CHAPTER 8. - TABULAR DATA AND ECONOMIC ESTIMATES

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Earlier chapters of this report have described processes by which synthetic liquid fuels can be made from coal and discussed some of the experimentation on these processes. This chapter summarizes studies on coal reserves for potential synthetic-fuel production, data on yields by the various processes, and estimates from the various sources cited (1-12) on the cost and materials requirements for commercial-scale plants.

Potential Sites for Synthetic-Fuel Plants

In studies on potential sites for synthetic fuel plants (5), the minimum sizes considered for economic estimates were 11,000 barrels per operating day for synthetic liquid fuel, or 90 million cu. ft. per operating day for synthetic pipeline gas. Operating such plants for 20 years would require 30 to 40 million tons of coal for liquid fuel, or 35 to 45 million tons for pipeline gas.

The following specific requirements were made for potential sites: Within a 3-mile radius 30 million tons of coal must be accessible for underground mining, with coal seams at least 24 to 48 inches thick at a maximum depth of 1,500 feet, and 5 million tons of coal available for strip mining of a minimum seam thickness such that for maximum depths of 75 and 200 feet the maximum stripping ratios would range between 40:1 and 7:1. Requiring further an adequate water supply and eliminating some otherwise unsuitable areas, recoverable coal reserves suitable for synthetic fuels industries were estimated at 110 billion tons. This most easily minable, most advantageously located portion of our coal reserves could replace completely our supply of liquid and gaseous fuels for a period of about 45 years at present rates of consumption.

Suitable areas in each State and their daily liquid-fuel potential for a 40-year period are given in table 14. Group 1 includes preferred areas, most suitable for a total U. S. production of 2 million barrels daily, distributed by States on the basis of estimated demand; Group 2 includes slightly less desirable areas, to total with group 1 about 5 million barrels daily production; and group 3 includes the remaining areas considered physically feasible for coal-to-oil plants.

Gasification of Coal

Table 15 shows materials requirements, gas yields, and compositions for two types of coal gasifiers. As compared with the entrained-bed generator, the fixed-bed generator yields a gas that is richer in hydrogen and contains appreciable amounts of methane. Yields of $CO + H_2$ alone are lower from the fixed-bed generator, but combined with the equivalent of the methane yield they are higher than from the entrained-bed generator, and oxygen requirements are about half or less. However, fixed-bed generators are suitable only for noncaking or only mildly caking coals.

In general, yields and oxygen requirements in both generators increase with increasing carbon content and rank of coal, as indicated in figure 76. Yields based on weights of coal as received would be roughly the m. a. f. yields shown, times the m. a. f. coal content of the as-received coal.

TABLE 14. - Available coal reserve areas, classified by their relative overall desirability for coal-to-oil plants, with estimated production capacities 1/

	Number of suitable areas (in parentheses), and their production capacities in thousands of barrels of liquid fuels per day, considering total coal reserves per State alternatively for:															
	Coal hydrogenation plants								Fischer-Tropsch plants							
	2/Group 1 (Preferred areas)		Group 2 (Less suitable)		Group 3 (Others feasible)		Total		Group 1 (Preferred areas)		Group 2 (Less suitable)		Group 3 (Others feasible)		Total	
Alabama	(1)	86	-	-	(2)	108	(3)	194	(1)	67	-	-	(2)	84	(3)	151
Arkansas	-	-	-	-	-	-	-	-	(1)	37	-	-	-	-	(1)	37
Colorado	(2)	147	(2)	161	(9)	944	(13)	1,252	(2)	106	(5)	212	(6)	643	(13)	961
Illinois	(6)	296	(3)	372	(27)	1,705	(36)	2,373	(5)	225	(7)	659	(24)	960	(36)	1,844
Indiana	(1)	226	(3)	537	(2)	273	(6)	1,036	(1)	176	(3)	418	(2)	212	(6)	806
Iowa	-	-	-	-	(8)	233	(8)	233	-	-	-	-	(8)	182	(8)	182
Kansas	(1)	26	-	-	-	-	(1)	26	(1)	20	-	-	-	-	(1)	20
Kentucky	(5)	298	(4)	955	(10)	925	(19)	2,178	(5)	360	(6)	808	(8)	529	(19)	1,696
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	(1)	23	(1)	23
Missouri	-	-	-	-	(4)	83	(4)	83	-	-	-	-	(4)	64	(4)	64
Montana	(4)	48	(2)	184	(20)	1,829	(26)	2,061	(3)	32	(4)	166	(20)	1,404	(27)	1,602
New Mexico	-	-	-	-	(2)	173	(2)	173	-	-	(1)	61	(1)	73	(2)	134
North Dakota	(1)	10	-	-	(16)	563	(17)	573	-	-	(1)	10	(16)	427	(17)	437
Ohio	(2)	20	(1)	46	(12)	768	(15)	834	(2)	20	(1)	217	(11)	412	(14)	649
Oklahoma	(3)	73	(2)	53	-	-	(5)	126	(1)	38	(4)	112	-	-	(5)	150
Pennsylvania	(3)	106	(1)	267	(12)	983	(16)	1,356	(5)	109	(1)	205	(15)	1,188	(21)	1,502
South Dakota	-	-	-	-	(1)	19	(1)	19	-	-	-	-	(1)	13	(1)	13
Tennessee	(1)	46	(1)	69	(2)	64	(4)	179	(1)	35	(1)	54	(2)	50	(4)	139
Utah	(2)	161	(1)	24	(1)	21	(4)	206	(2)	126	(1)	19	(1)	16	(4)	161
Virginia	(3)	238	-	-	-	-	(3)	238	(3)	247	-	-	-	-	(3)	247
Washington	-	-	-	-	(1)	15	(1)	15	-	-	-	-	(1)	12	(1)	12
West Virginia	(6)	422	(1)	48	(16)	1,424	(23)	1,893	(8)	376	-	-	(22)	1,832	(30)	2,209
Wyoming	(1)	44	(2)	158	(10)	253	(13)	455	(2)	142	(3)	64	(8)	129	(13)	335
Total United States	(42)	2,246	(23)	2,874	(155)	10,384	(220)	15,504	(43)	2,116	(38)	3,004	(153)	8,254	(234)	13,374

