carthage Hydrocol Corp. at Brownsville, Tex. Cost figures for this plant would help materially in estimating costs for the gas-synthesis process and for producing oxygen on a large scale. As the plant operates on natural gas, it will not furnish data for the coal-gasification step. This information, however, will be available from the pilot-plant work being conducted by industry and the Government.

## Gas-Synthesis-Process Development

Several gasification processes are in the pilot-plant stage of investigation in the Bureau of Mines. These include three pilot plants operating on pulverized coal and oxygen, together with a field-scale experiment on the possibilities of underground gasification of coal. Considerable progress has been made, but a great deal of work remains in developing the most economical method of carrying out the gasification step.

It is probable that the cost of synthesis gas always will be a large fraction (50 to 70 percent) of the cost of liquid fuels from the gas-synthesis process, when coal is used as the raw material. This relatively high cost of synthesis gas has oriented Bureau of Mines work on the synthesis process in the direction of high efficiency of conversion to liquid and minimum yield of normally gaseous fuel. Another objective in the synthesis process development has been to provide sufficient flexibility for control of product distribution (that is, relative amounts of gaseous hydrocarbons, gasoline, and Diesel oil).

Pilot-plant development of one process is almost completed. The liquid product of this process is about 65 percent gasoline (75-80 motor octane number without tetraethyl lead addition), 15 percent Diesel oil (80 cetane number, 20°F. pour point), 10 percent wax, and 10 percent oxygenated organic compounds (chiefly ethyl alcohol and acetic acid). The heat of reaction is removed by circulating an oil through the catalyst bed and through a heat exchanger. As compared with the Ruhrchemie process, the yield per unit of reactor volume is 8 to 10 times larger when the gaseous hydrocarbon yield is about the same. The amount of gaseous hydrocarbons can be reduced to about one-half, but the yield of product from a given size reactor will decrease concurrently to four to five times that of the Ruhrchemie process.

These improvements in the synthesis operation, coupled with progress in gasification, will assist in achieving lower costs for products of good quality.

## Oil from Coal

### Demonstration Plants, Louisiana, Mo.

In 1949 major activities at the new Coal-to-Oil Demonstration Plants near Louisiana, Mo., underwent a transition from the plant-design and construction phase to completion of equipment installations, testing, "break-in" runs, and initial operations.

First of their kind in this country, these two demonstration plants above St. Louis on the Mississippi River will employ different processes to convert coal and lignite to high-quality synthetic liquid fuels. They were dedicated on the anniversary of VE-Day, May 8, as a proving ground for American coals, equipment, and processing methods.

The initial unit completed - the 200- to 300-barrel-a-day Coal - Hydrogenation Plant - was turned over to the Bureau by the contractor on January 31. Built by the Bechtel Corp. of California, this plant was designed for pressures up to 10,300 pounds a square inch in two major operations: (1) Liquid-phase hydrogenation, which accomplishes liquefaction of the coal; and (2) vapor-phase hydrogenation, which converts the liquefied coal to gasoline and byproducts. After considerable pressure testing and mechanical check-up work, the first vapor-phase hydrogenation test run at 10,000 pounds pressure was conducted in April and lasted 9 days, using crude petroleum first and then lignite tar.

At the dedication in May, specification Diesel fuel produced from lignite tar during this run was used to fuel a Diesel-electric locomotive that hauled a loaded, eight-car, special passenger train from St. Louis to the plants and back - a round trip distance of approximately 200 miles. Burlington officials and the engineer expressed complete satisfaction with performance of the fuel. Synthetic gasoline made during the same run has been used since May in all plant passenger automobiles, trucks, and cranes.

A 7-week "break-in" run for the liquid-phase hydrogenation system was completed successfully on December 2, the first time in this country that substantial quantities of oil have been made from coal. The basic plant design proved to be sound and operable, and this initial run was made without serious interruptions, even though the operators had only the limited high-pressure experience obtained during the vapor-phase operation in April. High-temperature coal-tar oil was used as the charging stock at the outset and later was replaced with a coal paste containing 25 percent bituminous coal from Rock Springs, Wyo. The run was terminated when the stock of Rock Springs coal was exhausted. Under current plans, a wide variety of coals from other fields will be tested later.

Extensive use of automatic controls in the Hydrogenation Demonstration Plant has resulted in a comparatively much smaller operating force than was customary in the commercial synthetic fuels plants of Germany.

With this plant now in operation, the Department of Defense is planning to test the products. Units of each service-the Army, Navy, and Air Force-will determine their suitability for specialized purposes. Both coal-hydrogenation and oil-shale plants also offer sources for byproducts valuable in time of war. Processes are being developed for the extraction of these products if needed.

Design work has been finished on the second plant - an 80- to 100-barrel-a-day Gas-Synthesis Demonstration Plant - and construction was estimated to be 70 percent complete on December 1.

