Fuel	Brown coal (Lausitz)	Brown coal (middle Germany)	Hard coal (noncoking coal from the Ruhr)
Specific gravity	0.448	0.435	0.410
B.t.u. per cubic foot of dry gas at 60° F. and 30 inches Hg	456	479	437
Oxygen used per 1,000 cubic feet of dry gas ... cu.ft.	150	147	198
Steam used per 1,000 cubic feet of dry gas ... lb.	66	77	83
Tar recovered ... percent of analytical value	72	84.3	0.0
Yield of dry gas (at 60° F., 30 inches Hg.) per ton of 2,000 pounds of coal ... cu.ft.	25,600	22,800	53,100
Coal consumed per 1,000 cubic feet of gas made ... lb.	78.2	87.8	37.8

It is noted that the O_2 consumed in making gas from the relatively high-rank noncoking coal is about 35 percent higher than when gasifying the lower-rank fuels. No doubt the lower reactivity of the high-rank fuel made necessary operation at higher temperatures, which in turn called for a greater amount of O_2. Under these conditions, one would expect the resulting gas to contain somewhat less CH_4 and more CO, and this is shown to be the result obtained.

It is recognized that the differences in moisture contents and volatile matter in the different fuels has a definite bearing on the amount of oxygen consumed per pound of coal gasified. Comparing columns 1, 2, and 3, it is noted that the volumes of gas made per ton of coal gasified are not proportional to the calorific value of the different fuels, but, on the contrary, the gas volume is greater than this ratio for the high-rank low-moisture-content fuel.

Factors Relating to Comparative Costs

Interest centers in the relative cost of ordinary water gas and Lurgi-process gas. Although the major item favoring the Lurgi process is its adaptability to handle fuels unsuitable for use in standard gas-generating sets, the following comparison is made to show some important relationships:

Relative costs of materials used making water gas and Lurgi pressure-process gas

	Ordinary water gas, 1 atmosphere[a]		Lurgi pressure-process gas, 20 atmospheres[a]	
	Per 1,000 cu. ft.	Per therm	Per 1,000 cu. ft.	Per therm
Coke, 40 pounds per 1,000 cubic feet at $6 per ton	$0.120	$0.040	-	-
Coal, crushed and screened, 1/8- to 1/2-inch subbituminous quality, 90 lb. at $3 per ton	-	-	$0.135	$0.030
Oxygen, 145 cubic feet per 1,000 of purified Lurgi gas at 18¢ per 1,000 cubic feet	-	-	0.026	0.006
Steam, 40 pounds per 1,000 cubic feet of water gas at 25¢ per 1,000 lb.	0.010	0.003	-	-
Steam, 66 pounds per 1,000 cubic feet of Lurgi gas at 25¢ per 1,000 pounds	-	-	0.017	0.004
	0.130	0.043	0.178	0.040
Credits per 1,000 cubic feet and per therm of gas made:				
Tar, 112 pounds per ton of coal at 4¢ per gallon	-	-	$0.024	$0.005
Benzine (light oil), 6.31 gal. per ton of coal at 8¢ per gallon	-	-	0.024	0.005
Total credits	0.000	0.000	0.048	0.010
Net materials cost, less credits	0.130	0.043	0.130	0.030

a/ Water gas calorific value = 300 B.t.u. per cubic foot; Lurgi gas, 450 B.t.u.

The gas made in the pressure gasification, as above, is at 20 atmospheres absolute pressure and need not be compressed further for transmission or for use in the Fischer-Tropsch process. Without further treatment, however, it is noted that 1,000 cubic feet of water gas contains 900 cubic feet of $CO + H_2$, whereas the same amount of scrubbed pressure gas contains only 700 cubic feet of $CO + H_2$.

