INSTITUTE OF GAS TECHNOLOGY
IIT CENTER
CHICAGO, ILLINOIS 60616

PREPARATION OF A COAL CONVERSION SYSTEMS TECHNICAL DATA BOOK

OCR Contract No. 14-32-0001-1730
Report No. 3
January 1975

Project 8964 Status Report
for
OFFICE OF COAL RESEARCH

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Project Title: Preparation of a Coal Conversion Systems Technical Data Book
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I. Project Objective

The objective of this work is to provide a single, comprehensive source of data on coal conversion systems. This compilation shall be entitled The Coal Conversion Systems Technical Data Book and shall provide up-to-date data and information for the research, development, design, engineering, and construction of coal conversion processes and/or plants. Other concurrent objectives are to identify those areas where data are required and to suggest research programs that will provide the required data.

II. Summary

Liquefaction

We have started to analyze the heat-transfer coefficients involved in the heating of coal-oil slurries — an important area of coal liquefaction. OCR reports on coal liquefaction are also being reviewed and abstracted.

Gasification

Steam-oxygen gasification curves — indicating percent carbon conversion as a function of solids residence time for various operating conditions — are presented. These are based on the "solids backmixed" model.

A correction chart, which gives a multiplication factor to convert the residence time for the solids backmixed model to that for "solids plug flow" model, is also given.

Fluidization

Various correlations to estimate the minimum fluidization velocity are being evaluated using the available data for coal and other solids encountered in coal conversion processes.

Combustion

Correlations have been developed to estimate the maximum heat-transfer coefficient between a fluidized bed and a submerged surface.

Coal Properties

Penn State data are being evaluated for possible inclusion in the data book.

Miscellaneous

The initial data book outline has been extended and slightly modified.

A contact letter is being prepared to solicit gasification data from organizations active in the field.

We plan to form an advisory committee of representatives of companies engaged in coal conversion activities to review the planning and material prepared for the data book.

Notice to Readers of Open File

Any comments about the material presented in this report or suggestions about the format and the content of the data book as well as the priorities of the needed data are most welcome. Please direct any communications to Mr. Bipin Almaula of the Office of Coal Research (202/634-6643) or to Dr. Al Talwalkar of the Institute of Gas Technology (312/225-9600, extension 869).

III. Work Accomplished

A. LIQUEFACTION

1. Literature Search

We have begun a search of the technical literature on coal liquefaction to establish the current availability of data on various aspects of the coal liquefaction process. We are starting with U.S. Government OCR reports because these generally contain the latest and most complete data. A summary of some of the results of our preliminary survey is shown in Table 1. Generally speaking, much information about pilot plant designs and projected demonstration plant cost data is available for the H-COAL, COED, SRC, and SEACOKE Processes. However, the amount of published experimental data to support these designs is quite small.

2. Heating of Coal-Solvent Mixtures

In the coal liquefaction processes, the coal-solvent mixtures (slurries or pastes) must be heated to the reaction temperature, either with or without hydrogen. To minimize operating difficulties such as coke formation, high-pressure drops, and excessive tube-wall temperatures, it is essential to have some knowledge of the transport properties, heat-transfer coefficients, and general behavior of the slurries as a function of temperature. We have begun to evaluate information of this nature; the results of the initial survey are outlined below.

