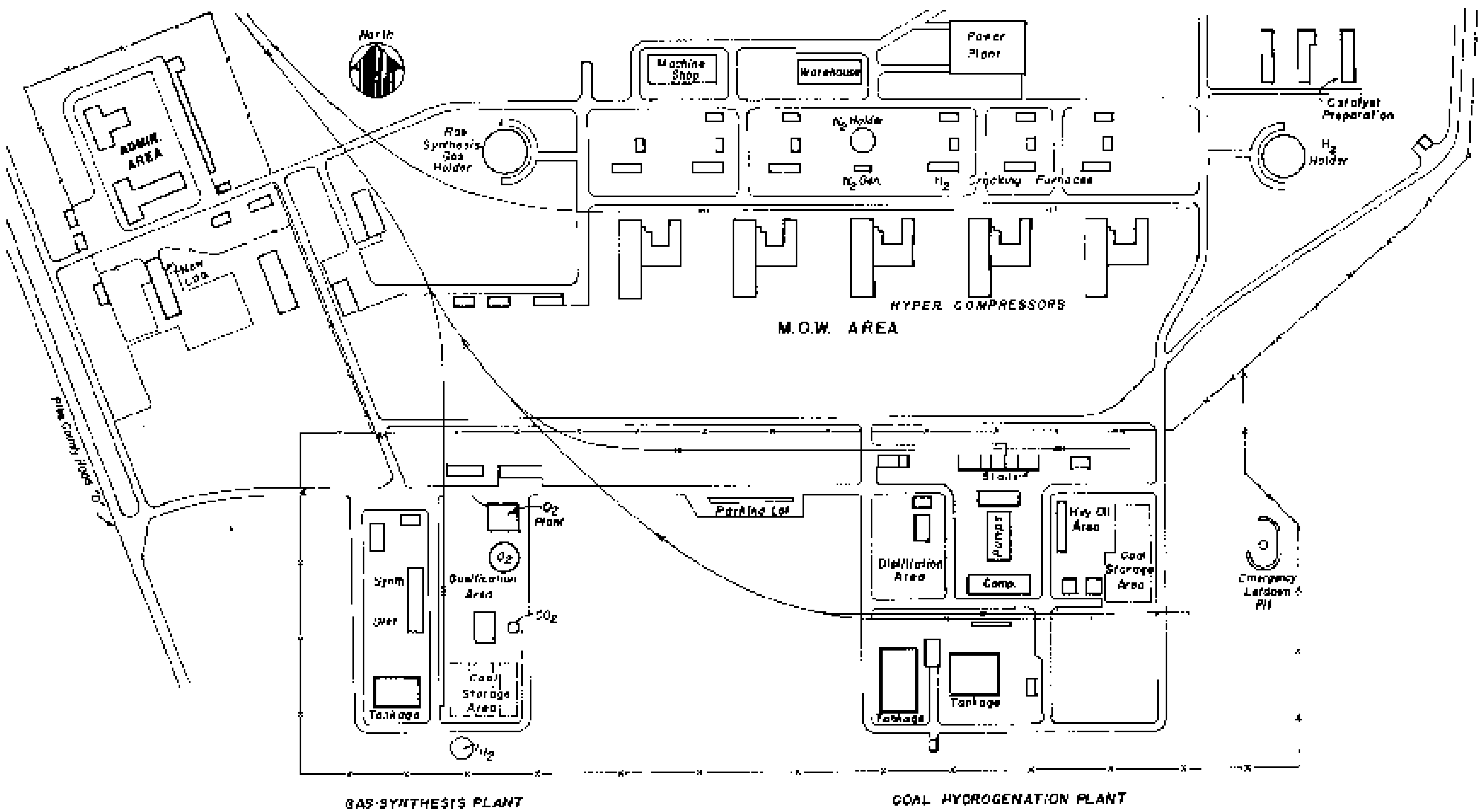

Figure 1. - Plot olans, Coal-to-Oil Demonstration Plants.

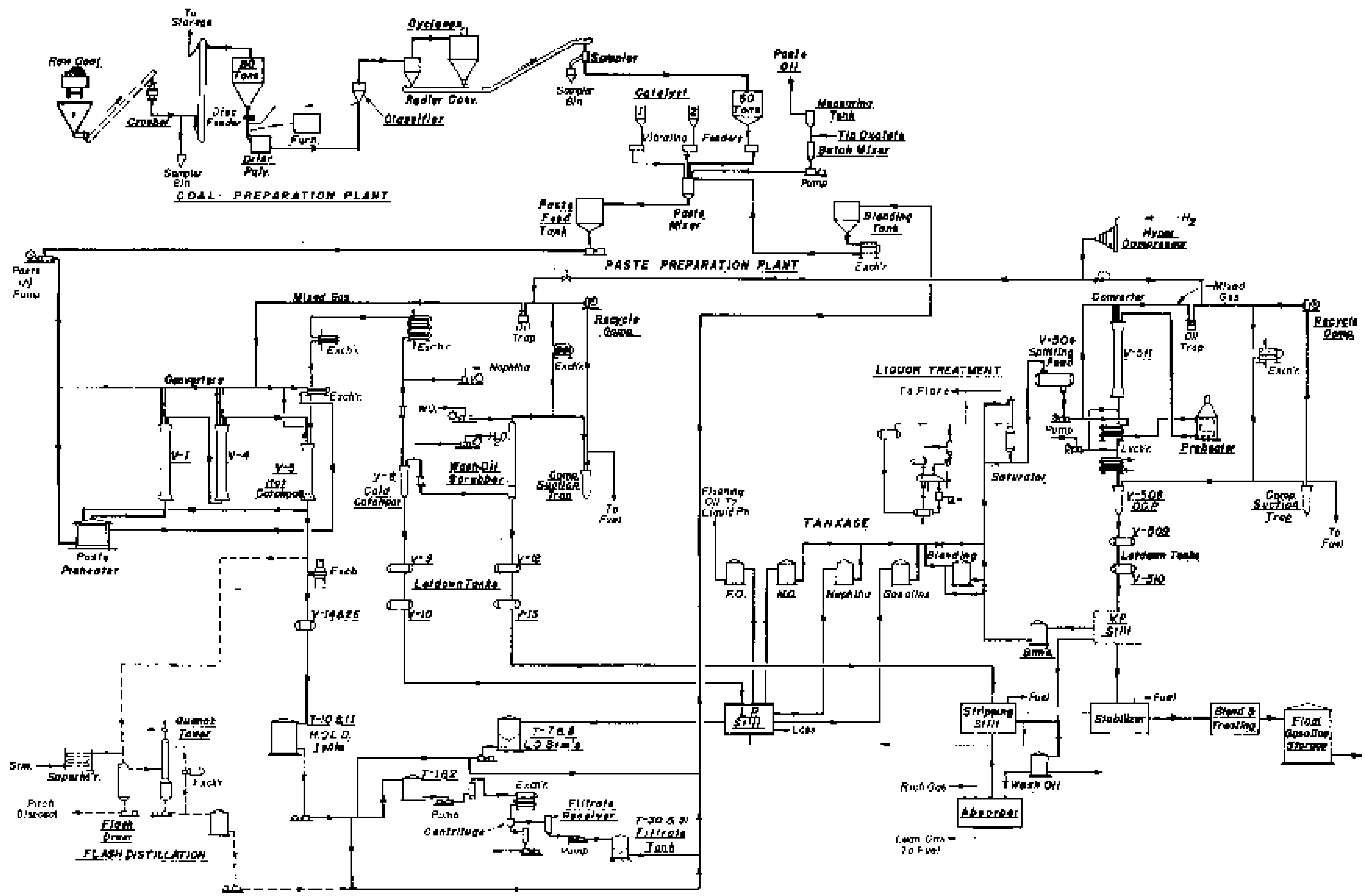

Figure 2. - Process-flow diagram of Coal-Hydrogenation Demonstration Plant.

PART I

PROCESSING, COAL-TO-OIL DEMONSTRATION PLANTS, LOUISIANA, MO.

Coal-to-oil demonstration-plant work of the Bureau of Mines is centered at Louisiana, Mo., where the utilities and services of a wartime synthetic-ammonia plant owned by the Government are available for synthetic-liquid-fuels production. The purpose of this work is to produce liquid fuels from coal on the minimum scale that will enable the Bureau of Mines to make available to industry the necessary cost and engineering data for commercial operations.

Two demonstration plants for converting coal to liquid fuels are under construction, one using the direct-hydrogenation or Bergius process and the other the gas-synthesis or modified Fischer-Tropsch process (see fig. 1 for plot plan). The 200-barrel-per-day Hydrogenation Demonstration Plant is nearly completed. A contract was let in 1948 for constructing the 100-barrel-per-day Gas-Synthesis Demonstration Plant, which will employ oxygen gasification of coal and Fischer-Tropsch Synthesis.

Coal-Hydrogenation Demonstration Plant

Design

A description of the process employed in the 200-to 300-barrel-per-day capacity, 700-atmosphere working pressure, Hydrogenation Demonstration Plant was published in the 1947 annual report (see fig. 2 for flow diagram). By December 1947, 93 percent of the contract design was done, and the remaining work was completed in 1948.

Nevertheless, engineering detail continued throughout 1948. Daily routine included making drawings and sketches in connection with field problems; checking contractors' drawings, specifications, and bills of material for approval; checking manufacturers' drawings against specifications and design drawings; checking vendors' invoices for payment of materials and equipment; and field inspection of the construction work. More than 1,500 new Bechtel Corp., drawings were checked by the engineers during the year; and, since the average drawing is revised at least twice before the job is finished, between 4,000 and 5,000 reviews were made. In addition, thousands of bills of materials, specifications, manufacturers' prints, spare-parts lists, and vendors' invoices were studied. Bureau engineers and draftsmen prepared 400 new drawings, more than 600 sketches, charts, and diagrams and nearly 400 photographs for illustrating reports and translations, for engineering-design information, and other purposes.

The indexing of the Technical Oil Mission microfilm reels collected in Germany after World War II was continued. At present, some 185 of the 258 reels are indexed. Upon completion of the indexing of the individual reels, a cross index will be compiled by reel and by subject. Forty-seven German articles from the Technical Oil Mission reels have been translated during the year.

Two engineers spent full time in corrosion-control and material-inspection work. Records of the behavior of construction materials used in the demonstration plant are important for the safety of plant operations and will serve as the basis of the design of future commercial-size plants. Hundreds of parts were calibrated, and more than 200 isometric sketches were prepared to serve as permanent records of these calibrations.

To make accurate production records possible, all intermediate- and finished-product storage tanks and vessels were measured for capacity and 43 gage tables were prepared.

Following a visit to an oil-hydrogenation plant, a decision was made to install two oxygen recorders and alarms for the first stage of the hyper compressors. Experience has indicated that, when the oxygen content of the hydrogen gas is higher than 0.8 percent, explosions may occur. It also was confirmed that it will be necessary to hold the inlet temperature of the vapor-phase converter to within limits of 2° F. when in the operating range. Instrument provisions to accomplish this were included in the design.

Realization of the great danger present when oxygen is in the system led to a review of the hydrogenation equipment, installations, and operating and safety procedures, with particular emphasis on the possible sources of oxygen contamination of the hydrogen. Except for the installation of a low-pressure shut-off and oxygen recorder on the nitrogen hyper compressor, it will not be necessary to alter or change the original installations to eliminate the possibility of a hazardous oxygen content in the hydrogen.

Detailed plans were formulated for operation of the hydrogen gas manufacturing and compression plants. Two of the six cracking furnaces and two of the five hyper compressors will be used to supply 98-percent purity hydrogen to the hydrogenation plant at high pressure. The necessary piping changes were made by the contractor. Until a small hyper compressor for high-pressure nitrogen compression arrives at the plant and is installed, one of the existing hyper compressors will be used for this purpose.

A study was made of all Missouri Ordnance Works equipment to determine what could be used in the demonstration-plant operation. The surplus was listed for disposal to other agencies.

Before operating the cracking furnaces, it will be necessary to reclaim and dip the cracking catalyst on hand. A survey was made of the manpower and material requirements for this task, and recommendations were set forth in a report.

German technicians brought to this country as consultants prepared many reports on problems pertaining to the hydrogenation process, both as practiced in Germany and in its proposed application to the design, construction, operation, and maintenance of the demonstration plant. Most of these reports, intended only for interoffice use, were retained for the information of the Louisiana, Mo., station.

Among the several problems developed in detail was the design of a shell and tube-type water cooler in the liquid-phase converter stall to replace the present double pipe cooler. Based on equal cooling surface, this newly designed unit will cost only about one-third as much as the old double pipe cooler, and it may prove important in the economy of future commercial coal-hydrogenation plants.

Another promising development toward economical and trouble-free operation was substitution of an expansion engine for the heavy-oil let-down valves. In addition to abrasive ash, catalyst, and unreacted coal, the heavy-oil let-down contains large quantities of absorbed gases. Reducing the pressure of this mixture from 10,000 pounds per square inch to near atmospheric conditions with the conventional let-down valves is a troublesome and costly operation because of rapid erosion of the valves. This engine will utilize the expansion energy which at present has to be absorbed by the expansion valves.