Two units of this plant, the oxygen producer and the coal gasifier, are in operation. The oxygen unit has been in continuous service since August and performance has been very satisfactory. The Koppers-type coal gasifier, operating at less than capacity, made its first run in May. Since then 36 runs have been conducted, each with definite fact-finding objectives in a search for the best conditions for coal gasification and steam reactions. Efforts are concentrated on reducing the oxygen and coal requirements for synthesis gas, a major cost factor in the production of synthetic fuels.

A cooperative agreement has been concluded with the American Gas Association for extensive tests with pure oxygen in a Kerpely gas producer that was installed to supply a stand-by source of gas during periods in which the powdered-coal gasifier is not functioning. Operation of the Kerpely unit, as adapted for using oxygen, is a matter of wide interest both in synthetic fuels work and the gas industry generally.

Construction of the gas-purification section of the demonstration plant is expected to be completed early in 1950, and it will be put in operation after the coal-gasification unit is functioning in a routine manner.

Many new commercial-size plant-cost estimates and engineering studies were conducted during the year.

An investigation of petroleum-residuum hydrogenation indicated that for a plant of 16,500-barrel-a-day capacity, operating with a combined liquid- and vapor-phase unit without intermediate pressure let-down, the total construction cost would be approximately $34,000,000. Pay-out time in various locations would range between 4.4 and 7.9 years, depending on the price of feed stock, which for the two limits cited was $1.45 and $1.60 a barrel, respectively.

A comparative cost estimate was made for producing different quantities of motor or aviation gasoline and jet fuels in a 30,000-barrel-a-day coal-hydrogenation unit.

Byproduct hydrocarbon gases from synthetic fuel plants were evaluated for use as a source of city gas. Use of these gases may have far-reaching effects on the gas industry when a synthetic fuel industry is established.

A study was made of the cost factors for a 10,000-barrel-a-day synthetic fuels plant, situated in Alaska and using Alaskan coals. Capital and product costs were estimated at well over twice those for the same plant in the United States.

In another estimate, the cost of plant facilities to make, purify, and compress hydrogen to 700 atmospheres was found to represent 36.5 percent of the cost of a 30,000-barrel-a-day coal-hydrogenation plant.

Chemical and byproduct costs from coal hydrogenation also were calculated, for such plants would be abundant sources of tar acids used in plastics and other industrial products. Detailed engineering studies continued on equipment for commercial-scale hydrogenation plants.

The problem of preparing preliminary plant design for establishing construction and operating cost estimates for a 10,000-barrel-a-day coal-gasification and gas-synthesis plant is 40 percent complete.

## Laboratories and Pilot Plants, Bruceton and Pittsburgh, Pa.

The work of the laboratories and pilot plants at Bruceton, Pa., during the calendar year 1949 has been concerned chiefly with the development of new or improved processes for the production of liquid fuels from coal. This work may be divided into two broad categories: (1) The synthesis of liquid fuels from the gasification products of coal (Fischer-Tropsch and related processes), and (2) the direct hydrogenation of coal (Bergius process).

In the first category, two pilot-plant units were operated on the liquid-cooled (by oil circulation) process to study the effect of catalyst grain size and synthesis-gas composition. Because of operating difficulties encountered in this "fixed-catalyst-bed" system, a "moving-catalyst-bed" was adopted in which the catalyst is lifted by an increased liquid velocity and kept suspended in a stream of liquid and gas.

Studies also were made of operating techniques and design modifications of the circulating slurry process, in which synthesis gas is bubbled through a suspension of finely powdered catalyst in high-boiling range oil.

The search for suitable commercially available catalysts for these processes was continued. Extensive research on the relation of catalysts to the synthesis mechanism included the effect of particle size, alkali content, reduction conditions, carbide content, free-carbon content, surface area, and porosity of the catalyst. The substitution of nitrogen for carbon in the crystal lattice of carbided iron synthetic-ammonia-type catalysts has opened a new field for explorations into the mechanism of contact catalysis and for the development of highly active catalysts.

Studies of the OXO process, by which aldehydes and alcohols are produced from olefinic hydrocarbons, have revealed a process variation of marked commercial significance. By using an alcohol as the starting material, a homologous alcohol (consisting of one more carbon atom than the original) is produced. This direct conversion of one alcohol into the homologous alcohol normally is a tedious, multistage process in commercial operations. The reaction also has important implications in the Fischer-Tropsch process and may even replace it in the manufacture of synthetic liquid fuels if catalyst and temperature conditions can be found under which the alcohol homologation is rapid enough at pressures of not more than about 70 atmospheres.

Two coal-hydrogenation pilot plants were placed in operation, one for the first or liquid-phase stage and one for the second or vapor-phase operation. These plants are concerned with tests on raw materials, catalysts, and operating procedures. Studies in batch autoclaves of the conversion of coal to oil by direct hydrogenation indicated that this conversion could be carried out most efficiently by dividing the liquid-phase operation into at least two steps. Extensive laboratory tests to discover new catalysts as efficacious as tin for the hydrogenation of coal have indicated that the state of physical distribution of the catalyst in the reaction mixture is important.