1/ From Ford, Bacon & Davis report (5).

2/ Basis for classification into groups 1, 2, and 3 is explained in more detail in the text.

TABLE 15. - Data on gasification of coal

	Fixed-bed (Lurgi) gasifier			Entrained coal-dust gasifier		
	Brown coal[1]	Subbituminous[2]	Anthracite[3]	Subbituminous[4]	Bituminous[5]	Bituminous[4]
Gasification pressure..... atmospheres	26	25	23	1	1	22
Proximate analyses, wt.-percent:						
Moisture.....	20.2	9.7	-	7.3	1.1	1.5
Ash.....	4.6	26.4	26.4	11.0	15.2	14.4
Volatile matter (m.a.f.).....	52.9	33.0	8.0	53.0	37.8	38.6
Fixed carbon (m.a.f.).....	47.1	67.0	92.0	47.0	62.2	61.4
Ultimate analyses (m.a.f.), wt.-percent:						
Carbon.....	68.7	73.4	91.4	71.1	81.9	83.3
Hydrogen.....	4.7	4.7	2.9	5.1	5.1	5.6
Nitrogen.....	1.2	1.9	1.1	1.0	1.5	1.7
Sulfur.....	0.8	0.6	1.5	0.8	1.3	1.4
Oxygen.....	24.6	19.4	3.1	22.0	10.2	8.0
Materials required/1,000 cu. ft. of $CO + H_2$:						
Coal (m.a.f.)..... lb.	60	48	40	35	31	31
Oxygen..... cu. ft.	170	240	280	300	360	360
Steam..... lb.	75	65	80	5	17	12
Materials required/1,000 cu. ft. $CO + H_2$ + CH_4 equivalent:[6]						
Coal (m.a.f.)..... lb.	32	27	30	-	-	-
Oxygen..... cu. ft.	90	135	205	-	-	-
Steam..... lb.	40	37	60	-	-	-
Gas analyses, vol.-percent:						
CO_2 (includes H_2S).....	32.3	30.3	26.0	10.2	12.9	10.4
CO.....	17.4	19.5	26.3	53.2	51.1	51.6
H_2.....	37.2	38.7	40.6	34.5	34.0	32.0
CH_4.....	12.1	11.1	5.4	.1	-	-
Illuminants.....	.5	-	.2	1.0	-	1.3
N_2.....	.5	.4	1.5	.9	1.9	4.7
H_2:CO ratio.....	2.1:1	2:1	1.5:1	0.6:1	0.65:1	0.6:1
Calorific value (CO_2-free)..... gross B.t.u./cu. ft.	450	430	375	330	315	320
Yields per ton m.a.f. coal:						
Total gas..... cu. ft.	60,600	72,000	76,300	64,600	76,100	78,200
CO + H_2..... do.	33,100	41,900	51,000	56,700	64,800	65,400
CO + H_2 + CH_4 equivalent[6]..... do.	62,300	73,900	69,000	-	-	-
Methane..... cu. ft.	7,300	8,000	4,500	75	-	-
Tar..... gallons	19.6	5.4	-	-	-	-
Light oil.....do.	11.1	0.8	-	-	-	-
Thermal efficiency..... percent[7]	81	82	72	79	73	74