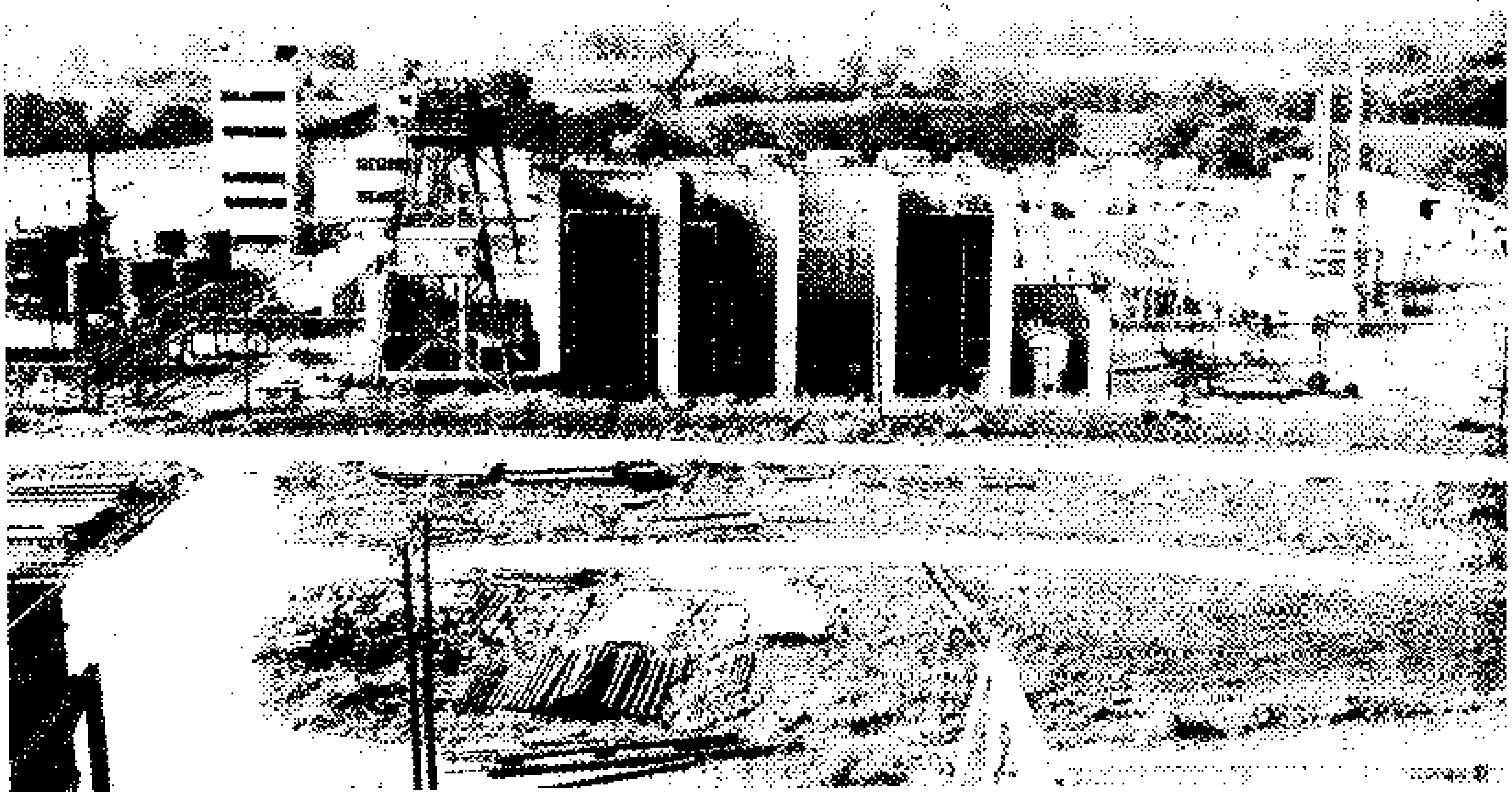

Figure 3. - Hydrogenation Demonstration Plant, looking south from the Missouri Ordnance Works, Louisiana, Mo. Converter stalls in foreground.

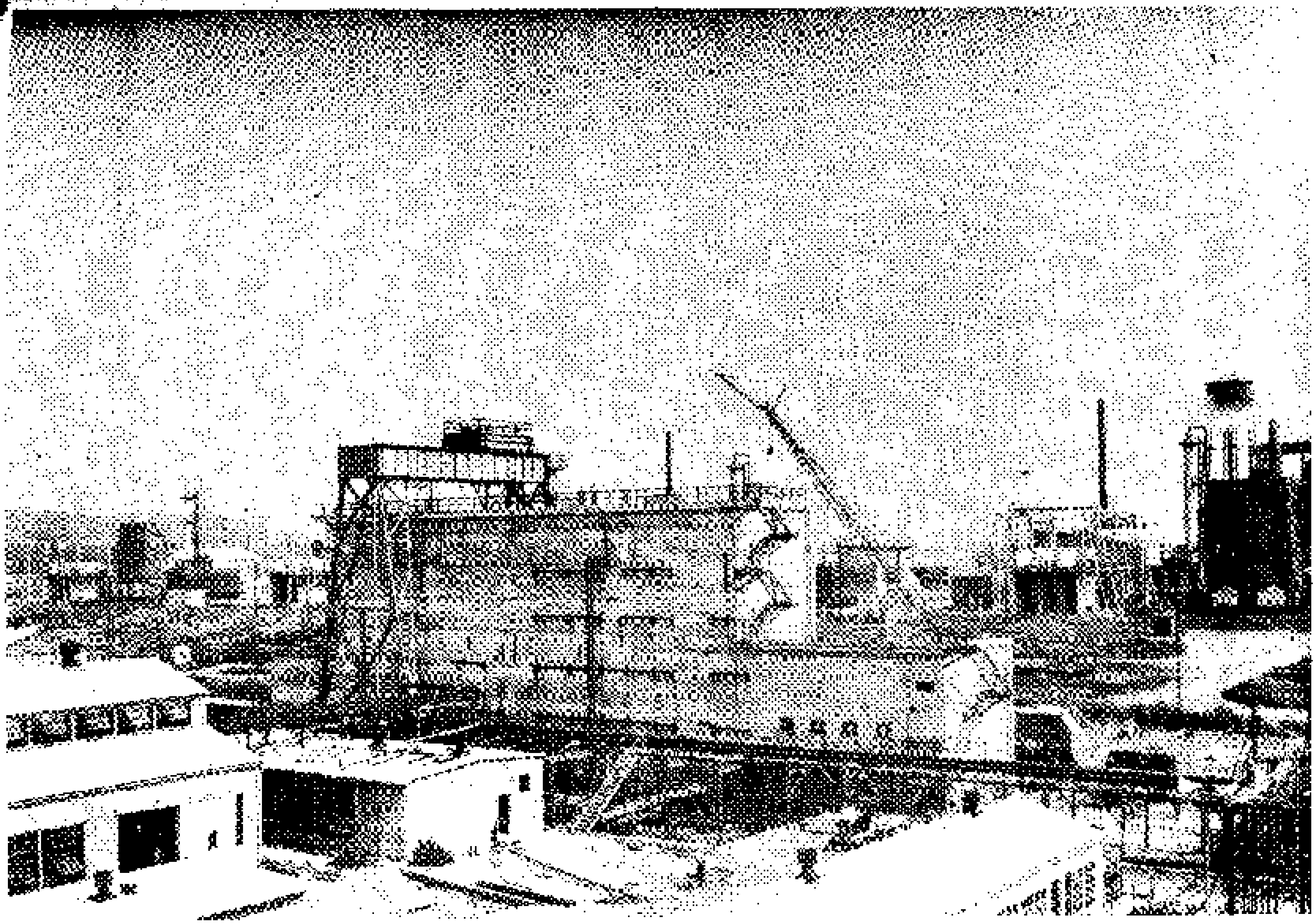

Figure 4. - Converter stalls with Gantry crane, looking northwest. In foreground, left to right, are the high-pressure pump house, instrument house, and heavy-oil pump house.

Construction

In December 1947, 35 percent of the construction had been completed. The work was continued vigorously throughout the year.

During the first week of January, the convertor stall was finished (fig. 3). This is a heavy, reinforced-concrete structure, 28 by 193 feet and 58 feet high, enclosed on three sides but open on one side and the top. It is partitioned by 14-inch-thick reinforced-concrete walls into six separate compartments or "stalls" to isolate each group of high-pressure and high-temperature equipment from the others in case of failure. Three of the six stalls contain the liquid-phase preheater, the converters, and the cold separating equipment. The other three contain the corresponding vapor-phase units.

A 130-ton-capacity Gantry crane was erected in January, tested in February, and from then on was used continuously for installing converters, preheaters, exchangers, catchpots, and piping in the stall area. The coal-preparation building and distillation-control house were erected in January.

In February, installation of equipment in the coal-preparation building was begun. Two large recirculating compressors were moved from the Missouri Ordnance Works area and installed in the high-pressure compressor house. The new laboratory building was roofed in.

In March the underground yard piping was completed and back-filled. Much of the heavy equipment was placed during this month, including tanks, vessels, pumps, preheater framework, catchpots, and two converters. Refractory lining of the paste preheater was completed. The oxygen-plant building was erected, and installation of the German Linde-Frankl plant equipment got under way.

Aboveground piping work increased steadily during the initial months of the year and by April represented the major part of the construction activity. The reinforced-concrete instrument building (fig. 4) was completed in that month, and the framework of the central control panel was built. Tanks were installed in the heavy-oil area, and piping work was begun between the tanks and the completed heavy-oil pump house. Process piping was completed in the distillation and tank-yard pump houses.

The second group of houses for employees, consisting of 20 units, was completed by the subcontractor in April. By May, all houses were occupied. Being subordinated to the main project, the construction of group garages and the completion of street lighting, yard drainage, heating steam mains, roads, walkways, and landscaping for the entire 41-unit housing project was not accomplished until September.

By May, the installation of high-pressure (10,000-pound-per-square inch working pressure) piping was well under way. All equipment was installed in the coal and paste-preparation plants and in the heavy-oil area. Exchangers in the stall area and instruments in the control house were installed as rapidly as delivered. The steam superheater and most of the equipment and piping installation were finished in the heavy-oil let-down flash-distillation area. Erection of the plant cooling tower was completed.

In June the insulation of tanks and pipe lines was begun. All major building structures of the coal-hydrogenation demonstration plant were completed by July. The tankage area and cooling-water system were ready by September.

Following completion of the oily water separator, work on the plant sewer system was finished in October. The distillation unit (fig. 5) was completed in that month, and newly trained operators were testing the plant with petroleum by November. Surfacing of all roads and construction of walkways and the parking lot also were completed in October.

The German Linde-Fränkl oxygen plant was ready by November, and test runs are in progress.

Some of the materials used for the construction are listed in round figures to indicate the magnitude of the coal-hydrogenation-plant project.

Excavating and grading	cu. yd.	180,000
Concrete	do.	9,500
Paving (macadam and gravel)	do.	37,500
Structural steel	tons	900
Tanks and pressure vessels	do.	1,200
Pipe and tubing (more than 40 miles).......	do.	1,000
Sewers	miles	3

Covering only some of the principal items, these figures do not include all the mechanical and electrical equipment for a plant having an electrical power demand of 4,000 kw., and a steam consumption of 100,000 pounds per hour.

Six design engineers were assigned continuously to field inspection work. They checked materials and workmanship in the vendors' shops, on arrival at the job site, and after erection or installation. It was found that it is not enough to write rigid and seemingly "airtight" specifications for construction materials and workmanship. Close inspection was necessary at every step in fabrication, assembly, and erection. Because of their familiarity with the process and the operation of all equipment, five trained coal-hydrogenation plant operators also were assigned to inspection duty.

In January 1948, the contractor estimated that the coal-hydrogenation plant would be completed by July. At present it is anticipated that the contractor's construction work will be finished in January 1949. Reasons for the delay were: slow procurement of material and equipment, broken delivery promises resulting from strikes in manufacturers' plants, difficulties in obtaining a sufficient number of trained pipefitters on the construction site, minor strike disturbances, delicate situations developing from supervision of the efficiency of union workers, repeated difficulties in getting satisfactory welds on high pressure piping and equipment, and unavoidable design alterations inherent to a complex project which does not have a precedent in American industry.

As of December 1, plant construction will be 97 percent complete. The major items still undelivered are two recycle hydrogen compressors of 10,000-pound-per-square-inch working pressure; a 15,000-pound-per-square-inch nitrogen compressor, and the laboratory furniture and equipment. None of these items will cause serious delay in getting the plant started. Delivery of the nitrogen and the circulating compressors is expected in February 1949. Operations will not be delayed, for the No. 3 ammonia-unit hyper compressor has been temporarily hooked up for nitrogen service, and the two installed recycle compressors will take care of the preliminary reduced-scale runs. Temporary laboratory facilities are available in the old Missouri Ordnance Works and will have to suffice during initial operations, for the new laboratory equipment will not be delivered before February 1949. It is felt that the end of the year will find the construction essentially complete and the plant ready for operation.