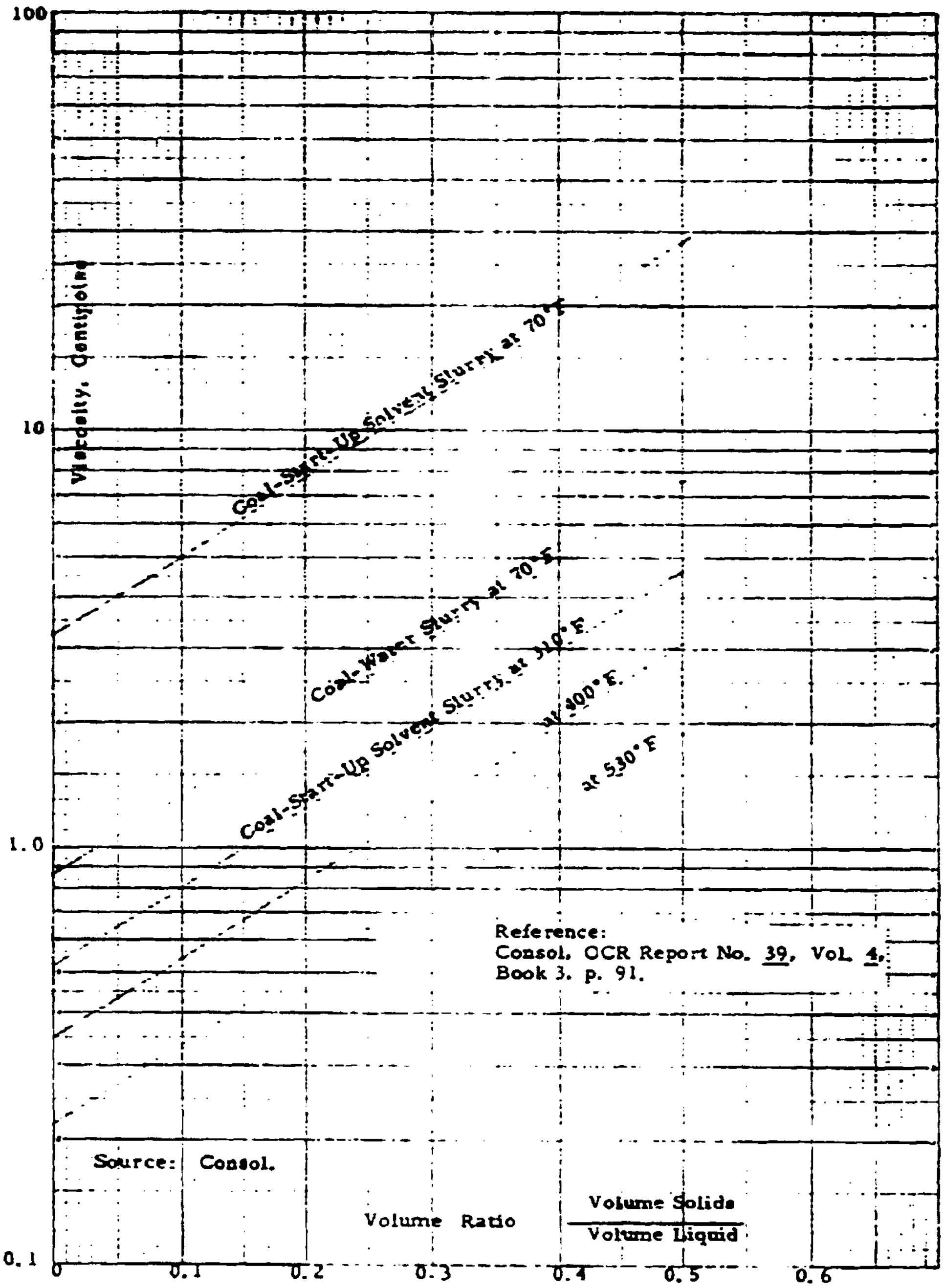
a. Viscosity

Consolidation Coal Co. determined the viscosity of coal-water slurries for its pipeline work. The results are shown in Figure 1 and were taken from Reference 4. Consol assumed that the viscosity of coal slurries with its start-up solvent would be parallel to that of the water-slurry line, starting with the viscosity of the solvent at 0% coal, at the temperatures shown: 70°, 310°, 400°, and 530°F.

Sacks et al. [5] give some determinations of viscosity of coal char-water and oil slurries at 100°F as a function of char content. They appear to be of a different order of magnitude from Consol's data, as shown in Figure 2. This may possibly be caused by the porosity of char and its ability to "soak up" the liquid.