Analysis of the products obtained from the direct hydrogenation of coal and those obtained by synthesis of hydrogen and carbon monoxide was improved by the development of new equipment and techniques. Of particular importance is the use of countercurrent distribution for the separating and identifying tar acids produced in the liquid-phase hydrogenation of coal. A study of these phenolic materials has yielded some information concerning the constitution of coal and indicated possible industrial processes for separation of the marketable constituents.

Work was continued at Pittsburgh on the preparation of synthesis gas by the gasification of powdered coal with oxygen and steam in a vortex combustor. The results were definitely encouraging, and an operable, high-capacity gas generator probably will be developed. The cost of the oxygen used in the gasification of coal is an important factor in the economy of the process. An investigation is being made of a possible method for a more economical production of oxygen, based on the fact that many organic membranes are appreciably more permeable to oxygen than they are to nitrogen.

Collecting, arranging, classifying, and indexing of the foreign documents from German and other sources containing information of interest on synthetic liquid fuels were continued. The review and compilation of the literature on the pressure of hydrogenation of liquid and solid carbonaceous materials has been completed, and the current literature is being thoroughly covered and abstracted.

Synthesis-Gas Laboratory and Field Tests, Morgantown, W. Va., and Gorgas, Ala.

In laboratory and field tests at Morgantown, W. Va., and Gorgas, Ala., respectively an intensive search was being made for a coal-gasification process that will reduce materially the cost of synthesis gas - hydrogen and carbon monoxide - required in the production of synthetic liquid fuels.

On March 18 at Gorgas, the Alabama Power Co. and the Bureau of Mines, having completed site preparations, put in operation their second cooperative experiment in the underground gasification of coal. Gases produced by burning unmined coal under controlled conditions offer a potentially low-cost fuel for generation of electric power as well as materials for conversion to liquid fuels. In addition, underground gasification promises to recover the energy of thin or impure coal seams that cannot now be mined economically.

Two parallel entries were driven into the coal bed for 1,200 feet and a single entry for an additional 300 feet. At crosscuts linking those entries, the underground workings were connected with the surface by five large boreholes through which compressed air may be admitted or product gases withdrawn.

All operations thus far have been conducted in the 300-foot single entry, and there has been no difficulty in maintaining combustion. Approximately 3,000 tons of coal has been burned, and no limit has yet been found as to the quantity of coal that can be consumed from an area surrounding a given, initial entry or passageway in the seam. As installed, the equipment and the gas inlet and outlet passages have operated quite successfully.

There has been no emphasis on quality of gas during these initial operations, for the essential objective is to produce a gas and then to exercise control. If a producer gas is obtained, the quality may be improved through the use of oxygen and steam with the aid of fluid catalyzers.

At times, under the proper conditions, the calorific value of the product gas has been high enough to make it combustible. However, owing to the bypassing of air through void spaces underground and subsequent combustion of the product gas before removal from the system, the energy content of the coal as brought to the surface has been largely in the form of sensible heat. This could be used, of course, for generating steam at the system outlets. There is evidence that a good-quality producer gas is being made along the burning coal ribs, but it has not yet been possible to recover such gas.

A measure of success has been attained in blocking the void spaces, which cause the air-bypass difficulty, by introducing fluidized sand into the original entry through small boreholes from the surface. Roof action away from the line of the original entry apparently has left no void spaces, and no trouble of this nature is anticipated there.

By additional drilling and the introduction of sand at the proper points, it is believed that the product gas can be recovered. Without enrichment, this gas would not be suitable for domestic use, but it could be employed as a source of power - to heat a boiler to make steam, or to turn a gas turbine, which would make electricity. Enriched through the use of oxygen and steam with the aid of fluid catalizers, it may be suitable as a synthesis gas for conversion to liquid fuels.

At Morgantown, pilot plants employing other principles for the coal gasification were in operation. Test runs in a small unit, having a capacity of 25 to 50 pounds of pulverized coal an hour, indicated that this plant will gasify virtually any type of coal, regardless of its ash or sulfur content. In a larger unit, about 56,000 pounds of coal was gasified during the year at rates up to 490 pounds an hour and at temperatures approximating 3,600° F. Owing to these high steam temperatures, the tests were made with lower oxygen consumption than any previously reported for other plants (121 to 265 standard cubic feet for each 1,000 standard cubic feet of synthesis gas produced). The percentage of gasification of the total carbon content of the coal was very satisfactory, ranging from 70 to 90 percent.

Design work is about 40 percent complete on a pilot plant to gasify 500 pounds of coal hourly at pressures up to 450 pounds per square inch gage.