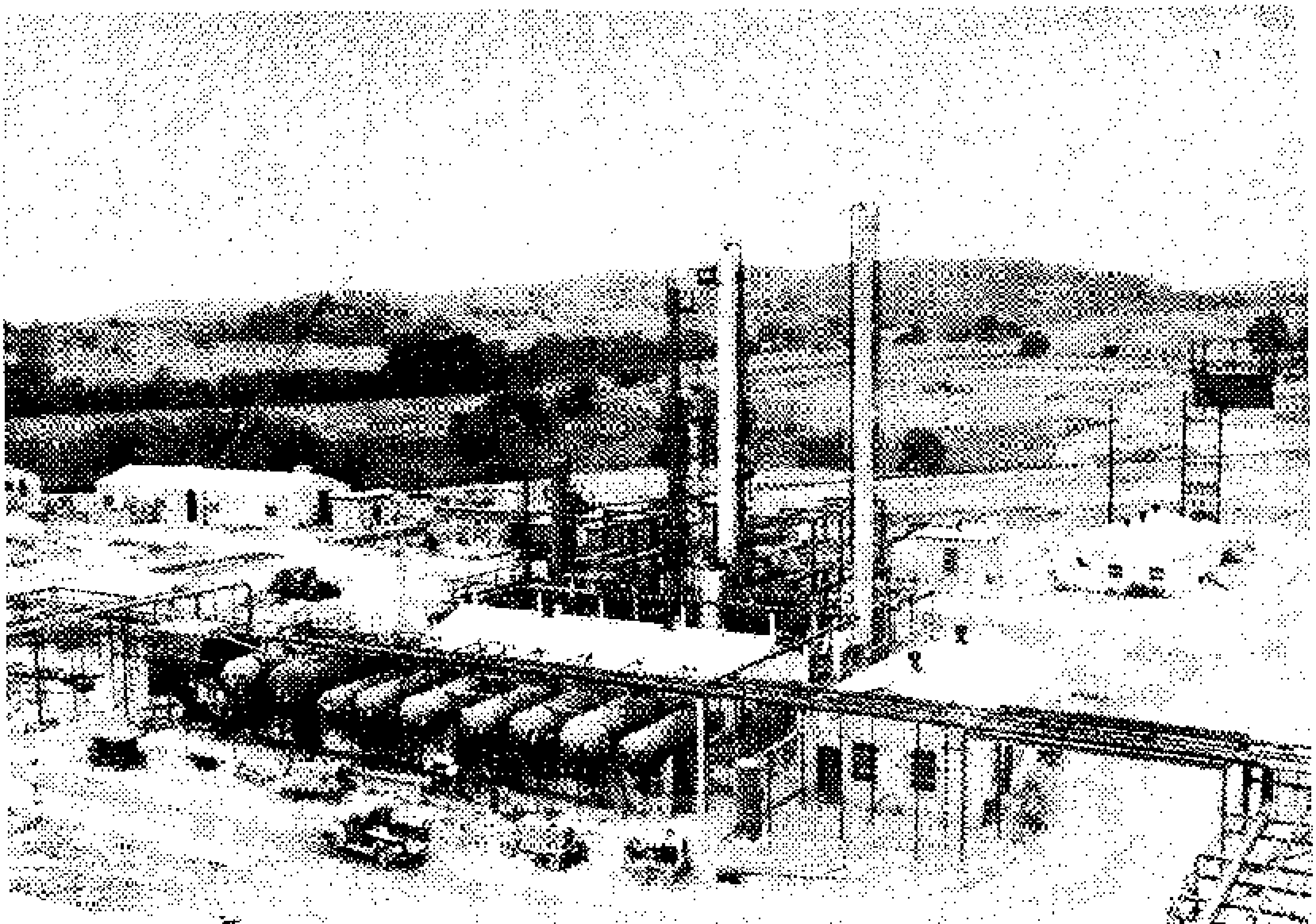

Figure 5. - Distillation area looking southwest from converter stalls. Oxygen holder in right background.

Operation

Paralleling the construction program, plans and preparations for the safe, efficient operation of the plant were pushed forward on a definite schedule.

Manuals entitled "Standard Operating Procedures" and "Operational Safety Bulletins" were largely completed by early 1948. Owing to changes in design, operating practices, and additional information from equipment manufacturers, these procedures have been revised and enlarged repeatedly. For normal and satisfactory operation of the plant, 45 log-data forms and other miscellaneous operating blanks were prepared and multilithed.

During the year a strong, basic operating organization was assembled and trained for the hydrogenation plant. Expanding from a nucleus of a few engineers and subprofessional employees, the organization now is a well-balanced, minimum, operating and planning group capable of undertaking the initial operations of the plant.

To carry out the instruction systematically and efficiently, a training program was inaugurated and a training manual prepared. Using the training manual as a written guide, a 20-hour course was established for all new employees. The manual includes sections on program and orientation, hydrogenation process, instrumentation, machines and equipment, laboratory, accounting and records, rules and regulations, and safety. A number of design engineers also spent part time for several weeks studying operating procedures for various operations so that they could act as auxiliary operators and instructors in starting up the plant.

As training progressed, it became apparent that there was a need to expedite the program by the use of simplified process-flow diagrams. Consequently, 22 drawings were prepared from the piping and instrumentation designs. Each drawing incorporates an entire system, such as the wash and absorber oil, injection water, and blowdown and relief lines, that normally would be shown on many drawings. Much time already has been saved in the training program by the use of these aids. The training has progressed until there is now a staff qualified to operate the distillation area and a nucleus of operators capable of assisting in training additional personnel and operating the hydrogenation area.

To assure satisfactory operations, it was necessary to write specifications for operating supplies, such as lubricants and special tools. A survey of lubricants was made, and other necessary supplies have been ordered for each section of the plant.

An intensive study has been made of the German documents on catalysts, from which it was possible to prepare specifications for the vapor phase hydrogenation catalyst. These specifications were based on the 700-atmosphere Welheim catalyst and will be used if the available Welheim catalyst proves unsatisfactory or after the supply on hand is depleted.

It was considered advisable to break in the equipment on petroleum oil for several reasons: (1) Operators have had little or no experience with distillation equipment; (2) the equipment would be tested with an oil free from solids; and (3) any faults could be discovered and corrected before the more critical coal-hydrogenation operation.

Preliminary calculations were made to determine the amount and type of petroleum oils needed for initial break-in operations. Specifications then were prepared, and approximately 110,000 gallons of 37° A. P. I. Oklahoma crude oil was purchased in August.

A detailed engineering study then was made to determine in advance the optimum operating conditions for the initial distillation area runs on the oil received. Test runs were begun in November (fig. 6).

After a satisfactory run of all equipment on petroleum oil, the hydrogenation system will be flushed before starting the coal-hydrogenation operation with coal-tar pasting oils. A detailed engineering study has been made to determine all of the operating conditions for this step and the quantity and properties of the coal-tar oils required. Specifications have been prepared for these oils and inquiries sent to possible suppliers.

Coal from Rock Springs, Wyo., will be used for the initial run. This coal will be mixed with the purchased coal-tar oils to form the initial paste charge to the plant. Calculations have been extended to determine the equilibrium operating conditions using this coal and normal pasting oil from the process. These studies, covering the entire period for early runs, also are necessary to determine the use and storage requirements for the oils produced during the period until normal and combined vapor-and liquid-phase operations are established.

Owing to the great importance and relatively new methods of instrumentation, special emphasis was put on all instrumentation studies. Thermocouple and alarm equipment, calculation of orifice factors, and installation of all instruments were some of the points under study by hydrogenation engineers during the year.

As construction progressed in the hydrogenation plant, the gas-manufacturing facilities of the former Missouri Ordnance Works plant were prepared for operation. Hyper compressors were put in operating condition, and each compressor now is being idled 4 hours each week. The natural-gas cracking furnaces, inert-gas generator, purification, and synthesis plants were altered and repaired to suit the needs of the hydrogenation plant so that the equipment is ready when needed.

The distillation plant, first unit completed by the contractor, was the first put into operation. Before the unit was charged with oil it was necessary to flush all the lines with water and then remove the water with air. The various cuts of oil produced in the distillation plant are blended in the tankage area and returned to the unit as fresh feed. In this manner the plant can be run for an indefinite time on the original crude oil. After the hydrogenation area is completed and tested, a run of approximately 17 days will be made on both the liquid and vapor phases, hydrogenating the petroleum oil previously used or separated in the distillation plant. This operation not only will break in the equipment on an oil containing no solids but also will give some useful information on the hydrogenation of petroleum oil.

Late in the year a hydrogenation planning group was organized and has taken over many of its preliminary duties in connection with the preparation of calculation procedures and reporting forms. As operating data and experience become available, these functions will require further expansion of this group.

Commercial Plant-Engineering Studies and Cost Estimates

Gasoline

The cost of gasoline produced from coal is of prime interest to industry. The Coal-to-Oil Demonstration Plant staff has been investigating the possibilities of commercial production by the hydrogenation method for more than 3 years. With the aid of German technical personnel having years of experience in the field and through effective use of reports gathered and assembled by technical missions at the close of

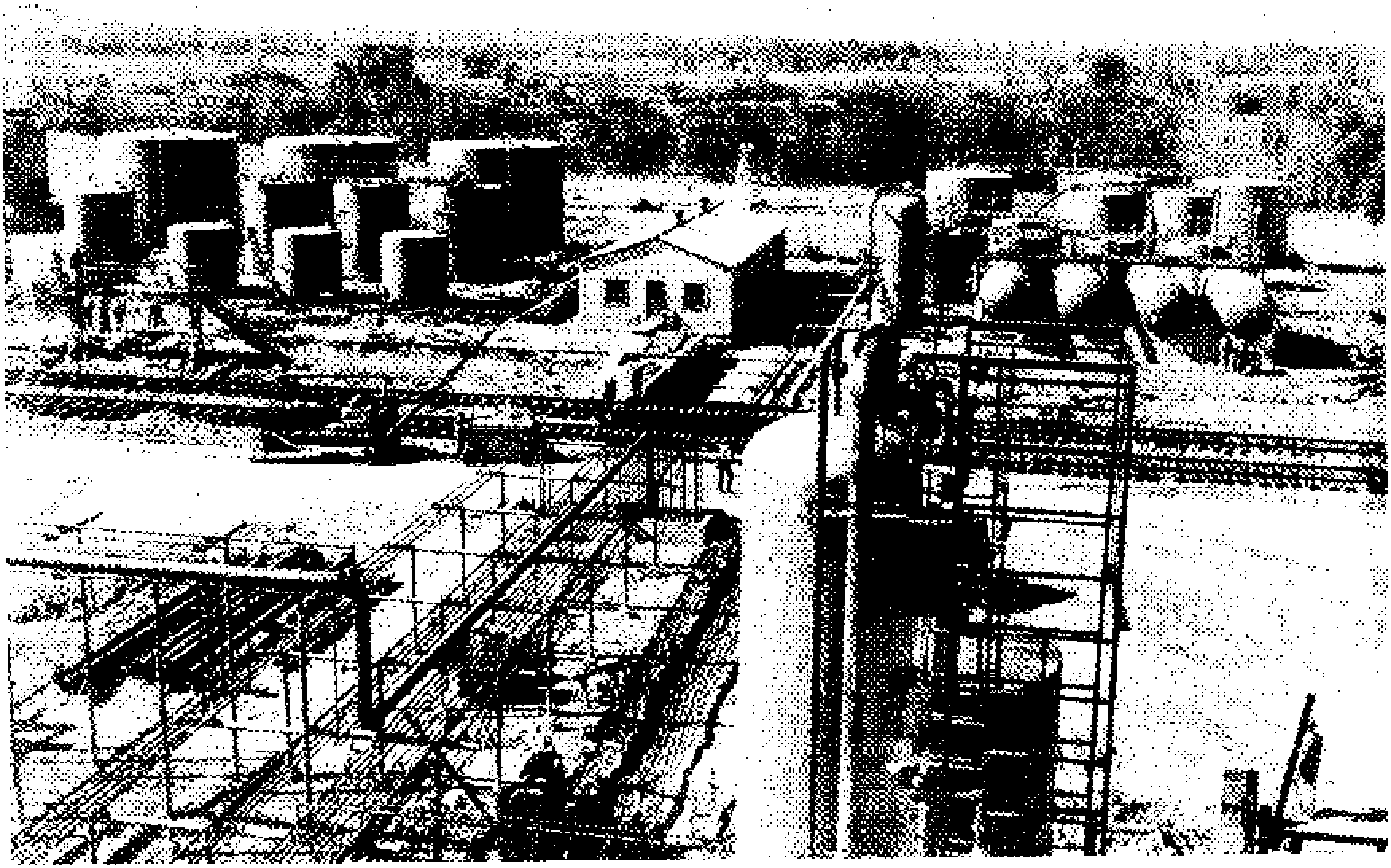

Figure 6. - Distillation tankage area and pump house as seen from the top of the distillation columns.

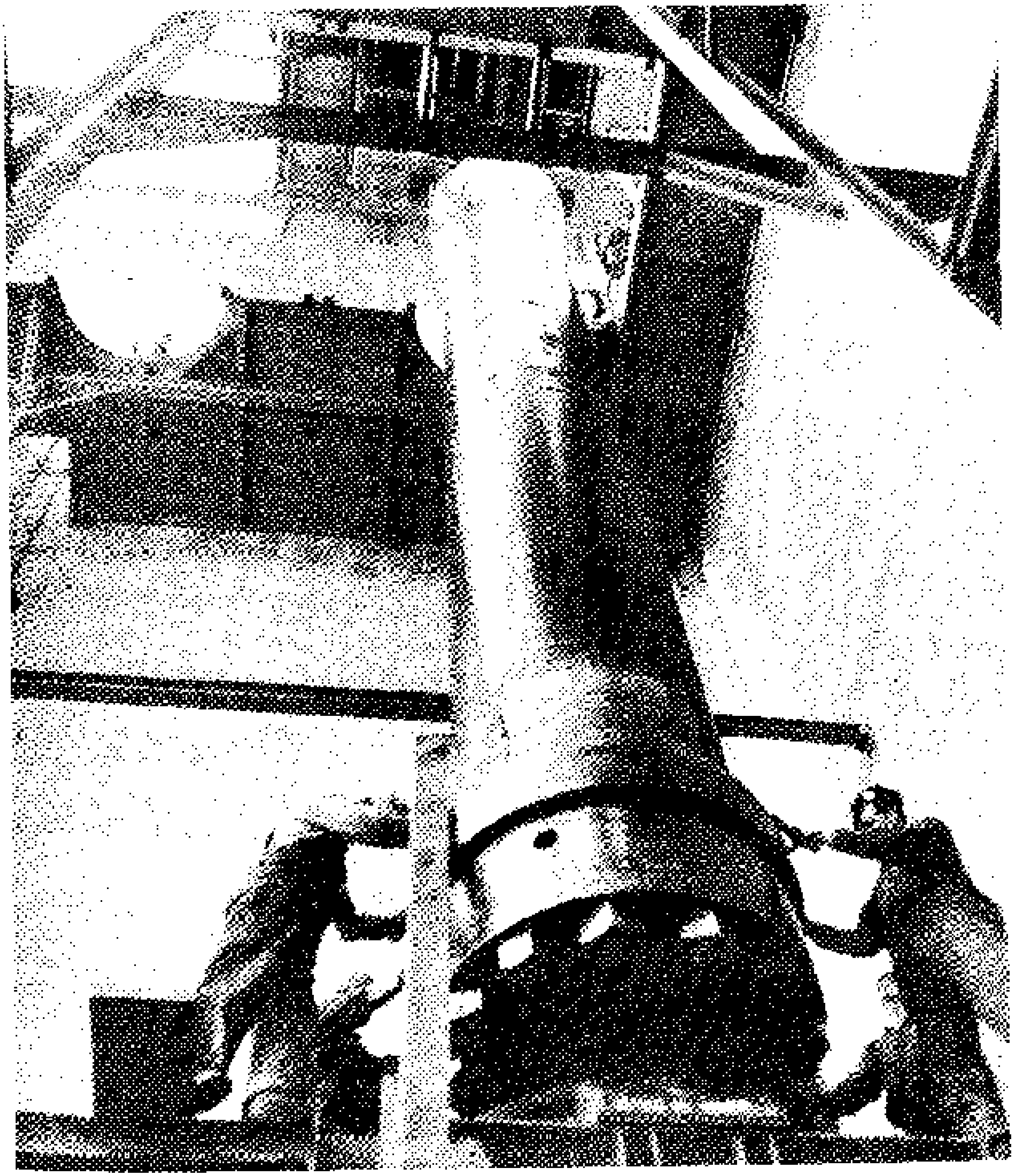

Figure 7. - A 100-ton converter is swung in place by the Gantry crane.