Table 1. PRELIMINARY SAMPLE OF COAL LIQUEFACTION DATA AVAILABILITY

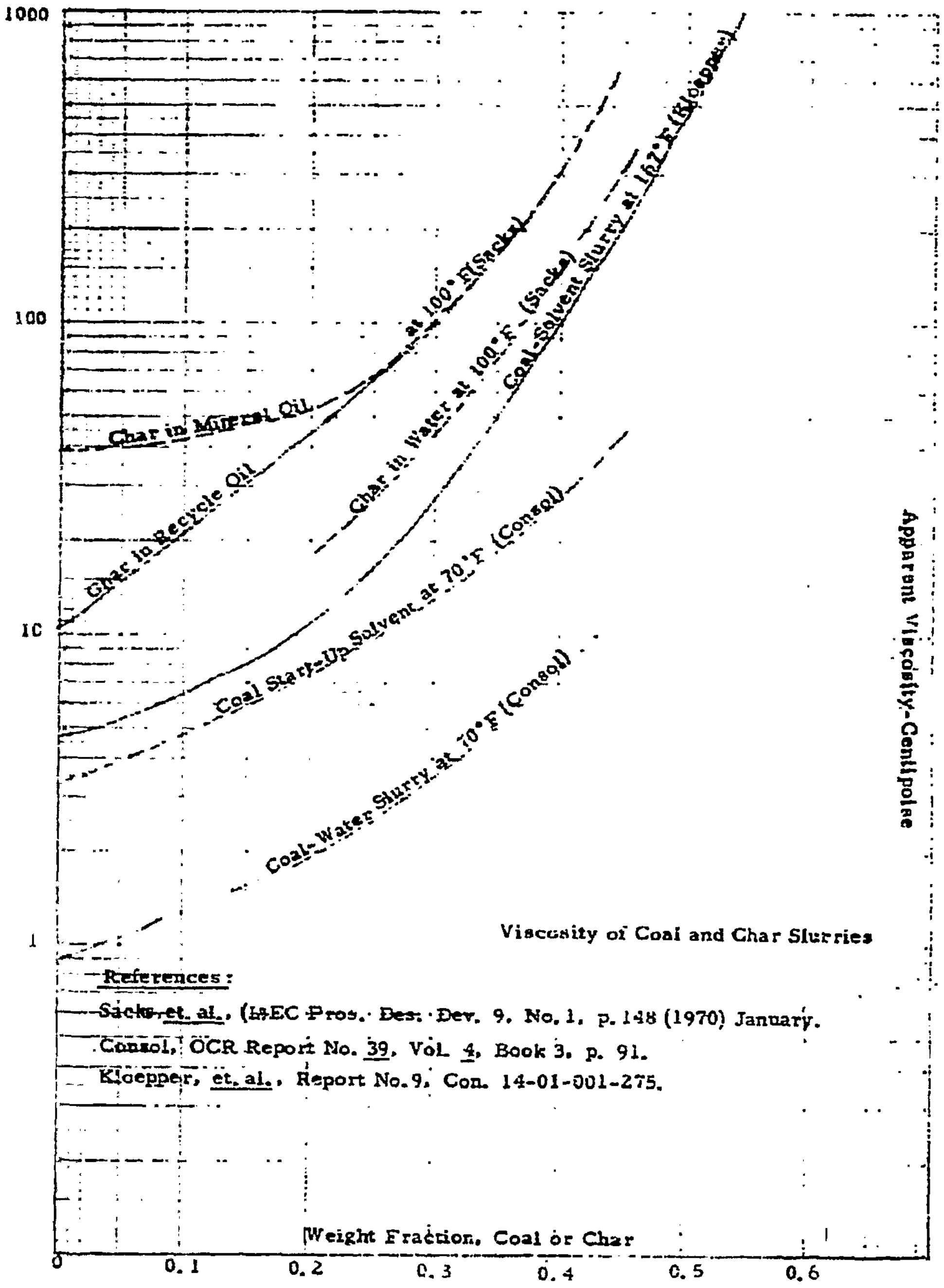
Project/Report Title	Solvent Properties	Coal Types Studied	Slurry Physical Properties and Heat-Transfer Data	Rate Data	Yield Structure	Catalyst	Product Liquid Properties	Product Gas Properties	Product Solid Properties	Solid/Liquid Separation
H-COAL										
OCR R&D Report No. 26, Project H-COAL Report on Process Development, Hydrocarbon Research Institute, no date	5 solvent types, hydrogenated and unhydrogenated	Illinois No. 6, Utah B-Seam, North Dakota lignite	Ultimate analyses, Sp Gr	Integral, deactivation data, pressure, temperature, solvent/coal ratios, catalyst type and size	Catalyst age, pressure, temperature, space velocity, catalyst size, solvent/coal ratios, recycle	Size, composition: MoO_3 + CoO on alumina; Ni-Mo on alumina	°API, % sulfur, distillation curve, gas chromatographic data, effect of hydrotreating	Composition	% sulfur	Particle size distribution, cyclone capacities
Consol Synthetic Fuel										
Final Report, Development of CSF Coal Liquefaction Process, OCR Report No. 39, Vol. 5					Solvent/coal ratio, recycle					Filtration rates, ΔP, hydroclone ΔP data, permeability filter cakes
Start-Up and Initial Operations at Cresap Pilot Plant, OCR, R&D Report No. 39, Vol. 4, Book 2	Viscosity, Sp Gr						Viscosity, carbonization data		Ash distribution	
Pilot-Scale Development of the CSF Process, OCR Report No. 39, Vol. 4, Book 1		Ireland mine	Viscosity, heater ΔP	Temperature, solvent type (integral)	Temperature, solvent type	Hydrogenation, catalyst aging	Sp Gr, viscosity, effect of hydrotreating		Size distribution, density, Fischer assay	Hydroclone ΔP, efficiency
Project Western Coal										
Final Report: Project Western Coal: Conversion of Coal Into Liquids, OCR, May 1970.		Colorado high-volatile bituminous		Batch	Temperature, pressure, catalyst/solvent ratio, H_2/coal ratio, coal size	MoO_3	Sp Gr, ultimate analyses, distillation curves, % sulfur, gas chromatograph data			
Project Seacoke										
Project Seacoke — Phase II Final Report, Catalytic Hydrotreating of Coal-Derived Liquids, OCR R&D Report No. 29, December 1966.	Anthracene, phenanthrene			Pressure, temperature, H_2/oil ratio for coal-derived liquids hydrogenation	Pressure, temperature, catalyst type (hydrogenation of coal-derived liquids)	Cobalt carbonyl, Co-Mo	Sp Gr, distillation curves, gas chromatographic data			