The foregoing costs are not representative of the relative cost of finished gas by the two processes, because other items, such as maintenance, taxes, amortization, labor, relative generator capacities, and other costs, which are not identical in the two cases and cannot be evaluated accurately at this time, are not included. The important consideration is that an appreciable difference in the relative costs of generator fuel and in the credits for byproducts are required, as indicated, to favor the pressure process. In view of the higher calorific value of the pressure-process gas, a more equitable comparison might be the materials costs of carbureted water gas and pressure gas; these costs are compared as follows:

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Relative costs of materials used in making carbureted-water gas and Lurgi pressure-process gas, per 1,000 cubic feet

	Ordinary carbureted water gas	Pressure, process gas
Operating pressure......................atmospheres	1	20
Calorific value..................B.t.u. per cu.ft.	466	466
Coal, 1/8- to 1/2-inch, 90 pounds at $3 per ton.cents	-	13.50
Coke, 30 pounds at $6 per ton...................do.	9.00	-
Carbureting oil, 2.08 gallons at 6¢ per gallon....do.	12.48	-
Steam (for generator, turbine, booster, etc.) 100 pounds at 25¢ per 1,000 lb. ....do.	2.50	-
Steam (total for pressure gas operations) 66 lb. at 25¢ per 1,000 lb. ....do.	-	1.65
Oxygen, 144 cubic feet at 18¢ per 1,000 cubic feet..do.	-	2.60
	23.98	17.75
Credits:		
Tar.......................................cents	2.0	2.4
Benzole and light oils......................do.	-	2.4
	2.0	4.8
Total materials, less credits..................cents	21.98	12.95

It will be noted that in the pressure-gas process the light oils are recovered by ordinary condensation on cooling the gas.

A plant for the complete gasification of coal under pressure and purification of the gas includes:

1. An oxygen-producing and compressing plant
2. Gas generator house with generators
3. Steam superheater
4. Condensing equipment
5. Pressure scrubbers
6. Dry purification equipment
7. Gas holder
8. Tanks, reservoirs, and water ponds
9. Light oil-recovery plant
10. General utilities, and
11. Coal- and ash-handling equipment.

In case steam and electrical power cannot be purchased economically "at the plant gate" a power plant is also required. Likewise, if the coal purchased is not sized as delivered, it is necessary that a coal-crushing and screening plant be a part of the whole, and means must be provided for disposing of the fines (dust coal). The fine coal, of course, can be used as boiler fuel for the generation of steam.

Information relating to the cost of such a gas plant and certain other costs under normal conditions for making gas by the pressure process at approximately 20 atmospheres pressure may be gleaned from the data given below, which the author obtained from engineers in Germany experienced in this field:

Basis:

Annual production of purified gas measured dry at 60° F., and 30 inches mercury	cu.ft.	3,720,000,000
Calorific value	B.t.u. per cu.ft.	458
Coal used, proximate analysis:		
Moisture	percent	15.00
Volatile and combustible	do.	75.00
Ash	do.	10.00
		100.00
High calorific value	B.t.u. per pound	7,740
Ash-softening temperature	° C.	1,100
Efficiency of gasification of coal (Including the heat energy of the tar and oil, but excluding heat input as steam)	percent	84.8

The efficiency of conversion of the fuel, not including the heat in the O_2 and steam, is given as follows:

$$\text{Efficiency} = 100\ \frac{[(4,300 \text{ cal. per Nm}^3 \text{ of gas})\ (0.65) + (850 \text{ cal. in tar and oil})]}{4,300 \text{ calories per kgm. of coal}}$$

= 84.8 percent.

The figure 0.65 is the number of cubic meters of gas from 1 kgm. of the coal. Calculated in terms of U. S. standard units, the conversion efficiency is:

$$\text{Efficiency} = 100\ \frac{[(458.7 \text{ B.t.u.})\ (10.97) + (1,530 \text{ B.t.u.})]}{7740} = 84.8 \text{ percent}$$

In the latter computation, 458.7 is the B.t.u. per cubic foot of dry gas made from 1 pound of coal; 1,530 B.t.u. is the heat of combustion of the tar and oil made in gasifying 1 pound of coal; and 7,740 is the calorific value of the coal in B.t.u. per pound.