Further studies and improvements were made on a method for continuously feeding pulverized coal into the gas generators. One accomplishment was measurement of the instantaneous ratio of solid to gas flowing through a tube when the volume percentage of the solid was about 20 percent. The instrument used is sensitive enough to detect a change of about 1 percent solids by volume, and it operates by measuring the change in capacity of a condenser as the mixture of solid and gas flows between the plates. Measurements have been made of the homogeneity of coal and air mixtures flowing to a synthesis-gas generator.

A gas-purification pilot plant has been completed and is ready for operation. Provisions are being made so that the plant can be operated either at atmospheric or elevated pressures. A moving-bed filter, designed as a modification of the German shaft filter for removing dust from gas, has been highly successful in reducing dust concentrations from 1,000 to less than 0.1 grain per 100 cubic feet of gas.

In gas-treating studies, the most promising catalysts studied for desulfurizing synthesis gas were those that remove hydrogen sulfide and organic sulfur compounds simultaneously. Data from numerous experiments show that several catalysts, when operated at 450° C., were capable of removing all of the organic sulfur and 99 percent of the hydrogen sulfide from the gas before revivification was necessary.

## Oil from Oil Shale

### Experimental Mine, Rifle, Colo.

A major advance toward the development of low-cost methods and equipment for mining the oil-rich Green River shale formation of Colorado, Utah, and Wyoming was achieved in 1949.

The Experimental Oil-Shale Mine is on Naval Oil-Shale Reserve No. 1, near Rifle, in western Colorado. A mountain road, 3-1/2 miles long, ascends to the mine yard at an elevation of 8,100 feet. The mine portals, driven into the base of vertical cliffs, overlook the Oil-Shale Demonstration Plant site and the Colorado River 3,000 feet below.

Methods, procedures, and equipment employed in the Underground Quarry section of the Experimental Mine were demonstrated publicly before more than 500 representatives of industry and Government in September. The average production rate maintained during this 4-week demonstration run was 148 tons of shale per man-shift of underground labor, or 116 tons per man-shift of total labor. It is believed that no other underground mining operation has approached these figures. The direct mining cost, excluding depreciation, general office expense, and overhead, was 29 cents per ton of oil shale. Total production for the 20 operating days was 32,560 tons.

Underground operations were carried on during 1949 in two sets of workings, including a Selective Mine as well as the Underground Quarry. However, with the requirements of the demonstration plant standardized on oil shale produced from the Underground Quarry, operation of the higher-cost Selective Mine was curtailed sharply in April 1949. Operations in this mine now are limited to research problems and the production of small quantities - 10,360 tons in 1949 - of selected-grade oil shale. During the year, 133,600 tons of oil shale was mined from the Underground Quarry.

Considerable progress was made in all phases of the research program, which was directed toward the solution of problems associated with the drilling and blasting of oil shale and determination of the maximum safe span that can be excavated without roof support in the oil-shale formation. Percussion-drilling research was virtually completed, and explosives costs have been lowered substantially through blasting research.

Experiments with rotary-drilling equipment continued throughout 1949. Some progress was made in developing better bits for this type of drilling, but further improvements are needed before rotary drilling can compete favorably with percussion drilling.

Assays of samples from core-drill holes completed during the summer of 1949 further support the estimate that western Colorado contains 300 billion barrels of shale oil in place. In all, 12 holes have been drilled by the Bureau and 14 by various oil companies exploring their own properties. The Bureau also collected further data on the oil-shale resources of other States.

The full complement of equipment necessary for operation of the Underground Quarry as one unit of a commercial-scale operation is now available. New equipment developed during the year included:

1. More efficient 15-foot drill feeds to replace the 11-foot feeds on the heading jumbo. These feeds make it possible to drill a deeper round and subsequently to break a greater tonnage with each blast.

2. A benching jumbo for drilling vertical blast holes. Like the heading jumbo, it mounts four 15-foot drill feeds and is operated by two men. The usual benching round consisting of 48 22-foot holes is drilled in 7-1/2 hours with this machine.

3. A telescopic-lift truck with a maximum lift of 65 feet which serves as a scaling rig for miners when trimming loose rock from the walls of the mine.

4. A water-tank truck mounting a 700-gallon water tank and a high-pressure, 50-gallon-per-minute, self-priming pump. This unit is used for transporting water for drilling, for wetting the piles of broken shale before loading, and for wetting down the mine haulageways.

<u>Demonstration Plant, Rifle, Colo.</u>

At the Oil-Shale Demonstration Plant near Rifle, Colo., attention was centered in 1949 on retorting and refining operations. Meanwhile, a process engineering and evaluation unit was established to study processes, design commercial-scale plants, and estimate costs for producing liquid fuels from oil shale.

The new demonstration shale-oil refinery was placed in operation in July. It consists of a thermal cracking unit and a continuous acid-treating and doctor-sweetening unit. The thermal processing unit is quite flexible and can be operated on any of the usual thermal refining procedures.