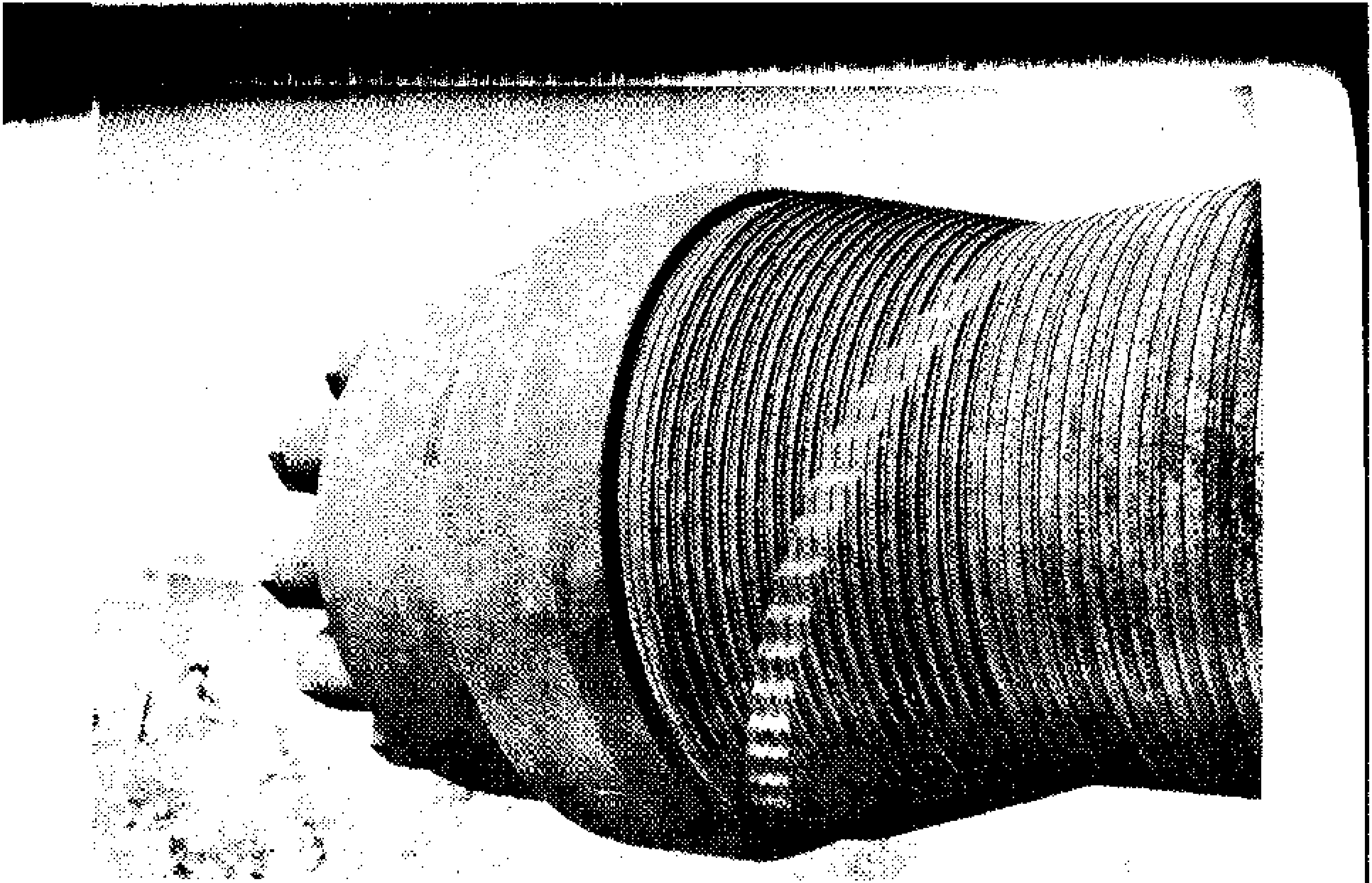

Figure 8. - Excellent view of head-flange construction on German "Wickelofen" or wrapped high-pressure vessel.

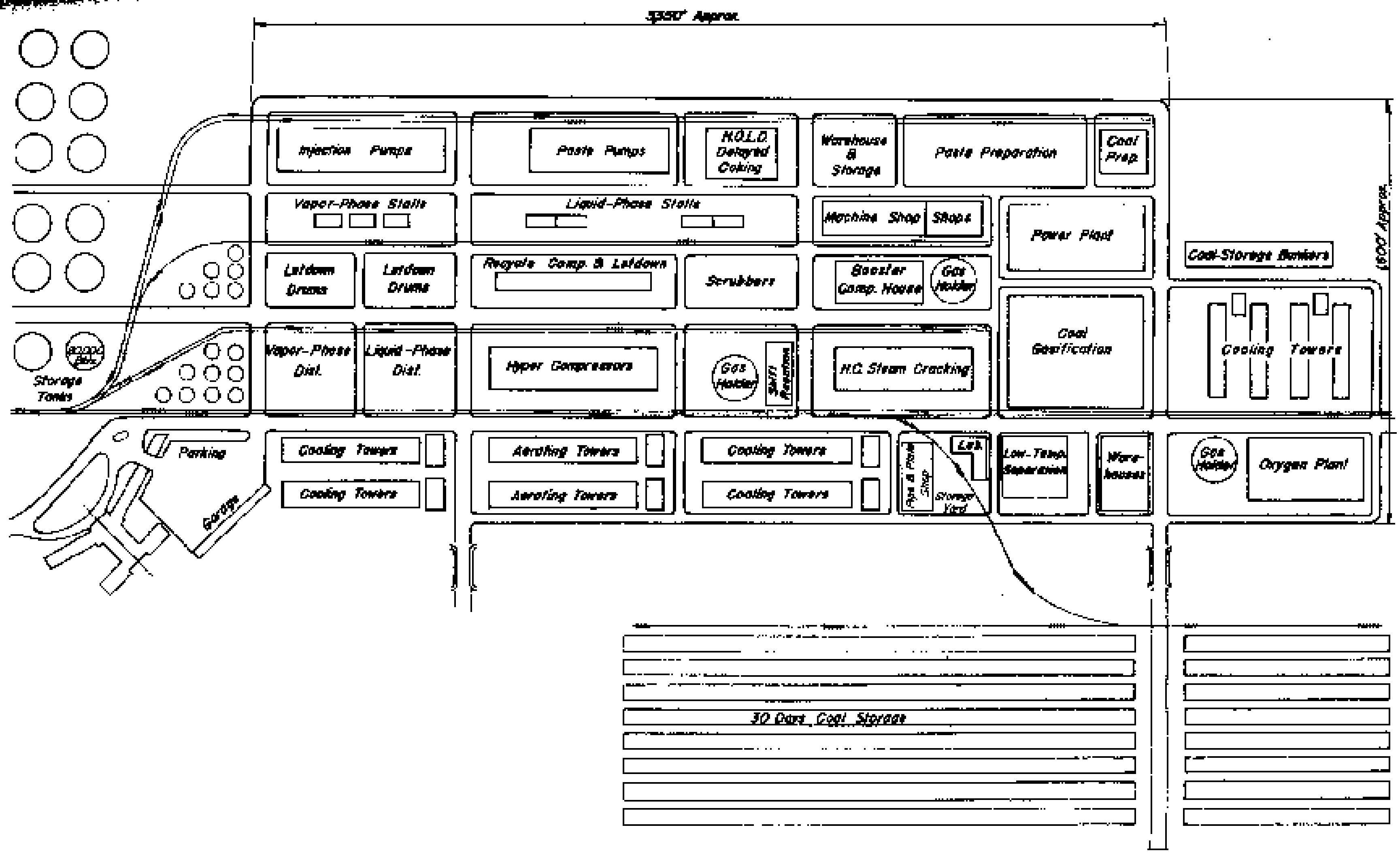

Figure 9. - Size of a 30,000-barrel-per-day coal-hydrogenation plant is shown by this typical plot plan.

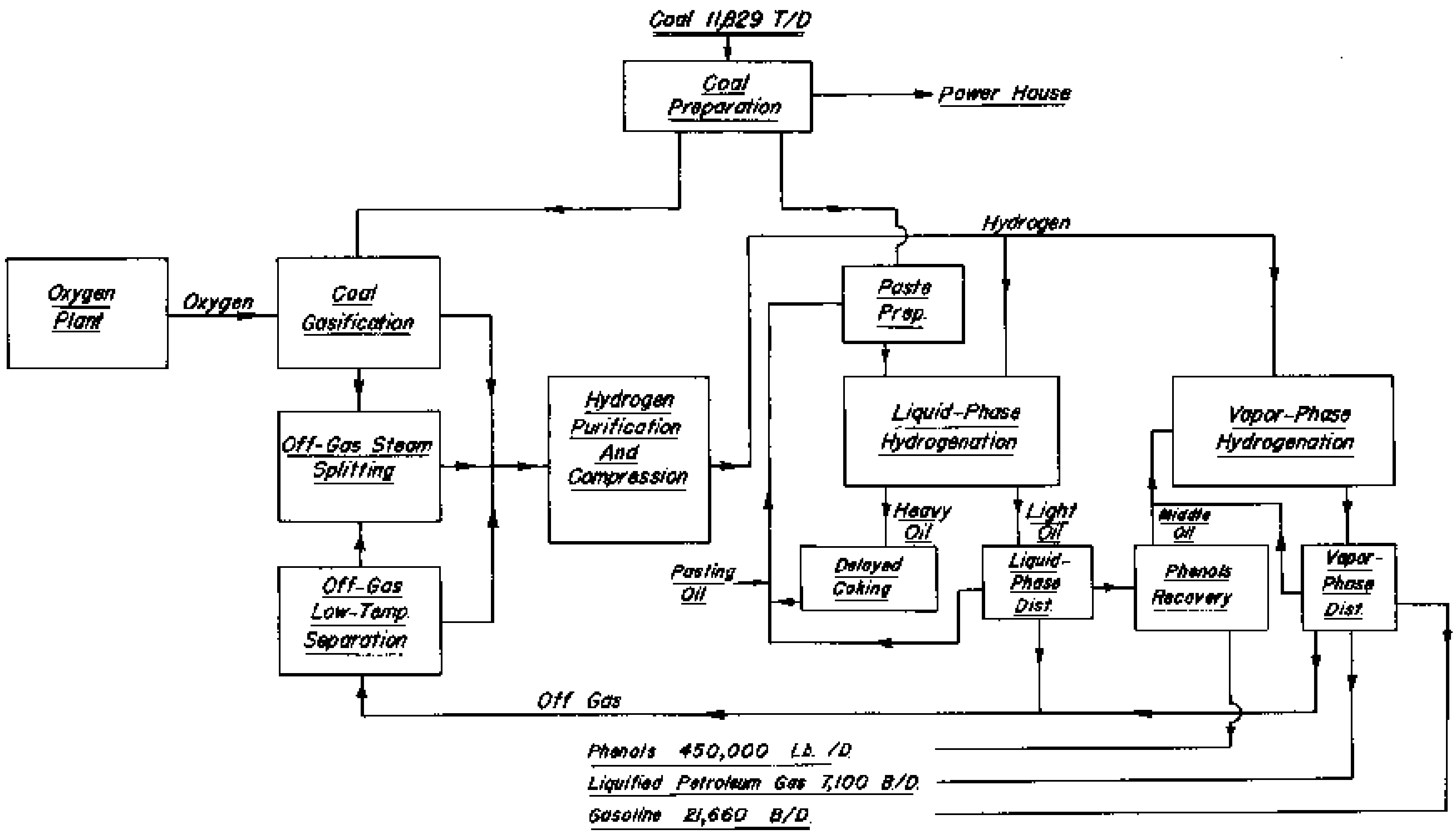

Figure 10. - Schematic arrangement of units shown in their process and comparative cost relationships. Costs are based on the use of Illinois bituminous coal to produce 30,000 barrels per day by hydrogenation.