1/ Data from Hubmann (7, p. 174).
2/ Data from Linton and Tisdall (8, pp. 444-445).
3/ Bureau of Mines data (9).
4/ Bureau of Mines data (12).
5/ Data from Osthaus (11, pp. 261-262).
6/ CH_4 equivalent is potential CO + H_2 from CH_4.
7/ Thermal efficiency is 100 x calorific value of gas/calorific value of coal.

Coal Hydrogenation

Approximate yields of gasoline and liquefied petroleum gas that may be expected from hydrogenation of 1 ton of raw coal are shown in figure 77. The correlation of yields with rank and carbon content of the raw coal is possible because of the decrease of moisture with increase of rank and the low ash specifications for coal suitable for hydrogenation.

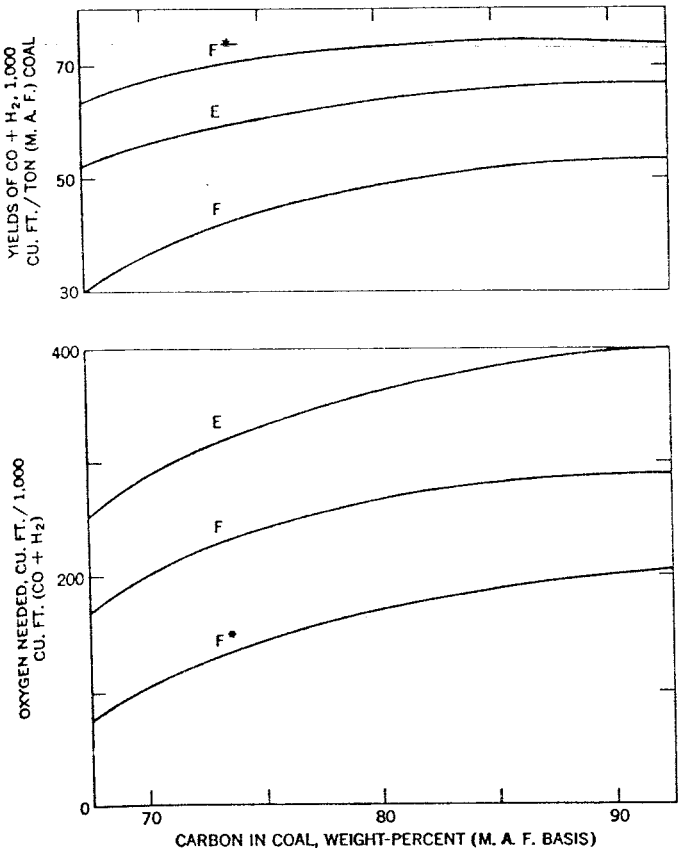

FIGURE 76. - Estimated Yields of ($CO+H_2$) and Oxygen Requirements in Fixed- and Entrained-Bed Gasification of Coal Under Pressure: E, Entrained bed; F, fixed bed; F*, fixed bed, including also methane formed expressed as $CO+H_2$ equivalent.

Typical yields of phenols from liquid-phase light oils are shown in figure 78. The quality of vapor-phase and of reformed gasoline is compared in table 16. Main process streams for a 30,000-bbl.-per-day coal-hydrogenation plant are shown in table 17 and composition of streams in table 18. Personnel and major materials requirements as estimated by the Bureau of Mines and the National Petroleum Council are listed in table 19 and the power required for the various process units in table 20. Table 21 summarizes some estimates of the cost of coal-hydrogenation gasoline. Significant differences between the Bureau of Mines-Ebasco estimates and the N.P.C. estimate as presented here are in the operating costs and in the credit taken for byproducts.

Fischer-Tropsch Synthesis

Several Fischer-Tropsch processes have been developed through the pilot-plant stage, and four have been used commercially (table 22). These processes differ in reactor design, manner of heat removal, temperature, throughput, H_2:CO ratio of the gas, and catalysts (4). The products vary accordingly (table 23). The synthesis yield varies with coal rank approximately as the yield of $CO + H_2$ varies in gasification (fig. 76). The yield per ton of total as-received plant coal has been estimated as 84 to 90 percent of the yield based on the as-received gasification coal. Approximately 27,600 cu. ft. of $CO + H_2$ is required per barrel of liquid product (10).