Shale gasoline and Diesel fuel produced in the refinery were burned in passenger cars, buses, Diesel trucks, and other equipment during the 4-week public mining demonstration. Performance was excellent.

Shale was crushed for retorting operations at Rifle and for shipment to cooperators. Crushing the richer shales in the jaw-type crushers now in use has been found troublesome because rich shale breaks parallel to the bedding plane, forming long slabs, whereas lean shales break across the bedding. Testing of different types of crushers is planned.

Experimental work on the N-T-U retorts has been completed and these units now are being operated on a production basis to supply the burner oil requirements of the project. These retorts have provided feed stock for the demonstration shale-oil refinery, together with information useful in designing continuous retorts. However, operations thus far have indicated that the continuous gas-flow retort developed at Rifle is superior to the batch-type N-T-U retorts for processing oil shale.

Pilot-plant work has been devoted primarily to (1) developing the gas-flow retorting process, (2) studying the combustion of residual organic matter in retorted shale, (3) investigating means of breaking shale-oil emulsions, and (4) preparing process designs for several proposed retorting processes.

In the gas-flow process, gas is heated in pebble stoves and passed horizontally through a shale bed which moves downward continuously. Preliminary experiments on a retorted-shale burner indicate that the organic residue in shale discharged from a process such as the gas-flow can be utilized to provide part of the heat required for retorting. Although several methods have been found effective in breaking shale-oil emulsions, more work remains to be done to determine whether any of them are economically feasible. Several new retorting processes are under study; and at least one of these, the Bureau's counter-flow process, is thought to have possibilities pending pilot-plant evaluation.

Ten cooperative agreements have been added to those that already were in effect with industry and universities at the beginning of 1949. Under these agreements, the Oil-Shale Demonstration Plant supplies oil shale, shale oil, and shale-oil products to cooperators for experimental work in exchange for information on the results of their experiments. Furthermore, a new type of agreement has been initiated under which the cooperator lends equipment to the Bureau for test purposes and in return receives the results of the tests.

Laboratories and Pilot Plants, Laramie, Wyo.

At Laramie, Wyo., scientists in the Bureau's Petroleum and Oil-Shale Experiment Station were at work studying the composition of oil shale and shale oil, developing methods of processing and using these materials. Lessons learned in the laboratory there are applied in the demonstration plant at Rifle, where the processing, engineering, and economic factors can be analyzed more fully in larger equipment.

Studies to determine the heat required to retort oil shale were extended to include a 57-gallon-a-ton shale. Data now are available from which it is possible to calculate such requirements in the temperature range of 750° to 1,000° F., for virtually any grade of Colorado oil shale. Similar data are available on spent shale for the same temperature range.

For example, a value of 100 B.t.u. per hour, per cubic foot, per degree Fahrenheit difference between gas and shale temperature was obtained for the heat transfer coefficient from a hot gas to a bed of 28-gallon-a-ton crushed shale over the temperature range of 500° 1,100° F., and a gas-flow rate of 31 cubic feet a minute. For spent shale, this coefficient ranged from 85 to 130 B.t.u. per hour over the same temperature range.

It was found, too, that the presence of small volumes of oxygen in the retorting gas decreased the oil yield during retorting from 2 to 19 percent.

Recoveries of 100 percent of the organic matter from oil shale were obtained with a thermal solution extraction process when using hydrogen pressure. Low-cost separation of the converted organic matter from the spent shale is still the major problem to be solved in this process.

In studies of the catalytic cracking of shale-oil fractions, the yields that can be obtained in using each of several commercial cracking catalysts were determined. Gasoline of good octane rating can be made by this process, but coke formation on the catalyst causes a short catalyst life. Investigations now in progress on the effects of organic nitrogen compounds on cracking catalysts should aid in developing better catalysts than those now in use.

American shale oils have higher nitrogen contents than those produced in other countries and, hence, present different problems. The heavy gas-oil fraction from shale oil extracted in an N-T-U retort was found to contain more than 40 percent nitrogen compounds. As this is the charge stock for current cracking operations, the importance of determining the types of compounds and their reactions to cracking conditions is apparent.

Moreover, evidence is accumulating that much of the color and gum formation in shale-oil products is attributable to the presence of nitrogen compounds of the pyrrole type. The first member of the series - pyrrole - has been isolated and identified.

Hydrogenation now appears to be the most practical method of refining shale oil to reduce sulfur and nitrogen contents and produce good quality synthetic liquid fuels. It has been possible with suitable catalysts to improve the quality of shale oil greatly by this process at pressures as low as 500 pounds a square inch. Coke deposition on the catalyst, with consequent short catalyst life, is the major problem in this process, and efforts are being made to develop better catalysts or more suitable hydrogenation conditions.

The organic content of oil shales from Colorado and seven foreign countries ranged from 7.3 to 95.5 percent, while the oil yields ranged from 21 percent for Swedish oil shale to 78 percent for Australian torbanite. The organic matter in four Colorado oil shales yielded 65 to 71 percent oil by assay.