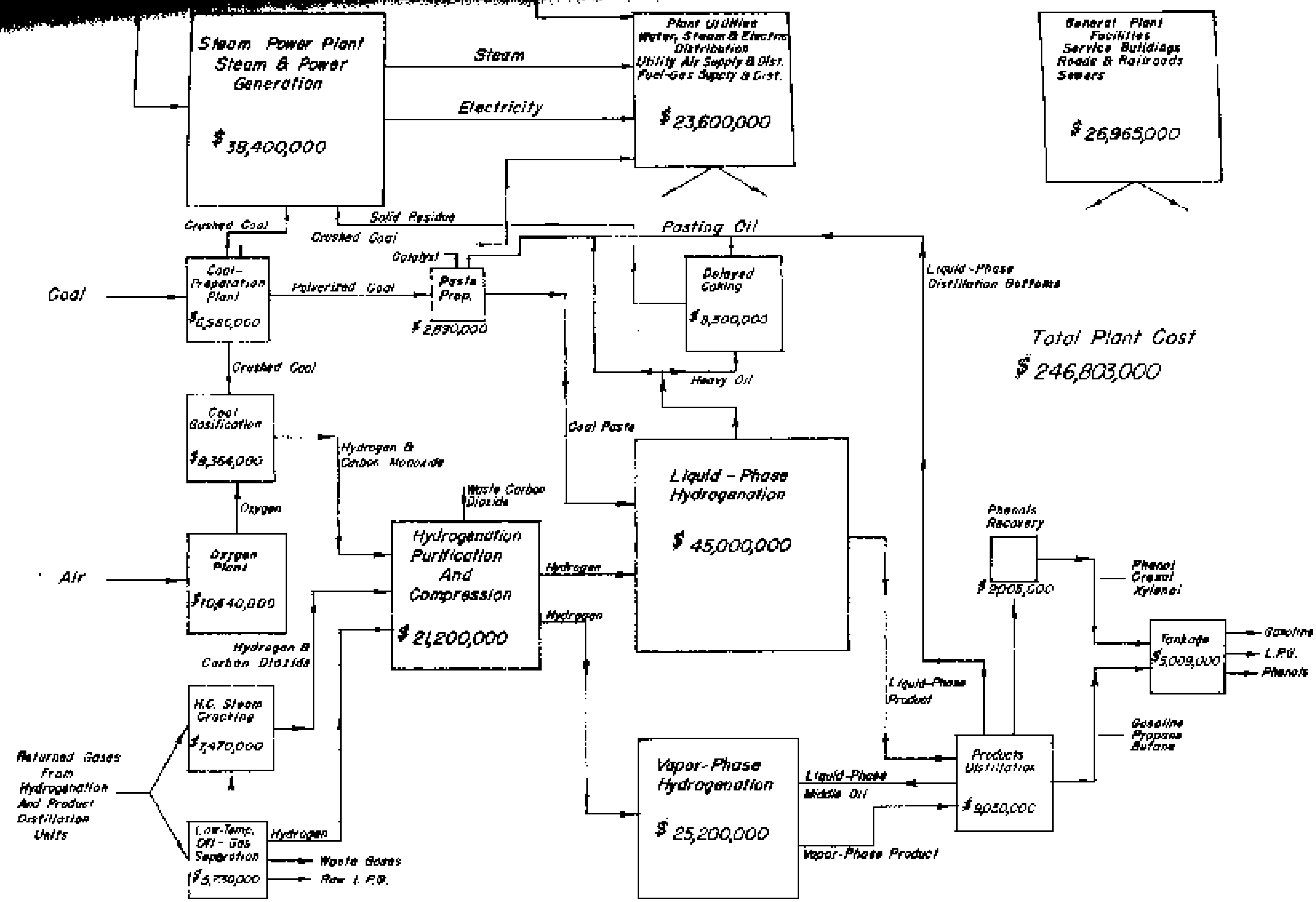

Figure II. - Simplified flow diagram of hydrogenation process (30,000 bbl./day plant). Raw coal from the mine is converted to gasoline, liquefied petroleum gas, and phenols.

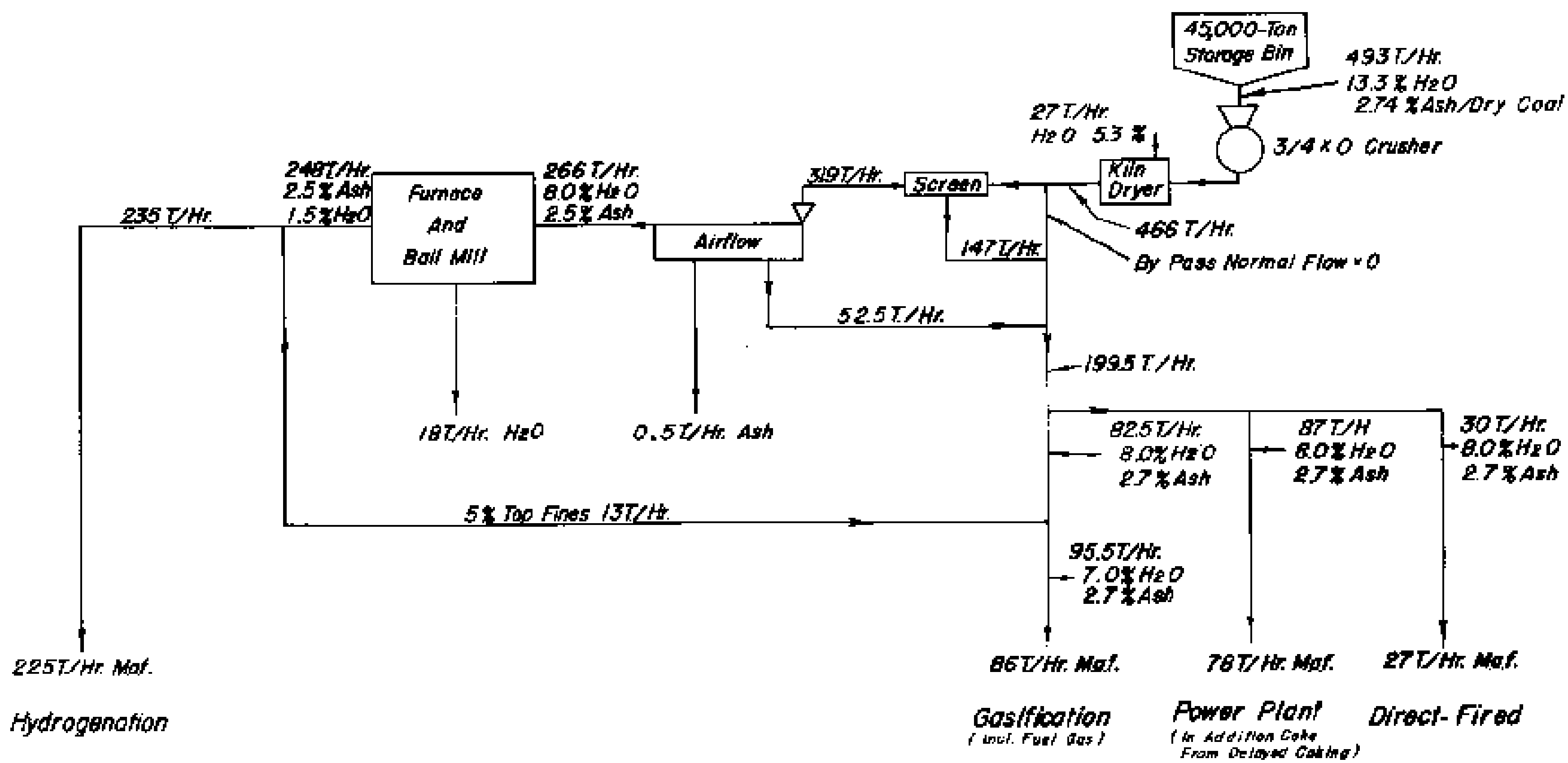

Figure 12. - Distribution of coal to produce 30,000 barrels per day by hydrogenation method. Shown here is flow of Wyoming bituminous coal. Other coals would be slightly different in flow and quantities.

World War II, it has been possible to develop process designs and select suitable equipment for the commercial hydrogenation of coal in this country. It must be emphasized that the process improvements incorporated in these estimates will be tested in the demonstration plant and until they pass the test should be considered only as the best present available estimate.

Late in 1947, Bechtel Corp. was engaged to prepare, under the direction and supervision of the Bureau, preliminary designs and estimates of the cost of a hydrogenation plant to produce 30,000 barrels per day of liquid products. The contractor's phase of the work was completed in July. Basic process information for the estimate was supplied by the Bureau. For ultimate economy, the estimate used larger units but otherwise followed conventional British and German practice. However, by adopting some improved processes and construction methods, it has been found that investment and operating costs can be reduced substantially below those in the report. This revised estimate reflects the savings attainable with the pressure gasification of coal, automatic controls, delayed coking of residues, and the replacement of solid forged converters (fig. 7) with spirally wound vessels (fig. 8).

A plant capacity of 30,000 barrels per calendar day was selected to obtain maximum savings in capital and operating cost. By comparison, this capacity is about 60 percent greater than the yearly production of the largest German hydrogenation plant and about equals in size the largest German plant ever planned (see fig. 9). Capital costs are substantially reduced by the use of larger single units and improvement in process design (fig. 10). An even larger plant size would yield some economy in operation, but adequate raw materials, water, and labor supply might be more difficult to provide.

To cover comprehensively the coals suited for the hydrogenation process, five coals were selected that are representative of the large deposits found in this country. A general process flow diagram of the plant was published in the 1947 annual report (for simplified diagram, see fig. 11). Basic calculations were made using Wyoming bituminous coal because this coal is very suitable for hydrogenation (fig. 12) and it is fairly representative of vast coal deposits in Colorado, Wyoming, and Utah in the Rocky Mountain area. North Dakota lignite is representative of that type of fuel occurring in large quantities in that State and Montana. Montana subbituminous coal represents another type of solid fuel found in large deposits, and it can be mined at a low cost. Illinois bituminous coal is representative of the high-volatile bituminous coals found in the midwestern area, including Indiana and western Kentucky. Pittsburgh-seam coal is reasonably typical of large deposits of coal in Pennsylvania, West Virginia, eastern Kentucky, and Alabama. Care was taken not to use coals that are suitable for coking. Analyses of each of the coals selected are shown in Table 1.

For these coals, material balances and flow diagrams were prepared to determine the coal consumption, including power and utility requirements. Table 2 summarizes the coal consumption and the products obtained per day.

TABLE 1. - Hydrogenation coal analyses

Coal		1 Wyoming bituminous	2 N. Dak. lignite	3 Mont. sub-bituminous	4 Illinois bituminous	5 Pittsburgh-seam bituminous
As received ..... H_2O	percent	13.3	39.5	25.1	14.7	3.0
Dry .... ash	do.	2.7	7.5	10.1	9.8	9.0
Ash content after cleaning	do.	2.5	(7.5)	5.5	5.0	5.0
Moisture- and ash-free basis						
Volatile matter	do.	44.0	46.5	42.3	41.3	38.3
Carbon (ultimate level)	do.	79.7	72.0	76.7	80.0	83.6
B.t.u. per pound		14,000	12,150	13,210	14,070	15,000

TABLE 2. - Coal consumption and final products

Coal		Wyoming bituminous	N. Dak. lignite	Mont. sub-bituminous	Illinois bituminous	Pittsburgh-seam bituminous
Coal consumption						
Run-of-mine coal	tons/day	11,830	22,200	16,550	13,120	10,760
Moisture- and ash-free coal	do.	9,980	12,420	11,130	10,090	9,500
Production						
Gasoline	bbl./day	21,660	22,500	22,360	21,630	20,250
L.P.G.	do.	7,100	6,260	6,400	7,130	8,510
Phenols	do.	1,240	1,240	1,240	1,240	1,240
Phenols	lb./day	(450,000)	(450,000)	(450,000)	(450,000)	(450,000)
Total	bbl./day	30,000	30,000	30,000	30,000	30,000

The gasoline produced is a high-grade antiknock motor fuel, low in sulfur content (below 0.01 percent, and higher in aromatics and British thermal units per gallon than gasolines obtained from crude oil. The octane number (motor method unleaded) is 78 for bituminous coal as raw material and somewhat lower for the other coals.

The phenols contain about 20 percent carbolic acid, 35 percent cresols, and 45 percent xylenols. The composition of the liquefied petroleum gases (L.P.G.) is about 3 percent ethane, 65 percent propane, and 32 percent butane.

With this basic information, the cost of major equipment, other materials, construction labor, and construction overhead was calculated individually, and the total represents the investment required for a fully integrated plant.

The estimated capital costs of these plants are shown in table 3 for the three main plant sections.

TABLE 3 - Plant-cost estimate, thousands of dollars

Coal	Wyoming bituminous	N. Dak. lignite	Mont. sub-bituminous	Illinois bituminous	Pittsburgh-seam bituminous
Hydrogenation Section	97,292	96,865	98,635	99,625	106,805
Gas-Production Section	54,749	60,074	57,710	53,204	54,750
General and auxiliary Plants Section	90,879	98,303	97,678	93,974	96,265
Total, thousands of dollars.	242,920	255,242	254,023	246,803	257,820
Dollars/bbl./day	8,097	8,508	8,467	8,227	8,594
Field labor .... thousands of man-hours	21,736	22,968	22,733	22,013	22,803
Steel .... tons	158,000	165,000	164,000	159,000	167,000

The table shows also the estimated man-hours of field labor and the total steel requirements. These figures do not include the development of mines, employee housing, or rail and pipe-line facilities for the movement of raw materials and finished products. The total investment is between 8,100 and 8,700 dollars per daily barrel of liquid products. Steel required per daily barrel of capacity is 5.3 to 5.6 tons.

With these capital costs, the product quantities and the coal consumption from table 2, manufacturing costs given in table 4 were obtained. The coal prices are taken from the Bureau of Mines Mineral Market Report 1558 (1946) with 10 percent added to approximate current costs.

TABLE 4. - Manufacturing costs

Coal	Wyoming bituminous	N. Dak. lignite	Mont. sub-bituminous	Illinois bituminous	Pittsburgh-seam bituminous
Coal as mined .... dollars/ton	3.56	1.65	1.10	3.12	4.02
Personnel required	3200	3360	3345	3250	3385
Daily costs 30,000 bbl./day Liq. Products					
Coal	$ 42,111	$ 41,066	$ 18,162	$ 40,925	$ 43,243
Other materials	17,156	18,103	18,212	17,443	19,286
Other direct costs	28,177	29,591	29,462	28,636	29,913
Indirect costs	17,847	18,746	18,662	18,136	18,945
Fixed costs	51,020	53,613	53,357	51,840	54,154
Total	$156,311	$161,119	$137,855	$156,980	$165,541
Credit for L.P.G. at $0.08/gal.	23,856	21,034	21,504	23,957	28,594
Net cost gasoline (without recovery of phenols)	$132,455	$140,085	$116,351	$133,023	$136,947
Unit costs, dollars/gal. gasoline	0.14	0.14	0.12	0.14	0.15

These estimates allow 3 percent of the total investment for maintenance and 6.67 percent (15 years) for amortization. For operating labor, an average rate of $1.75 per hour was taken. The gasoline-manufacturing costs obtained are 12 to 15 cents per gallon, crediting L.P.G. (liquefied petroleum gas) at 8 cents per gallon. The differences are due to variation in coal prices as well as to different suitability of the various coals for the process. If phenols are recovered to the extent of 450,000 pounds per day and credited at 10 cents per pound, the cost of gasoline is reduced by 4 cents per gallon, giving net costs ranging from 8 to 11 cents per gallon.