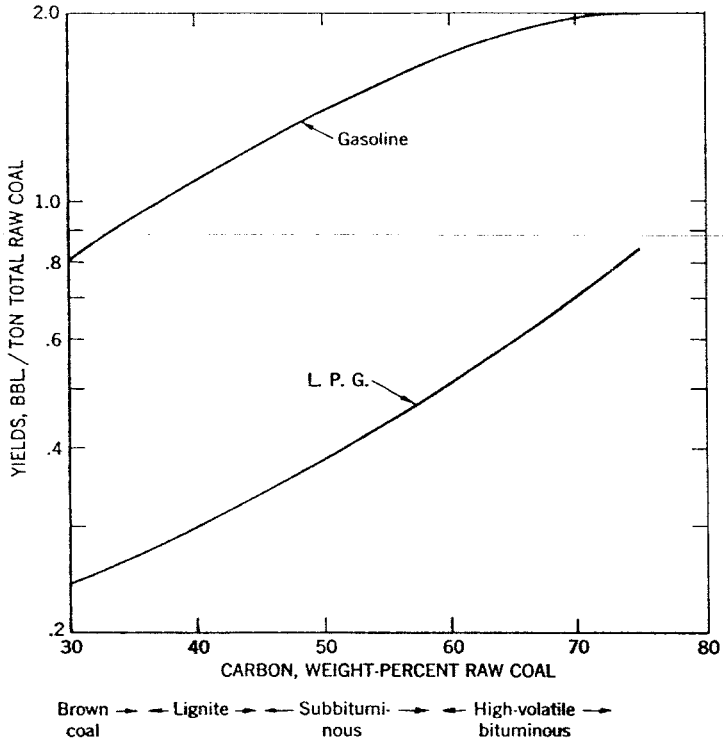

FIGURE 77. - Estimated Yields of Gasoline and Liquefied Petroleum Gas (L.P.G.) in Coal Hydrogenation.*

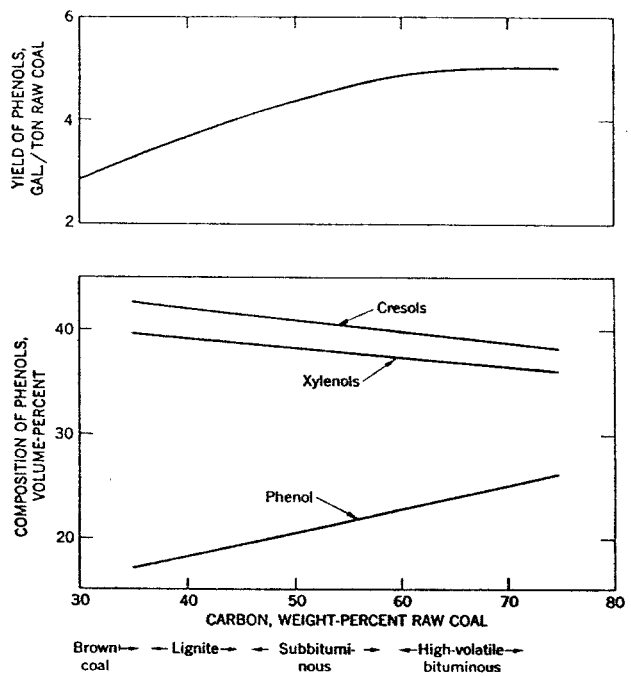

FIGURE 78. - Estimated Production of Phenol, Cresols, and Xylenols in Coal Hydrogenation.*

*For figures 77 and 78, yields shown are related to the total raw coal, as used for making hydrogen, for power, and for hydrogenation; were only the hydrogenation coal considered, the yield per ton would be approximately doubled.

The principal streams and process quantities are given in table 24 for a plant producing 30,000 bbl. of product per operating day. Operating personnel and major materials requirements are given in table 25 as estimated by the National Petroleum Council (10), and their estimate (1952) of the cost of producing gasoline by the Fischer-Tropsch process is shown in table 26.