A preliminary study of the constitution of the organic matter in Colorado oil shale indicated that this material occurs largely in a high molecular weight form but with some interspersed structures of low molecular weight. The high-molecular-weight material consists, apparently, of a loosely interconnected structure of partially unsaturated polyisoprenoid, resinlike chains and rings. Bound also in this structure are oxygen-containing and oxygen heterocyclic fragments condensed with some benzenoid and pyridine ring structures.

Waxes designated as crude and semirefined "shale-oil waxes," as well as fully refined paraffin, were made by conventional petroleum solvent extraction and refining processes from a shale-oil-wax distillate similar to petroleum-wax distillate. The fully refined wax met the specifications for fully refined petroleum paraffin, while the "shale-oil waxes" contained unsaturated hydrocarbons.

Tar acids amounting to 4 percent were separated from a shale-oil fraction boiling from 160° to 260° C. Further purification gave a very small percentage of phenol and larger amounts of orthocresol, metaparacresol, xylenols and higher alkylated phenol fractions.

N-T-U crude shale oil was vacuum-distilled to yield a series of residual asphalts having consistencies within the paving asphalt range. The properties of the products were determined by common asphalt tests. In general, the shale-oil asphalts contained more wax and had higher temperature susceptibilities than petroleum asphalts. The shale-oil asphalts also showed expected evidence of previous cracking.

## Liquid Fuels from Agricultural Residues

Semiworks Plant, Peoria, Ill.

From appropriations authorized by the Synthetic Liquid Fuels Act, the United States Department of the Interior has transferred to the United States Department of Agriculture $510,000 for research and development on the production of alcohol and other liquid fuels from such agricultural residues as corncobs and the hulls of cottonseed, oats, and rice. With these funds, the Bureau of Agricultural and Industrial Chemistry late in 1946 started operations in a small industrial plant at Peoria, Ill., to determine the manufacturing steps and costs of a process of its own development.

The Liquid Fuels Plant was located on the site of the Northern Regional Research Laboratory at Peoria to permit coordination of the programs of the two groups and more rapid evaluation of the possibilities of the process. The Northern Laboratory, therefore, is studying the fermentation of the pentose and dextrose sugars to liquid fuels and is testing the various fuels produced.

Basically, the hydrolysis process under investigation consists of converting one of the fractions of agricultural residues - pentosans - to pentose sugars and subsequently converting the cellulose fraction to dextrose. The pentose sugars may be fermented to the liquid fuels butanol, isopropanol, acetone, and ethanol or they may be converted to furfural. Dextrose, on the other hand, may be converted to the liquid fuel ethanol. The fundamental economic advantage of this particular process is that pentose sugars and dextrose can be almost quantitatively separated; therefore, each one in its turn can be converted to maximum yields of end products.

A survey has been conducted for the four largest corn-producing States, namely, Iowa, Illinois, Nebraska, and Indiana, to determine the "average density" of corncobs available for industrial use in each county of these states. In the zones having the highest density, 12 cob-collecting centers have been selected, each center having a potential cob-collecting capacity of more than 200,000 tons within a 50-mile radius. Since each collecting area is synonymous to one corncob saccharification plant having a processing capacity of 100,000 tons annually, 1,200,000 tons of cobs from these areas would be available for conversion to liquid fuels.

A material balance diagram for the pentosan hydrolyzation phase based on the average production data accumulated from last year's routine operation of the semiworks plant was prepared. This diagram indicates that about 18 percent of the pentosans present in air-dry cobs is not converted to pentose sugar with the present processing procedure. The cause of this phenomenon probably can be traced back to a recent change in the composition of the cellulosic material. By varying the hydrolyzation procedure for the pentosan fraction, the amount of unattacked pentosans can be decreased to an economical level as demonstrated by large-scale laboratory experiments.

For the development of the important operational steps of the lignocellulose hydrolyzation phase, redesigning and alterations of the special equipment have been necessary to obtain efficient performance of the machinery. Adaptation of the Myers-Sherman mixing procedure solved the problem of uniform mixing of the dried, pentosan-extracted corncobs with sulfuric acid. At present, the hydrolyzation procedure under investigation yields a cellulose hydrolyzate with a glucose concentration of 7 grams per 100 ml. representing a 65-percent conversion rate; however, a higher concentration of glucose and an improved conversion rate are anticipated.

Studies regarding the kinetics of the conversion of xylose in the pentosan hydrolyzate to furfural are under way and will lead to investigations for a higher yielding conversion process on a semiworks-plant scale.

Pentosan hydrolyzates can be fermented successfully to the liquid fuels, butanol, acetone, and ethanol if the hydrolyzate in the fermentation media is supplemented with cornmeal. Large-scale fermentations with hydrolyzate liquors and cornmeal have been made in 3,000-gallon pilot-plant runs.