The versatility of this plant must not be overlooked. It can be used without change for the production of aviation-gasoline base stock, which can be manufactured at about the same cost and in about the same quantity as motor gasoline. For the production of alkylate from the liquefied petroleum gases, additional dehydrogenation and alkylation equipment is necessary.

The plant also can be used for the production of jet fuel by a minor change - replacement of the vapor-phase catalyst. The jet fuel will meet all the specifications for JP-1 or JP-3 fuels. If required, oils of higher specific gravity and heating value per gallon can be obtained.

The production is estimated as follows:

	JP-1	JP-3
Jet fuel ....bbl./day	18,000	24,000
Motor gasoline .... do.	6,000	-
L.P.G. .... do.	4,750	4,750
Phenols .... do.	1,250	1,250
Total	30,000	30,000

For jet fuel, according to the proposed specification JP-3, gasoline could be blended into the jet fuel. The manufacturing costs will be somewhat lower than those given for gasoline. Some of the equipment necessary for gasoline production in the vapor-phase and distillation area will be idle or eliminated altogether if only jet fuel is required.

Diesel fuel having a cetane number from 40 to 50 can be produced in the same quantity. The cetane number can be increased by using a special catalyst.

Heavy Fuel Oil

The present principal sources of heavy fuel oil are petroleum-refinery residuum and coke-oven tars and pitches, petroleum residuum being the major source. In recent years an increased demand for gasoline and distillate fuels has resulted in the thermal and catalytic cracking of heavy fuel oils to produce more distillates, thereby continually reducing the supply of heavy fuel oil. With our present price structure for fuels, the cost of heavy fuel oil may be expected to increase as the supply dwindles.

The recent short supply of heavy fuel oil from petroleum refining, particularly in the heavy industry areas of the eastern half of the United States, stimulated a search for supplemental sources of heavy fuel oil. These heavy-industry areas have access to large deposits of high-volatile bituminous coal that can be converted easily into an oil that will burn readily in existing equipment. At the suggestion of a number of large consumers of heavy fuel oil, the staffs of the Research and Development Laboratories and the Coal-to-Oil Demonstration Plants made a joint study of the possible methods of converting coal to heavy fuel oil.

Several methods were considered; and by a procedure of elimination, two basic processes were selected. The first was the direct hydrogenation of coal at 700 atmospheres (10,300 p.s.i.) to produce fuel oil, with gasoline, phenols, and liquefied

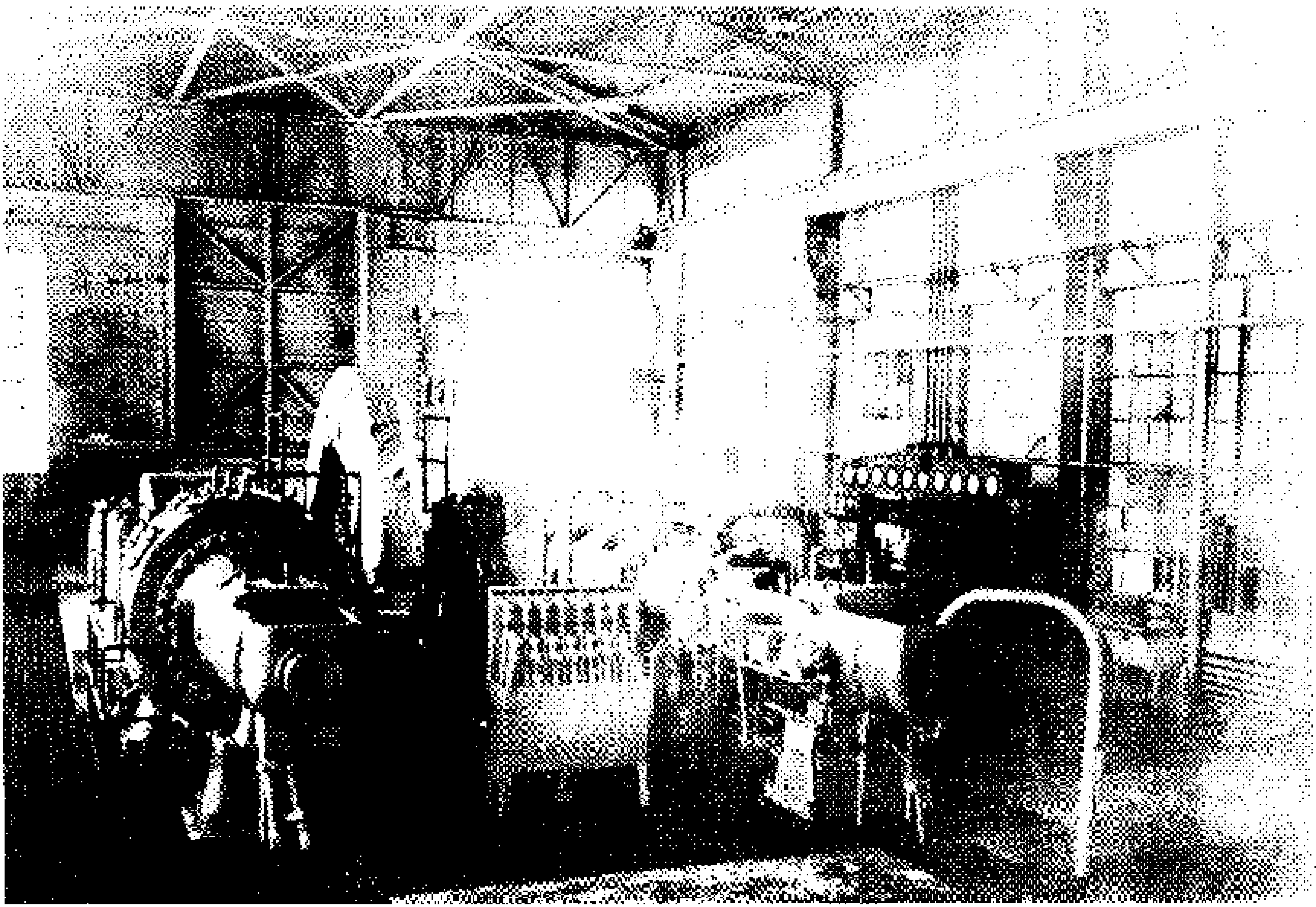

Figure 13. - Seven-stage hyper hydrogen compressor with 2,500-hp. motor.

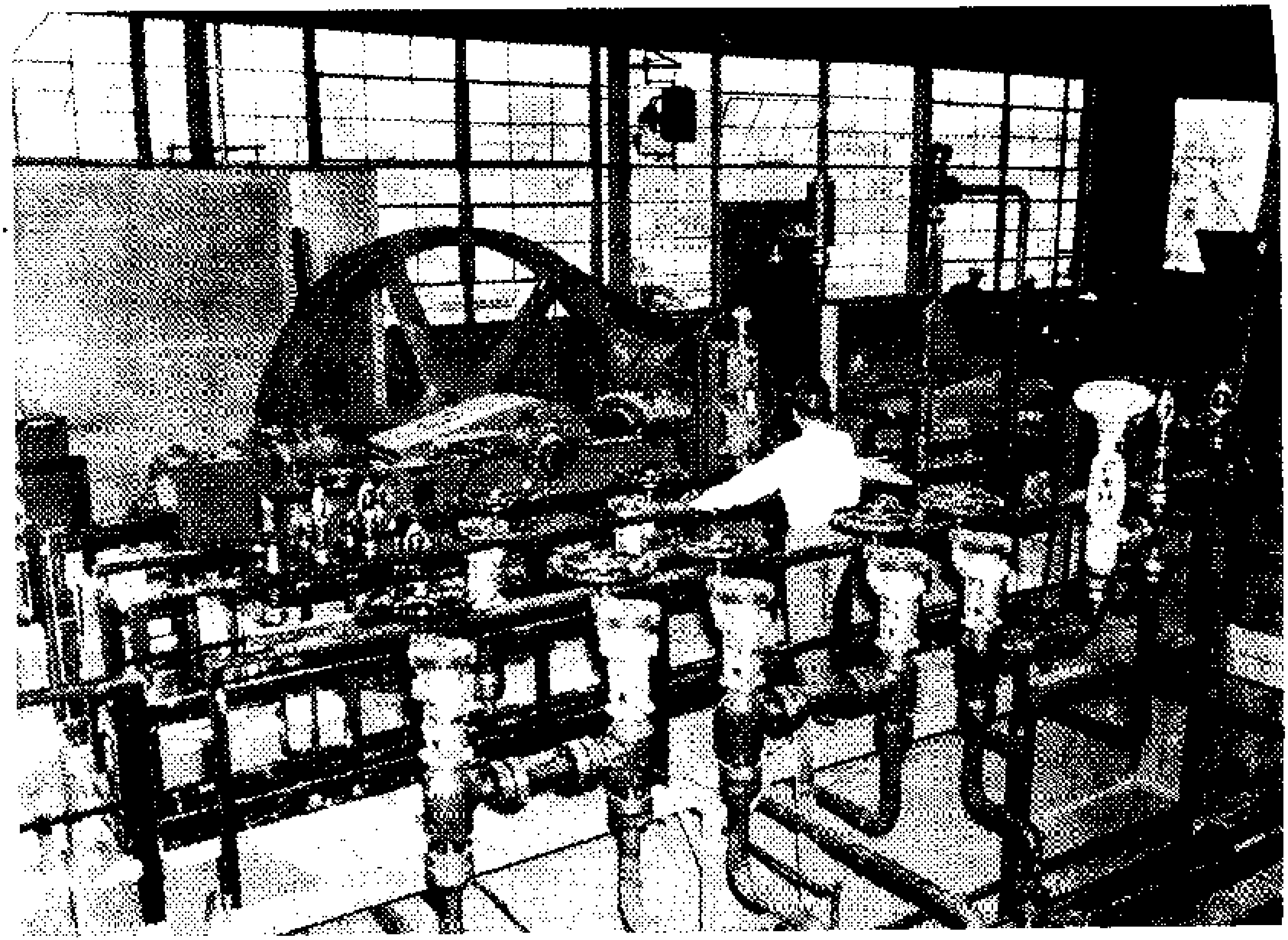

Figure 14. - One of four recycle hydrogen compressor units with valve group and pipe trench in foreground.

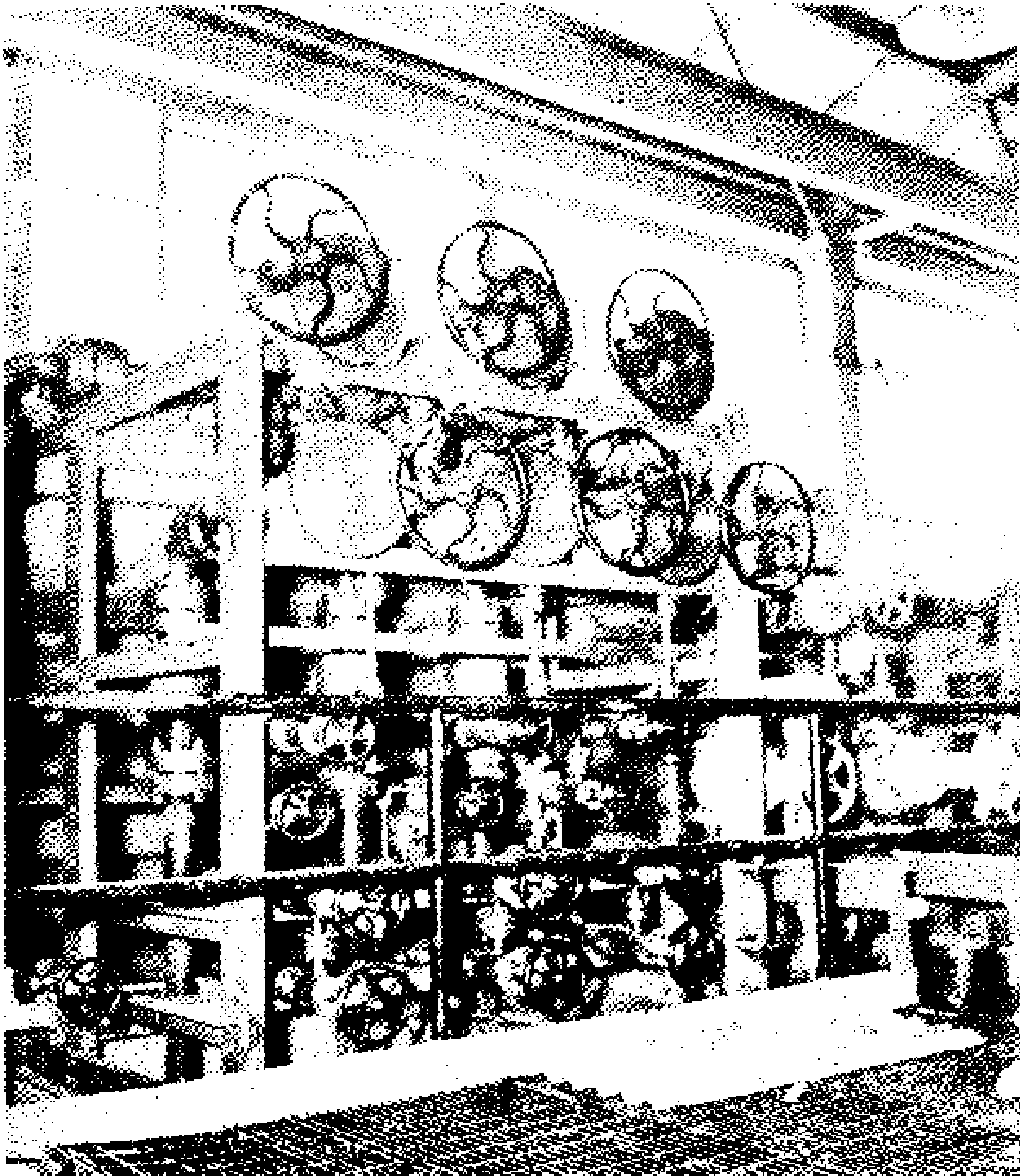

Figure 15. - High-pressure-valve group assembly on mezzanine floor of high-pressure pump house.