TABLE 16. - Typical analyses of coal-hydrogenation gasolines 1/

	Vapor-phase gasoline		Vapor-phase gasoline, reformed (80-percent yield)	
Gravity..... °A.P.I.	54.1		46.2	
10 percent evaporation..... °F.	125		128	
50 percent evaporation..... do.	220		227	
90 percent evaporation..... do.	327		340	
Residue..... percent	1.0		-	
Vapor pressure..... p.s.i.	9.9		9.7	
Gum content..... mg/100 ml.	1.6		-	
Sulphur content..... percent	0.023		-	
Corrosion copper strip.....	Negative		-	
Oxygen stability..... minutes	480+		-	
Composition after removal of phenols and bases, percent:				
Aromatics.....	29.5		57.5	
Olefins.....	2.5		1.0	
Naphthenes.....	26.2		17.0	
Paraffins.....	41.8		24.5	
Aniline point..... °C.	26.4		-	
Octane number	Motor	Research	Motor	Research
Gasoline (clear).....	77.3	83.7	85.3	97.2
Gasoline + 1 ml. TEL/gal.....	84.2	90.8	-	-
Gasoline + 2 ml. TEL/gal.....	86.8	93.7	-	-
Gasoline + 3 ml. TEL/gal.....	88.9	96.2	-	-

1/ Based on unpublished reports from the Bureau of Mines Demonstration Plant, Louisiana, Mo.

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TABLE 17. - Process conditions and main flow streams estimated for a 30,000-bbl.-per-day coal-hydrogenation plant using Wyoming high-volatile C bituminous coal[1/]

Liquid phase - 700 atm., 895° F.		
Input, m.f. coal to paste	tons/hr.	241
	lb./cu. ft.-hr.[2/]	36
Catalyst (iron oxide)	tons/hr.	4.6
	percent on m.a.f. coal	2.0
Coal-oil paste	tons/hr.	552
	lb./cu. ft.-hr.	82
H_2 recycle gas	million cu. ft./hr. (83 percent H_2)	35
	cu. ft. H_2/lb. m.a.f. coal	63
Liquid effluents:		
Light oils (gasoline, naphtha, middle oil)	tons/hr.	146
	lb./cu. ft.-hr.	21.6
Light-oil bottoms	tons/hr.	194
H.O.L.D. (heavy oil)	do	185
Feed to coking unit (H.O.L.D.)	do	65
Coke product	do	28
Feed to phenols recovery	do	126.5
Naphtha	do	46.5
Middle oil	do	80
Phenols recovery	do	9.4
Vapor phase - 700 atm., 920° F.		
Light-oil feed	tons/hr.	150
	lb./cu. ft.-hr.	38.5
Recycle bottoms	tons/hr.	100
Total feed	lb./cu. ft.-hr.	64
H_2 recycle gas	million cu. ft./hr. (83 percent H_2)	24
	cu. ft. H_2/lb. total feed	48
Gasoline	tons/hr.	121
	lb./cu. ft.-hr.	31
Overall plant		
Makeup H_2	million cu. ft./hr.	10
Low-temp separation	do	1.6
Hydrocarbon gas conversion	do	3.3
Gas feed	tons/hr.	29.5
Oxygen required	do	34.7
Coal gasification	million cu. ft./hr.	5.1
Gasification coal	tons/hr. (raw)	92.5
Oxygen required	tons/hr.	74.2
Yields, bbl./day:		
Gasoline		30,000
LPG		21,670
Phenols		7,100
Indicated overall thermal efficiency	percent	1,230
		52

1/ Based on National Petroleum Council Committee Report (10).

2/ Space velocity, based on hydrogenation reactor volume.

TABLE 18. - Approximate composition of main process streams in coal hydrogenation[1/]

	Liquid phase							Vapor phase		
	Pasting oil	Coal paste	H.O.L.D.	Light oil bottoms	Gasoline	Naphtha	Middle oil	Fresh feed	Recycle bottoms	Raw gasoline
Distillation, °F.:										
Initial	583	-	485	590	83	219	390	130	376	88
10	621	-	609	639	118	349	483	243	407	134
20	649	-	647	656	139	377	505	383	419	164
50	704	-	702	696	186	404	535	504	455	225
70	-	-	-	730	214	420	555	551	-	-
90	-	-	-	-	315	455	586	600	561	329
End point	738	-	734	756	370	501	625	627	628	365
Recovery, percent	63	-	60	74	93	98	98	97	98	96
Specific gravity	1.11	1.22	1.24	1.06	-	-	-	-	-	-
°API	-	-	-	-	63.3	17.9	11.8	22.7	21.3	55.4
Benzene-insolubles	5.4	44.6	20.1	Nil.	-	-	-	-	-	-
Asphaltenes	1.7	1.9	4.3	Nil.	-	-	-	-	-	-
Tar acids, volume-percent	-	-	-	-	0.6	35.3	23.6	17.4	3.4	0.7
Tar bases, do	-	-	-	-	1.4	.5	.1	.5	.7	.7
Aromatics, do	-	-	-	-	19.2	36.5	54.7	42.8	67.5	26.2

1/ Based on Bureau of Mines data (2, and unpublished report).