Annual costs:	Reichsmarks	Dollars
Coal used per year, 170,000 short tons at 5.88 Rm., or $2.352 per short ton	1,000,000	400,000
Electric power, purchased at 0.02 Marks or 0.8 cent per kw.-hr.	500,000	200,000
Steam, 154,000 short tons purchased at 2.28 Rm., or $0.912 per short ton	350,000	140,000
Cooling water, a/ 700,000 m^3 (24,717,000 cu.ft.)	35,000	14,000
Repairs, labor	280,000	112,000
Repairs, materials	162,000	64,800
Amortization (12 percent on investment)	780,000	312,000
Total annual costs	3,107,000	1,242,800
Estimated total cost of plant	6,500,000	2,600,000

a/ The total water consumed in actual operations appears to be approximately three times the figure given.

The plant can be operated, it is said, by four shifts of 28 men each, or 112 men per day, but the effective running time is considered to be 7,000 hours per year or 292 days. It is said that these men can handle the oxygen plant and purification equipment, as well as operate the generators. Steam and electric power are considered to be available by purchase "at the gate." On this basis, the cost of the scrubbed gas is given as 3 Pf. per m^3 (32.3 cents per 1,000 cubic feet) without allowing credit for the tar and oil. These cost data were compiled after the actual experience of building and operating a plant. It is interesting to note that the total cost of the plant ($2,600,000) included $676,000, or 26 percent of the total, as the cost of the Linde-Frankl oxygen plant. The oxygen required varies with the nature of the fuel used but averages 15 to 18 percent by volume of the purified gas made at approximately 20 atmospheres pressure. The electric power used for oxygen production included in the above cost data is 0.67 kw.-hr. per cubic meter of dry O_2 at 0° C. and 760 mm. pressure, equivalent to 19 kw.-hr. per 1,000 cubic feet similarly measured.

The foregoing cost data relate to the production of gas having a calorific value of approximately 450 B.t.u. per cubic foot. Calculating the cost to the equivalent of 1,000 cubic feet of 300 B.t.u. gas, the estimated cost would be $\frac{300 \times 32.3}{450}$ cents, or 21.5 cents, without allowing for credits for tar and oil.

In using these estimated costs, it must be kept in mind that in transposing the costs in Reichsmarks to dollars the arbitrary value of 1 Mark equivalent to 40 cents was chosen because it appears to express a proper relationship of values of things bought with the Reichsmark in Germany and the dollar elsewhere. It is believed that an attempt was made in the above estimate to figure costs as close to minimum as possible under the prevailing conditions. Some of the items, such as steam and electric current, cost less in the United States, but certain other items including taxes, insurance, and the like, must be included in applying the data to American conditions.