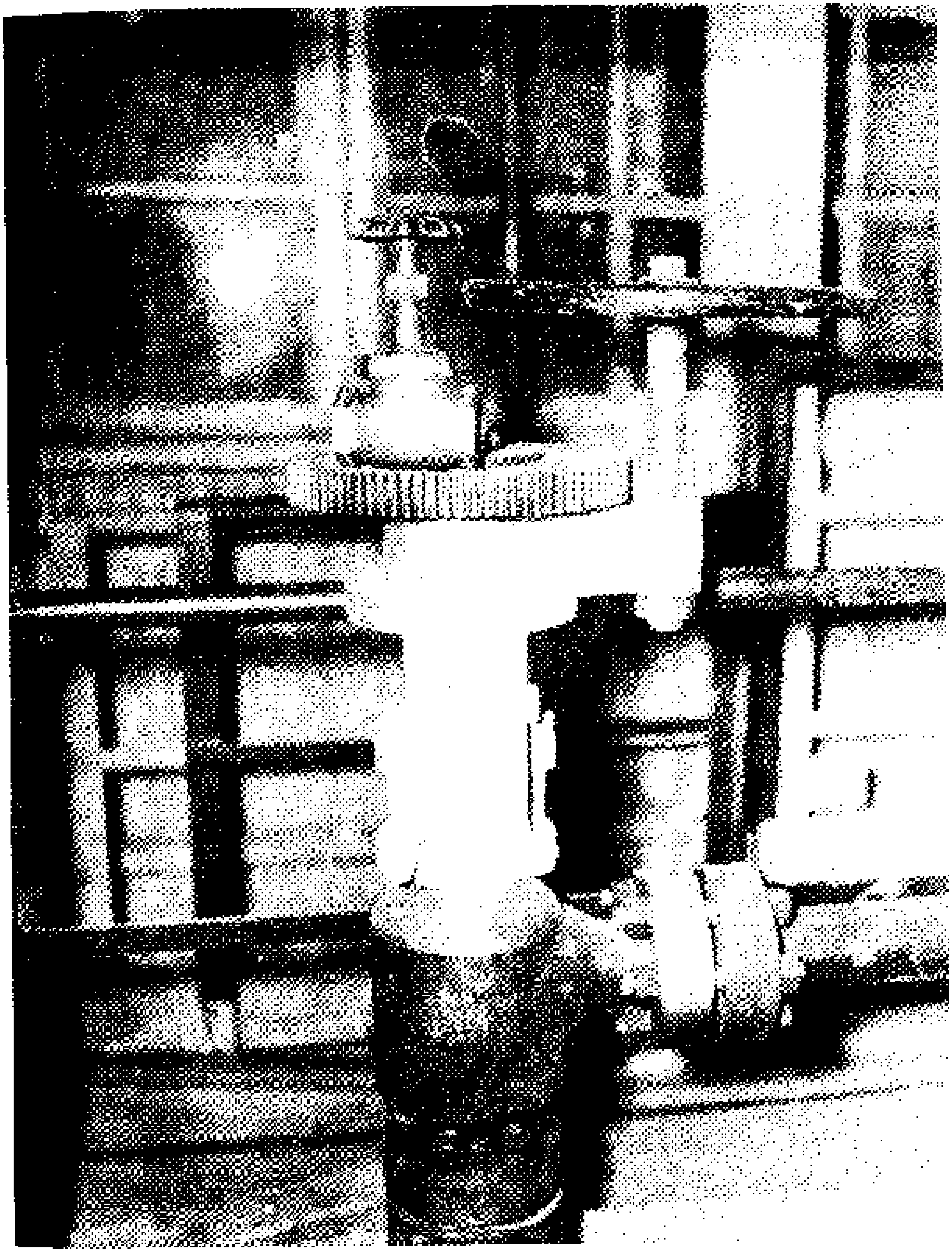

Figure 16. - Close-up of 2-1/2-inch high-pressure valve. Note comparative size of standard 2-1/2-inch valve on top of hand-operated gear wheel.

petroleum gases as byproducts. The second was a combination process involving hydrogenation at 700 atmospheres to produce a solvent oil for an extraction operation at 150 atmospheres (2,200 p.s.i.) to make fuel oil. Gasoline, phenols, and liquefied petroleum gases again were considered byproducts.

An Illinois high-volatile coal was used in this study. It was selected because a shortage of heavy fuel oil existed in the Chicago area.

The coal has the proximate and ultimate analyses shown in table 5.

TABLE 5. - Proximate and ultimate analyses of coal used

Proximate analysis	As mined	Moisture- and ash-free
Moisture ....percent	13.7	-
Volatile matter .... do.	31.7	41.3
Fixed carbon .... do.	45.2	58.7
Ash .... do.	9.4	-
	100.0	100.0
Ultimate analysis		
Sulfur ....percent	1.4	1.8
Hydrogen .... do.	5.6	5.3
Carbon .... do.	62.5	81.3
Nitrogen .... do.	1.4	1.8
Oxygen .... do.	19.7	9.8
Ash .... do.	9.4	-
B.t.u./lb., gross	11,127	14,470

The basic plant is to produce 10,000 barrels of fuel oil per calendar day or a little over 11,000 barrels per stream day. For construction- and operating-cost estimates, each plant was considered, first, as having no source of hydrogen except that which can be obtained by cracking the gases produced by the process and from the gasification of coal; and second, as having an adequate supply of coke-oven gas available to supply the make-up hydrogen requirements over and above that recovered from the off gases by low-temperature separation.

Insofar as original cost and operating expenses are concerned, the plant has been limited to actual processing equipment and auxiliaries, such as hydrogen production, fuel-gas production, and storage. Steam and electric power generating equipment have been excluded, as being outside the scope of the investigation.

For each process, the number, size, and details of major pieces of equipment required for each plant were determined. General specifications for the conventional equipment, such as pumps, compressors, heat exchangers, and vessels, were prepared and submitted to reputable manufacturers for quotations. By a comparison of quotations, prices were established.

For highly specialized high-pressure equipment (see figs. 13-16) such as injection pumps, compressors, converters, and heat exchangers, preliminary designs were prepared and submitted to qualified manufacturers and fabricators capable of furnishing such material. Quotations from these sources supplied reliable cost information covering the unit cost of equipment and in many instances the cost of erection.

Costs of integrated plants, such as oxygen, hydrogen low-temperature separation, producer gas, pulverized-coal gasification, and conventional refining were obtained as completely erected plants.

The plant costs include not only the equipment, but also foundations, supports, buildings, piping, instruments, electrical installations, insulation, painting, and other miscellaneous items. The cost of plant utilities and general plant facilities is included, except for power and steam-generating capacity, which is assumed to be purchased from outside sources. Administrative overhead, engineering, and purchasing are added as percentages of direct costs. A contingency factor and fee have been added to arrive at the total plant cost. Summaries are shown under general headings in table 6.

TABLE 6. - Comparison of plant costs and products, (thousands of dollars)

Type of plant		Hydrogenation		Hydrogenation-extraction	
Source of hydrogen		Coal gasification	Coke-oven gas	Coal gasification	Coke-oven gas
Coal and paste prep.	thousands of dollars	5,223	4,972	5,351	5,196
Hydrogenation .	do.	30,110	30,110	29,562	29,562
Extraction	do.	-	-	6,784	6,784
Gas supply	do.	16,905	11,829	19,337	14,249
Utility and storage	do.	12,154	11,035	14,100	12,998
Total plant cost.....	do.	64,392	57,946	75,133	68,789
Fuel oil	bbl./day		10,000		10,000
Gasoline	do.		1,001		1,464
L.P.G.	do.		890		1,300
Phenols	do.		159		304
Residue	tons/day		372		710
High-ash coal	do.	1,966	2,904	1,882	2,782
Coal required:					
Coal as mined	tons/day		6,575		6,631

The operating costs incorporate in each factor a realistic unit or cost of product based on German, British, and American industrial practices.

Direct costs include raw materials, such as coal, chemicals, and coke-oven gas when used, operating and maintenance labor and supervision, pay-roll overhead, maintenance materials, operating supplies, and utilities. Indirect costs include administrative and office overhead and indirect operating costs, such as utilities not used in operation, hospital, plant transportation, etc. Fixed costs, such as taxes and amortization also are included.

Credit is taken for byproduct gasoline, L.P.G., phenols, combustible residues and tail gas, where a surplus is available. The costs are summarized in table 7.

It has been assumed that, when coal is used as a source of hydrogen, the plant would be situated adjacent to the mine, and no transportation charges are added. When coke-oven gas is used as a source of hydrogen, it is anticipated that the coal must be transported to the plant from the mine, and a freight charge of $1.90 per ton has been added. In order to place both plants on a comparable basis, delivering oil to the same point, a freight charge of 85 cents per barrel for the oil has been added when the plant is located at the mine.

In setting up the fixed costs, it was assumed that the plant would be amortized in 15 years.

TABLE 7. - Comparison of daily operating costs at different coal prices

Cost of coal per ton at mine	$3	$4	$5
Hydrogenation - H_2 from coal gasification			
Cost of coal	19,425	25,900	32,375
Other direct costs	19,477	19,477	19,477
Indirect costs	4,720	4,720	4,720
Fixed costs	13,526	13,526	13,526
Total costs	57,148	63,623	70,098
Credits	19,359	21,284	23,208
Net cost plus contingency	41,568	46,513	51,579
Freight on oil	8,850	8,850	8,850
Net cost plus contingency & freight	50,418	55,423	60,429
Cost per barrel	5.04	5.54	6.04
Hydrogenation - H_2 from coke-oven gas			
Cost of coal	19,425	25,900	32,375
Freight on coal @ $1.90	12,303	12,303	12,303
Coke-oven gas	11,642	11,642	11,642
Other direct costs	18,992	18,992	18,992
Indirect costs	4,259	4,259	4,259
Fixed costs	12,172	12,172	12,172
Total costs	78,793	85,268	91,743
Credits	35,038	37,999	40,961
Net cost plus contingency	48,131	51,996	55,860
Cost per barrel	4.81	5.20	5.59
Hydrogenation-extraction - H_2 from coal gasification			
Cost of coal	19,893	26,524	33,155
Other direct costs	21,556	21,556	21,556
Indirect costs	5,516	5,516	5,516
Fixed costs	15,781	15,781	15,781
Total costs	62,746	69,377	76,008
Credits	28,953	31,155	33,356
Net cost plus contingency	37,172	42,044	46,917
Freight on oil	8,100	8,100	8,100
Net cost plus contingency & freight	45,272	50,144	55,017
Cost per barrel	4.53	5.01	5.50
Hydrogenation-extraction - H_2 from coke-oven gas			
Cost of coal	19,893	26,524	33,155
Freight on coal	12,599	12,599	12,599
Coke-oven gas	14,652	14,652	14,652
Other direct costs	21,397	21,397	21,397
Indirect costs	5,059	5,059	5,059
Fixed costs	14,449	14,449	14,449
Total costs	88,049	94,680	101,311
Credits	48,665	51,864	55,063
Net cost plus contingency	43,322	47,098	50,873
Cost per barrel	4.33	4.71	5.09

The cost of fuel oil from plants of this size would range from $3.07 to $4.16 per barrel at the plant, with coal at $3.00. With freight costs of $1.90 per ton for coal or $0.85 per barrel for oil added, the cost without profit at the point of consumption would range from $4.35 to $5.04 per barrel.

Care has been taken to include only completely developed or commercially proved processes in order that data and costs may be reported as accurately as possible. As a result, synthetic fuel oil does not show up in its most favorable position. Although complete data are not available on a number of important improvements which are currently in the experimental and development stage, the effect of such improvements can be predicted within reasonable limits. Most of these improvements will be ready for commercial application before a commercial-size plant for the production of fuel oil from coal would be fully designed and built.

Experience in one German plant and in the Imperial Chemical Industries plant at Billingham, England, has shown an increased plant throughput with a corresponding increase in yields by the addition of automatic control. This study includes the costs of full instrumentation but has not taken advantage of cost reductions from increased throughput and yields resulting from their use.

Savings up to 35 percent in the cost of high-pressure vessels are possible by the use of wrapped construction (Wickelofens) instead of conventional forged vessels. At least two manufacturers in this country are investigating the manufacturing methods required to produce wrapped vessels in larger quantities than is possible with existing forging equipment.

It has been estimated that the investment and operating costs of coal gasification at atmospheric pressure may be reduced appreciably by gasification at higher pressure. Pressure gasification is essential to economical operation of the gas-synthesis (Fischer-Tropsch) process, as well as coal hydrogenation. The Bureau of Mines and several industrial concerns are studying this development intensively.

A greater recovery of oil contained in the byproduct residue is considered possible through delayed coking. Such an increase would lower the coal required for a given output.

From results of parallel studies in which these features were incorporated, it may be concluded that a saving of at least 10 percent in investment and operating costs is possible in plants using coke-oven gas as the primary source of hydrogen. In plants depending upon coal gasification as the primary source of hydrogen, savings up to 20 percent are not considered unlikely. If these process improvements were incorporated in a larger-size plant (approximately 30,000 barrels per day capacity) and a cheaper means of transportation were used - pipe line or water - heavy fuel oil could be delivered within a radius of 150 miles as low as $3.10 per barrel. This is based on $3.00-per-ton coal and is the actual cost without profit.