Reference:
Consol, OCR Report No. 39, Vol. 4, Book 3, p. 91.

Source: Consol.

Figure 1. ESTIMATED SLURRY VISCOSITY



References:

Sacks, et. al., (I&EC Pros. Des. Dev. 9, No. 1, p. 148 (1970) January.

Consol, OCR Report No. 39, Vol. 4, Book 3, p. 91.

Kloepper, et. al., Report No. 9, Con. 14-01-001-275.

Figure 2. VISCOSITY OF COAL AND CHAR SLURRIES

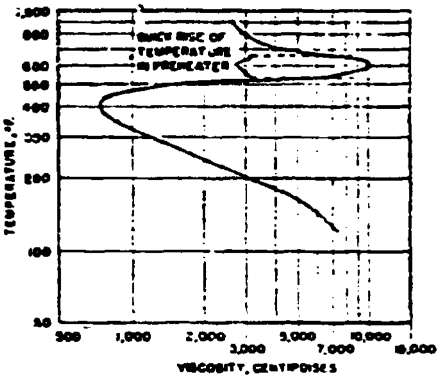


Figure 3. VISCOSITY OF COAL PASTE FEED: 36.4% COAL

Consol's viscosity data have been converted to a weight basis using a specific gravity of coal of 1.35, which was also given in the same source.

Laughrey et al.[2] and Kastens et al.[1] both show a curve for the viscosity of a coal-solvent-hydrogen mixture, with 36.4% coal by weight, as a function of temperature. This curve (Figure 3) shows a high viscosity for the coal-solvent mixture at low temperature, which decreases as the temperature rises to 400°F and then suddenly shows a sharp rise in viscosity, to a very high value, peaking at about 600°F; it then decreases again as the temperature continues to rise.

b. Heat-Transfer Coefficients – Three-Phase Systems

The coal-solvent slurry may be heated alone before being treated with hydrogen in the liquefaction reactors as in the Consol Cresap operation, or the three-component mixture, slurry plus hydrogen, may be heated as in the early German plants and as in that of the U.S. Bureau of Mines at Louisiana, Mo.

Laughrey et al.[2] and Markovits[3] both give some heat-transfer coefficients predicted for the Louisiana, Mo., operation based on German information. Just how these were arrived at was not disclosed. The plant did have sufficient instrumentation to provide meaningful data, however. Figure 4 is a copy of Markovits's preheater heat-transfer curve.

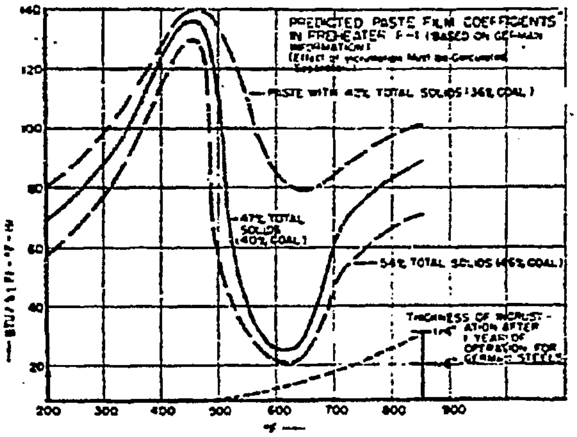


Figure 4. PREHEATER HEAT-TRANSFER CURVE[3]