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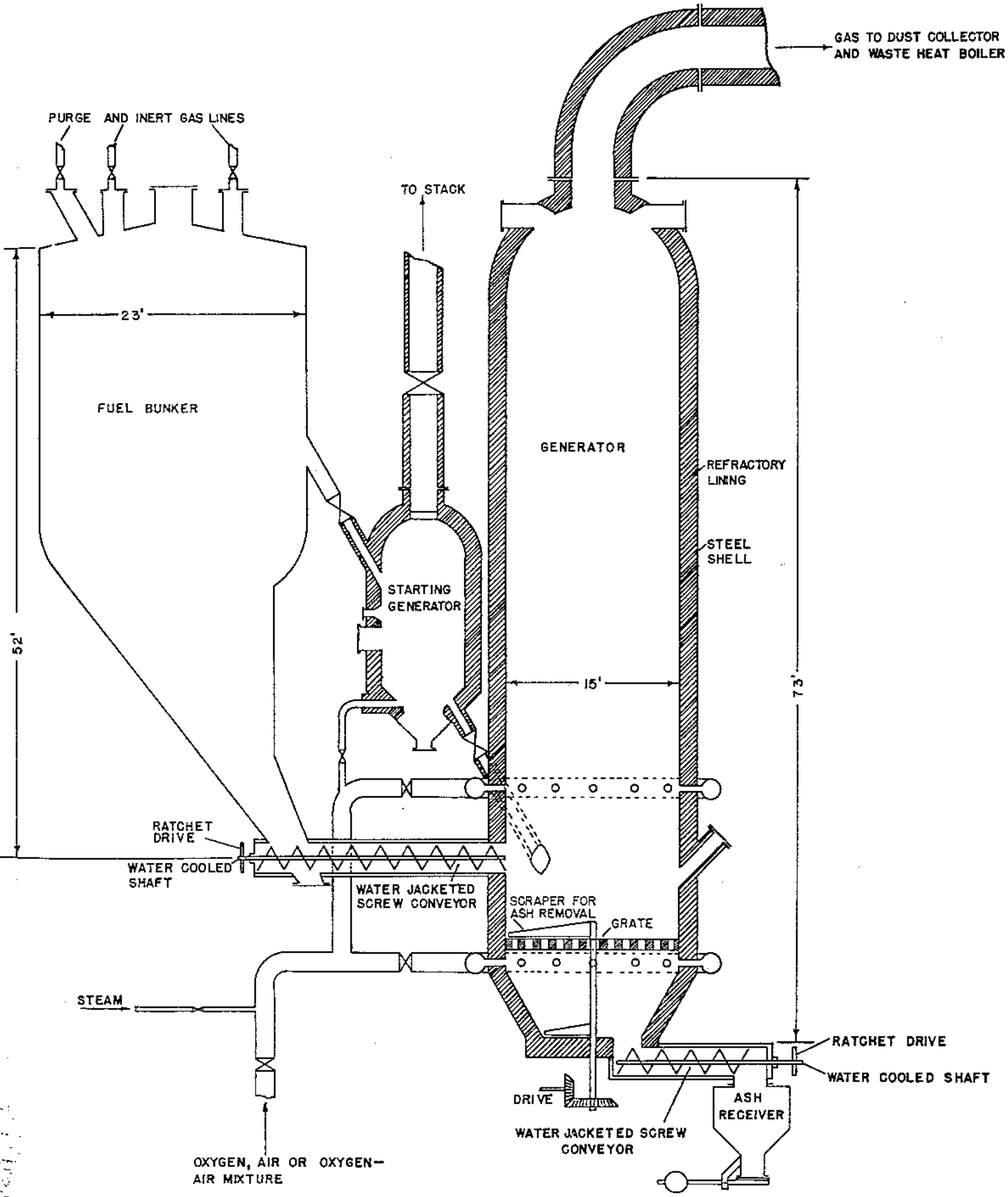

FIGURE 7.- DIAGRAM OF A WINKLER GENERATOR.

THE WINKLER GENERATOR AND GASIFICATION PROCESS

The Winkler process for making gas comprises the gasification of solid fuel in a finely divided state while it is in a fluidized state confined in a specially designed generator. The initial conception was that when a fire was kindled in a bed of fine fuel and it was blasted from beneath with mixed air and steam at a sufficiently high velocity, the mass would be fluidized, the particles assuming ebullient motion, and the reaction of the steam and air with the fuel would be continuous, with considerable equalization of temperature throughout the bed. It was believed that not only could a high gas-making capacity be obtained in this manner, but the ash could be removed in a fine granular or powdered state. It was found that with certain highly reactive fuels, this could be accomplished. The desire to reduce the nitrogen content and simultaneously raise the calorific value of the gas led to the use of O_2 instead of air in admixture with steam. It was found that the ash, to a large extent, was carried along entrained in the gas, and, furthermore, the partly burned particles of fuel still containing considerable combustible matter also were carried out of the generator entrained in the gas by virtue of their relatively small size. Thus, it became necessary, to reduce the loss of fuel in this manner, to introduce O_2 along with steam at a level above the top of the fuel bed. This was an important improvement in the process; the desired end result was obtained.