Results of motor fuels testing indicate that the addition of alcohol greatly increases the sensitivity of gasoline. Sensitivity is defined as the spread between the Research Method and the Motor method. It has been found that the Research Octane Number is more affected by the addition of lead than the Motor Method. This is significant since it is the Research Octane Number that appears to determine the road rating of high compression engines.

In addition to U. S. Patent 2,450,586 covering the different stages of the hydrolyzation process, various procedures as they are proved acceptable are being examined for their patent potentialities.

## Secondary Recovery and Refining Research

Under an amendment to the Synthetic Liquid Fuels Extension Act, funds became available on July 2, 1948, to conduct research on secondary recovery from stripper oil fields and in refining processes. The first 6 months of work, previously reported, was spent largely in initiating studies that not only would comply with the intent of the amendment but also would coordinate the existing programs of the Bureau of Mines in these fields. In effect, this first period was one of "tooling up" with specialized equipment and trained personnel. Now that the work has progressed an additional 12 months, measurable technical progress has been made.

In the 1948 Annual Report, the following field headquarters were named as centers of activity on secondary recovery research: Bartlesville, Okla.; Laramie, Wyo.; San Francisco, Calif.; Dallas, Tex.; and Franklin, Pa. In addition, a suboffice of the Dallas, Tex., Petroleum Field Office is maintained at Wichita Falls, Tex., and during the past year a suboffice of the Franklin, Pa., Petroleum Field Office was opened at Bradford, Pa. The studies of refining marginal crude oils continued at Laramie, Wyo., and Bartlesville, Okla.

It soon became evident that, to obtain proper correlations with work already in progress, a broad view of each program must be taken. Otherwise a distorted picture would be given of the Bureau's efforts to find new means by which industry will progressively lessen the quantity of oil in stripper fields that is called "unrecoverable." Also, in the work on marginal crude oils, so classified because of their high sulfur content, cognizance must be taken of related research.

Engineering field studies of secondary-recovery operations were conducted in the Mid-Continent, Texas, California, Rocky Mountain, and Appalachian regions. By collecting and studying data on the production histories and the reservoir conditions of representative stripper fields, those stimulative methods that are more efficient in producing oil under given conditions can be ascertained and applied to obtain the greatest benefit.

Fundamental research on the nature of the forces that hold crude petroleum in the underground reservoir rocks was advanced along three main fronts: (1) Experimental data were obtained and reported on observed surface phenomena at the contact surfaces or interfaces of fluids and solids. In effect this is a special study of permeability relationships. (2) Surface-active and film-forming substances were extracted from crude petroleum. (3) Interfacial tension studies were made that involve observation of phenomena at the contact surfaces or interfaces of two liquids or of a liquid and gas. The combinations of conditions are manifold, but the present work is restricted to the simpler cases.

Engineering research on secondary-recovery problems is diversified so far as individual problems are concerned, indicating attacks on many fronts, but in effect they all group together, regardless of where they are studied. The object of the project is to obtain more stock-tank oil from stripper fields by scientifically planned and engineered methods of stimulation. For example, an intensive effort is being made to apply the science of rock physics to the shooting of oil and gas wells with explosives. Another important study in this group pertains to the selective plugging of strata in air-gas injection wells so that the injection medium will enter those parts of the sand body containing the most oil and not bypass through the more permeable strata. Other engineering research includes: Studies of ways by which oil wells may be made to flow on gas-injection projects - highly important from the viewpoint of economic operation; studies of drilling fluids for cable-tool coring; means of locating abandoned wells, which in flood areas cause losses of injected water and contamination of fresh-water supplies if not plugged properly; investigations of water conditioning for injection purposes; determination of the effects of dissolved gases on the corrosion of metal by water; studies of the effect of heat on oil recovery; research on the possibilities of heating oil sands by electromagnetic radiation. One problem in this group that is being held in abeyance, but on which active work should start soon, is the use of radioisotopes as tracers in waterflooding operations. It is believed that this method affords an accurate "tool" to determine where the injected flood water is going and how effective it is in forcing oil to producing wells.

The fourth and final main division in the secondary-recovery program includes those problems requiring special techniques and laboratory analyses. These are exemplified by core and water analyses, electric logging in the shallow fields to find the "tops" and "bottoms" of the "pay" formations where well logs are missing or unreliable, electrical analogy flow studies, and the development of special tools - such as a small-diameter well caliber. This tool is urgently required in the Bureau's studies of efficient rates of injecting water and in determining the strata that should be selectively plugged.

The petroleum chemistry and refining program has been directed toward improving the utilization potentialities of the so-called marginal crude oils, especially those so classed because of a high content of sulfur. During the year this work has been closely correlated with the Bureau's broader program including the American Petroleum Institute Research Project 48A, both of which are designed to furnish fundamental data on the characteristics of the sulfur compounds in petroleum. Substantial progress was made in the work of determining the characteristics of the sulfur-bearing distillates of 17 selected crude oils. States from which samples have been obtained so far are Arkansas, California, Colorado, Michigan, Mississippi, Oklahoma, and Texas.