Miscellaneous Coal-Hydrogenation Studies

Because large reserves of coal suitable for coal hydrogenation are found in the western part of the United States where fresh water is scarce, a comprehensive study was made of minimum water requirements for 10,000-, 30,000-, and 50,000-barrel-per-day coal-hydrogenation plants. Using cooling towers, a conventional steam power plant, and Wyoming bituminous coal as the raw material, the total fresh-water requirement for a 30,000-barrel-per-day coal-hydrogenation plant is 13,710 gallons per minute during the summer months. By substituting air cooling for water cooling, where possible, the fresh make-up water requirements may be reduced to 8,880 gallons per minute, a decrease of 35 percent. If coal-fired gas turbines were substituted for conventional power generation, the fresh water requirements could be reduced by 6,470 gallons per minute with no increase in plant cost. The application of steam-jet water-vapor refrigeration for water cooling has been

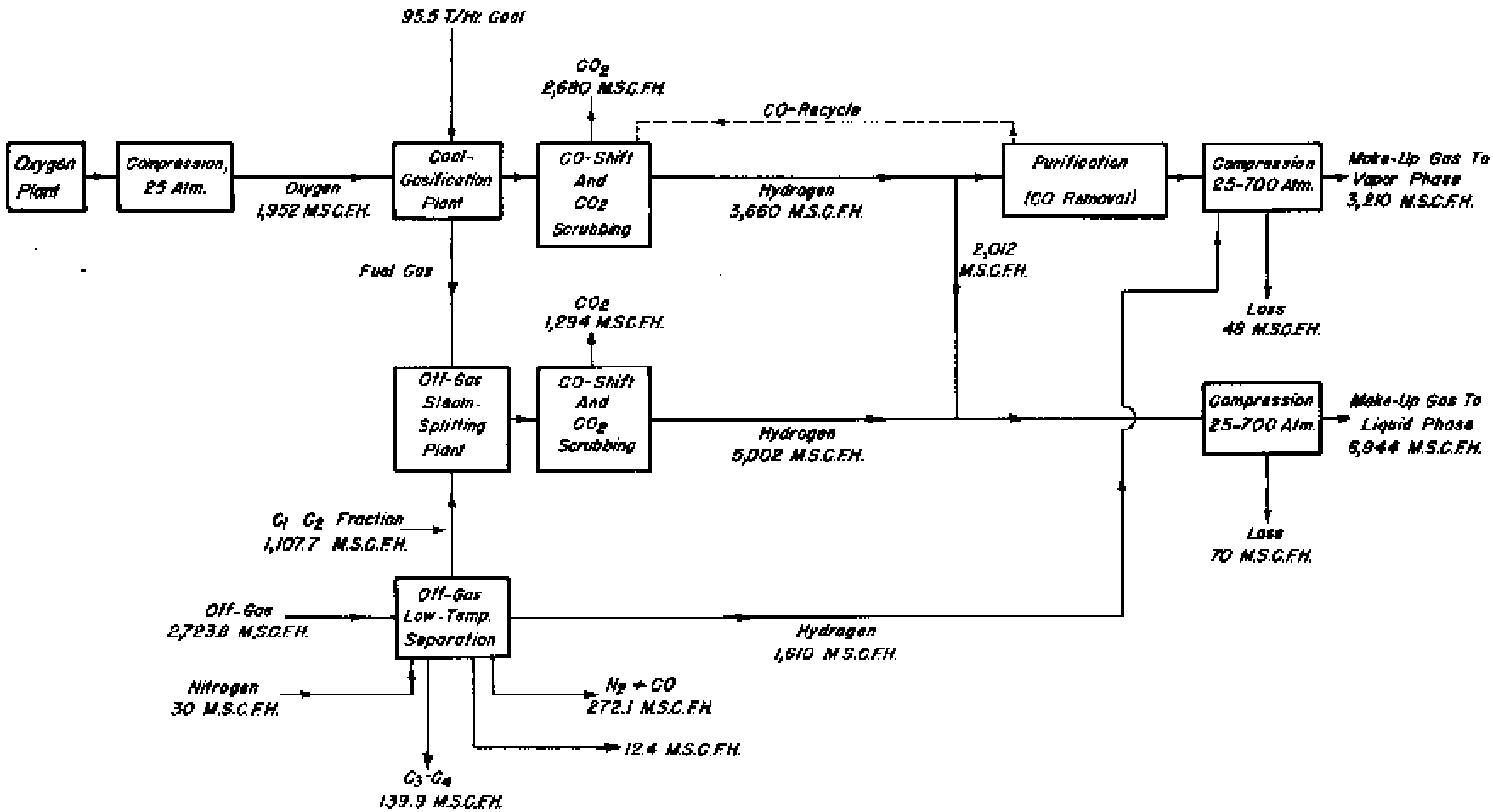

Figure 17. - The manufacture, purification, and compression of hydrogen constitute nearly one-fourth of the cost of a hydrogenation plant. Shown here are the operations required for making hydrogen from coal for a 30,000-barrel-per-day plant.

studied and when combined with air cooling, water requirements are reduced to an absolute minimum. However, economics would preclude the full use of steam jet refrigeration because of increased capital cost.

Chemical process studies have been directed toward increasing the thermal efficiency and the oil recovery in the coal-hydrogenation process. High-pressure hydrogen is a costly raw material for the hydrogenation process (see fig. 17), and any improvements that will increase the thermal efficiency of hydrogen production thereby will improve the economics of coal hydrogenation. Hydrogen can be produced most economically from cheap natural gas, but in the absence of any such source of natural gas it must be produced from coal by gasification and by the thermal cracking with steam of the light hydrocarbon gases produced in the process. Under present-day knowledge of gasification and hydrocarbon steam-cracking technology, both processes are carried out at essentially atmospheric pressure. Studies to date, however, indicate that there are many advantages in carrying these hydrogen-manufacturing processes out at higher pressures, say 20 to 30 atmospheres. The advantages are: (1) Greater throughputs per volume of furnace, (2) decrease in power consumption through saving in compression, and (3) decreased capital investment through saving in compressors and increased heat-transfer rates. There is, however, no established pressure-gasification process for coal at present. Work is in progress to design a pressure-gasification unit for powdered fuel at Louisiana, Mo.

In the hydrogenation step a heavy, viscous black oil is produced, containing solids of unreacted coal, ash, and catalyst. The maximum recovery of this oil will result in a dry residue containing little or no oil, thus decreasing the amount of coal, hydrogen, and energy required to produce a unit of liquid fuel. This constitutes an important process and economic problem in coal hydrogenation. In Germany this material was filtered; and the residue was coked in kilns, but processing in this manner was cumbersome and highly inefficient. Currently two different processes are being developed that are superior to the German method. One of these is the flash-distillation process, wherein the oil is vaporized and flashed off from the solid particles with superheated steam. The residue of solids containing a small amount of oil is then briquetted and burned as fuel. This process is incorporated into the Coal-Hydrogenation Demonstration Plant at Louisiana, Mo. The second method of handling the heavy solids containing oil is by the delayed coking process, which currently is being used in the continuous coking of petroleum residues. It is felt that its application to the processing of this heavy oil from coal hydrogenation will be especially beneficial, for maximum oil recovery is thereby attainable. A "fluid-bed" technique similar to the fluid catalytic cracking procedure may be used in the delayed coking process for maximum heat transfer. Products from the process are reclaimed heavy fuel oil and solid coke or producer gas.

At the request of Bureau of Mines, the Corps of Engineers is conducting a survey of the United States for the most advantageous regional sites for synthetic-fuel plants. As a prerequisite, the Bureau of Mines enumerated the basic requirements necessary for the following types of plants: Coal Hydrogenation, Fischer-Tropsch using coal, and Fischer-Tropsch using natural gas. Based on our estimate for a 30,000-barrel-per-day coal-hydrogenation plant and other available data, the information assembled and reported to the Corps of Engineers presented the basic requirements for such items as cost of construction, optimum size, coal and natural gas, water, and steel tonnage. Revisions in these requirements have been made since that time, based on calculations representing our latest knowledge of synthetic-fuel technology. The following tables are results of our latest calculations:

(1) Optimum size of plants:

	Barrels per day
Coal Hydrogenation	30-50,000
Fischer-Tropsch using coal	10-20,000
Fischer-Tropsch using natural gas	10,000

(2) Cost of construction:

Coal hydrogenation		Fischer-Tropsch using natural gas		Fischer-Tropsch using coal	
Bbl./day		Bbl./day		Bbl./day	
5,000	-	5,000	$ 36,000,000	5,000	-
10,000	$ 89,000,000	10,000	60,000,000	10,000	$ 75,000,000
30,000	244,000,000	30,000	180,000,000	30,000	225,000,000
50,000	400,000,000	50,000	-	50,000	375,000,000

(3) Coal and natural-gas requirements

Barrels per day	5,000	10,000	30,000	50,000
Coal hydrogenation, tons/day				
Bituminous coal, 11,900 B.t.u./lb.	1,966	3,933	11,800	19,655
Subbituminous coal, 9,500 B.t.u./lb	2,585	5,170	15,500	25,850
Lignite, 7,500 B.t.u./lb.	3,350	6,700	20,100	33,500
Fischer-Tropsch using coal, tons/day				
Anthracite coal, 14,000 B.t.u./ lb.	1,928	3,857	11,570	19,280
Bituminous coal, 11,900 B.t.u./lb.	2,380	4,760	14,280	23,800
Subbituminous coal, 9,500 B.t.u./lb.	3,141	6,283	18,850	31,410
Lignite, 7,500 B.t.u./lb.	4,065	8,130	24,400	40,650
Fischer-Tropsch using natural gas, in standard cu. ft./day				
Natural gas, 1,000 B.t.u./std.cu.ft.	50×10^6	100×10^6	300×10^6	500×10^6

(4) Water requirements.

Process	Fuel	30,000 bbl./day plant with 33° F. rise: Make-up water, gal./min.	Circulating water, gal./min.
Hydrogenation	Bituminous coal	13,710	250×10^3
	Subbituminous coal	14,825	274×10^3
	Lignite	14,800	273×10^3
Fischer-Tropsch	Anthracite	17,125	109.6×10^3
	Bituminous coal	18,175	117×10^3
	Subbituminous coal	19,465	125.6×10^3
	Lignite	19,785	127.6×10^3
Fischer-Tropsch	Natural gas	13,251	63.3×10^3

(5) Steel tonnage required

Bbl./day plant size	5,000	10,000	30,000	50,000
Coal hydrogenation	35,000	62,000	170,000	279,000
Fischer-Tropsch, using coal	38,000	65,000	195,000	312,000
Fischer-Tropsch, using natural gas	30,000	58,300	175,000	300,000

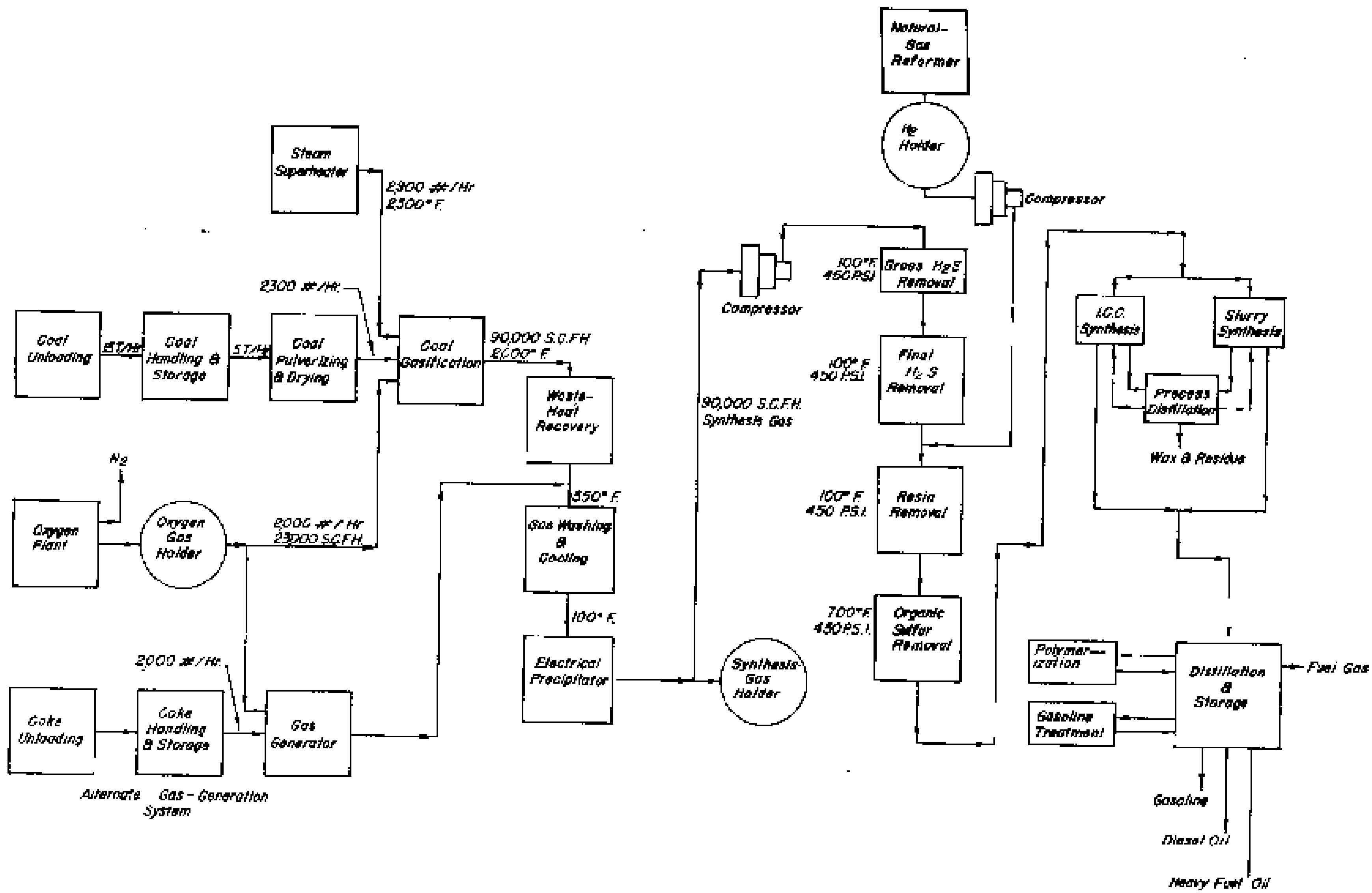

Figure 18. - Block diagram of flow, Gas-Synthesis Demonstration Plant.