The Winkler process has been used successfully in Germany at Leuna, where the latest developments were made, and at Zeitz, where large generators had been in daily operation. As in the pressure-gas process, it was necessary to control the temperature of the fuel being gasified, which is accomplished by regulating the proportions of steam and O_2 or steam and air. Tar is not recovered from the gas, nor is it present therein in appreciable amounts. Fuels that yield small amounts of tar only are preferable to other types of solid fuel. At Leuna, there were five Winkler generators, but only two were in use just prior to the close of the European war; one employed air and steam as gas-generating fluids in making power gas, and the other, similarly operated, was used to produce a high nitrogen-content gas for control purposes in making synthetic ammonia, that is, for controlling the amount of N_2 in admixture with H_2.

Figure 7 is a diagrammatic view of a Winkler generator. As shown, oxygen (or air) and steam are introduced beneath the grate at the bottom, and some of each also is introduced at a number of inlets at a common level above the ignited fuel bed. The depth of the fuel bed is 39 to 58 inches, although it is said to be preferable, usually, to maintain the depth at about 39 inches. A water-cooled arm rotating about a central axis helps to discharge ashes from the generator. The grates comprise fire bricks placed on edge a few millimeters (1/8 to 1/4 inch) apart. The upper inlets for steam and O_2 are located 9 feet 10 inches above the grate. The prepared fuel, stored in a reservoir adjacent the generator, is fed into the generator by means of a screw conveyor, which operates continuously.

Kind of Fuel Adapted for Use in a Winkler Generator

Although it is true that fine sizes of solid fuel may be used successfully in a Winkler generator, it does not follow that all solid fuels can be thus gasified. The physical and chemical properties of the fuel used have considerable to do with the results of gasification. Some of these properties are:

(a) Sizes and range in sizes of fuel used.

(b) Softening point of the fuel ash.

(c) Reactivity.

(d) Tar content of the fuel.

(a) Size of fuel. - When maintaining the mass of fuel in a fluidized state in the generator, it is necessary that the velocity of the fluids (gas-making fluids and reaction products) passing into and through the bed be greater than a fixed minimum, which latter is that at which particles begin to settle and separate from the fluidized state. Employing the necessary velocity, there is a tendency for the finer particles to be carried away entrained in the gas, hence a large variation in particle size in the fuel charged should not obtain. The ideal condition would be complete uniformity of particle size. Of course, even with this state the burning of the fuel in gas-making reactions would cause progressive variation in size, and the very small particles would be carried along with the gas stream. In commercial operation of the Winkler process employing carbonized brown coal as fuel, a satisfactory size (the size actually used) was 3 to 4 mm., which is 0.118 to 0.158 inch. Small amounts of fines and coarser particles also are present in the fuel gas as charged into the generator. Even with the exercise of care in preparing the fuel, the ash blown over or entrained in the gas stream contains considerable combustible matter. It appears that the greater the variation in size of the fuel particles in the fuel charged, the greater is the percentage of carbon in the ash. Accordingly, small and uniformly sized particles are preferred for Winkler generator fuel.

(b) Ash-softening temperature. - The particles of fuel in the fluidized state are in ebullient motion, and there is considerable contact or collision of these particles during the gasification process. It is obvious that should they be heated in the generator above the ash-softening temperature, they will adhere to one another and form larger particles. This could result in the formation of clinkers of appreciable size and hinder smoothness of operation. Furthermore, should the particles be heated above the ash-softening temperature, there would be a tendency for them to adhere to the wall of the generator and accumulate there with understandable deleterious results. Accordingly, it is desirable to keep the fuel particles in the fluidized bed in the generator at a temperature 30° to 50° C. below the ash-softening temperature. In some cases this is an important and definite limitation; thus, fuels having high ash-softening temperatures (2,400° to 2,700° F.) should not cause serious troubles from clinker formation, because it is possible to reach a suitable gas-making temperature appreciably below the ash-softening temperature. However,