The groundwork has been laid for the study of thermal stability of distillates and the thermal decomposition of sulfur compounds. Study of these closely related problems should provide valuable information pertinent to the design of equipment and development of processes in which high-sulfur crude oils will be utilized.

In 1949 the work in both fields has become better organized, and the emphasis on some of the problems has changed. This has resulted from more careful evaluation of the need for and interest in various parts of the work program by industry than could be obtained at the start. Through informal discussions with various technical groups, individuals, and representatives of industry, the Bureau technologists working on the assignments feel that with minimum effort and delay they have obtained a cross-sectional view of the efficacy of the programs of secondary recovery and in refining processes to meet present needs and to build for the future. Every evidence points to the fact that the problems have been well-chosen, as their solution seems essential to the fuel economy of the country.

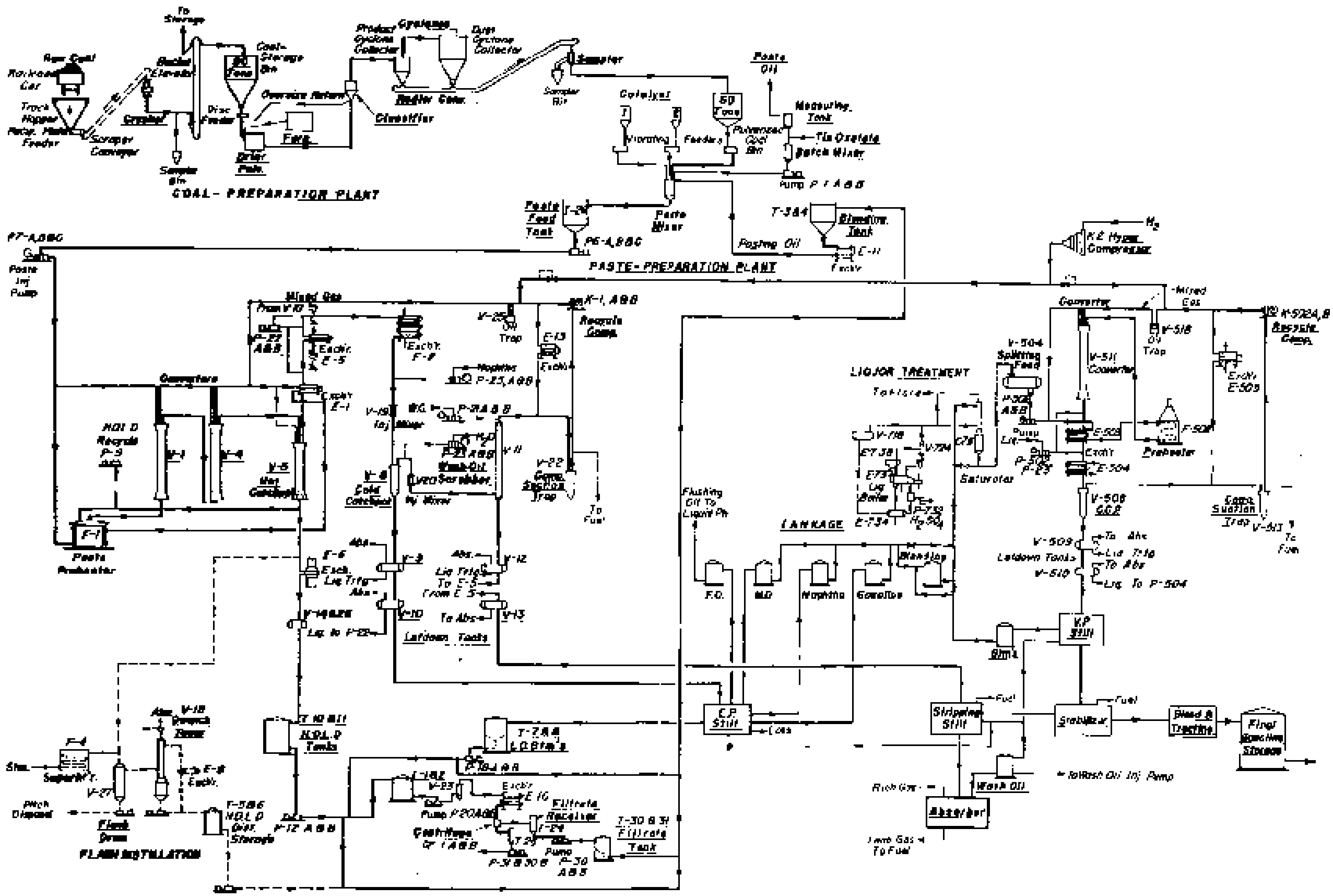

Figure 2. - Process-flow diagram of Coal-Hydrogenation Demonstration Plant.