These curves of paste film coefficient versus temperature are for three different concentrations of coal in the paste. These are —

Coal	Solids
wt %	
46.0	54.0
40.0	47.0
36.0	42.0

The presentation is for operation at 10,000 psi and a total fluid mass velocity in the range of 175 to 225 lb/sq ft-s with hydrogen concentration of about 10 weight percent. It should be noted that, as is to be expected, peaks and valleys of the viscosity curve are 180 degrees out of phase with the heat-transfer coefficient curves (Figure 4).

c. Heat-Transfer Coefficients — Two-Phase Systems

As mentioned above, in Consolidation Coal's Cresap operation, as distinct from the German and Bureau of Mines' very high-pressure operation, coal-solvent slurries are heated without hydrogen being present. Consol operated with a range of solvent-to-coal ratios, although most of the runs were made with slurries containing 25% by weight of coal. Many runs are reported in OCR Report No. 39, Vol. IV, Books 2 and 3.[4] The results of these runs are given, but, unfortunately, although metal-skin temperatures were taken at three locations on the heating coil, the only bulk temperatures actually read were the preheater inlet and outlet temperatures. As part of this month's work, these data have been analyzed to determine heat-transfer coefficients. The heat duty to the coil in each run was calculated, and the overall heat flux determined. Then, assumptions were made about the distribution of heat flux and temperature rise along the length of the coil. Taking into account the thickness of the tubes, and the thermal conductivity of the metal wall, the inside heat-transfer coefficient was calculated for each point where the tube-metal temperature was measured. The overall averages for the four different slurry concentrations treated, 17.6%, 25.0%, 31.9%, and 40.0% by weight of coal, were as follows:

No. of Runs	Coal, wt %	Average G, lb/sq ft-s	Average Temperature, °F	Average h, Btu/hr-sq ft-°F
1	17.6	433	382	68
			579	93
			742	126
47	25.0	412	377	72
			569	74
			747	177
7	31.9	406	391	69
			589	67
			751	157
12	40.0	391	383	61
			577	60
			738	186

Attempts were made to correlate the effect of the variables without notable success. The heat-transfer coefficients, although rather widely scattered, are apparently nearly the same for the two lower temperature ranges, whereas they are very much higher in the 750°F temperature range. There does appear to exist a slight effect of both temperature and mass velocity within the broader temperature ranges.

Further work on the matter of slurry heating will be carried out along the lines of –

1. Availability of any further basic data on the transport properties of both the two-phase and the three-phase systems, as a function of the variables, particularly of temperature, will be investigated.
2. An effort will be made to see [illegible] definite data can be obtained relative to the performance of the Bureau of Mines' paste preheater at Louisiana, Mo.
3. Investigation will be made as to what good heat-transfer data are available on other pilot plants and process development units.

3. References Cited

1. Kastens, M. L., *et al.*, "Liquid Fuel From Coal," *Ind. Eng. Chem.* *41*, 870-85 (1949) May.
2. Laughrey, P. W., *et al.*, "Design of Preheaters and Heat Exchangers for Coal-Hydrogenation Plants," *Trans. ASME* *72*, 385-91 (1950) May.
3. Markovits, J. A., "Coal Hydrogenation, Summary of Process and Brief Description of Special Equipment Used in Demonstration Plant at Louisiana, Missouri," *Mech. Eng.* *71*, 553-60 (1949) July.
4. "Pilot-Scale Development of the CSF Process" Vol. *IV*, Books 2 and 3, *U. S. Office of Coal Research R&D Rept.* No. *39*, *Int. Rep. 6.* Washington, D. C.: U. S. Government Printing Office, 1971; PB 234 131/AS. (Springfield, Va: National Technical Information Service, 1971.)
5. Sacks, M. E. *et al.*, "Some Pumping Characteristics of Coal Char Slurries," *I&EC Proc. Des. Dev.* *9*, 148-53 (1970) January.

B. GASIFICATION

The computations based on IGT kinetic data[1] for steam-oxygen gasification in a fluidized-bed reactor were continued.

Figures 5 and 6 give the solids residence time required for a given percent conversion for various steam and oxygen amounts in the feed gas at 70 atmospheres and 15 atmospheres, respectively. The following assumptions apply in the development of those charts:

1. The solids are totally backmixed.
2. The gases are totally backmixed.
3. The relative reactivity of the char = 1.0. (The Ireland mine bituminous char is assigned a reactivity of 1.0.)

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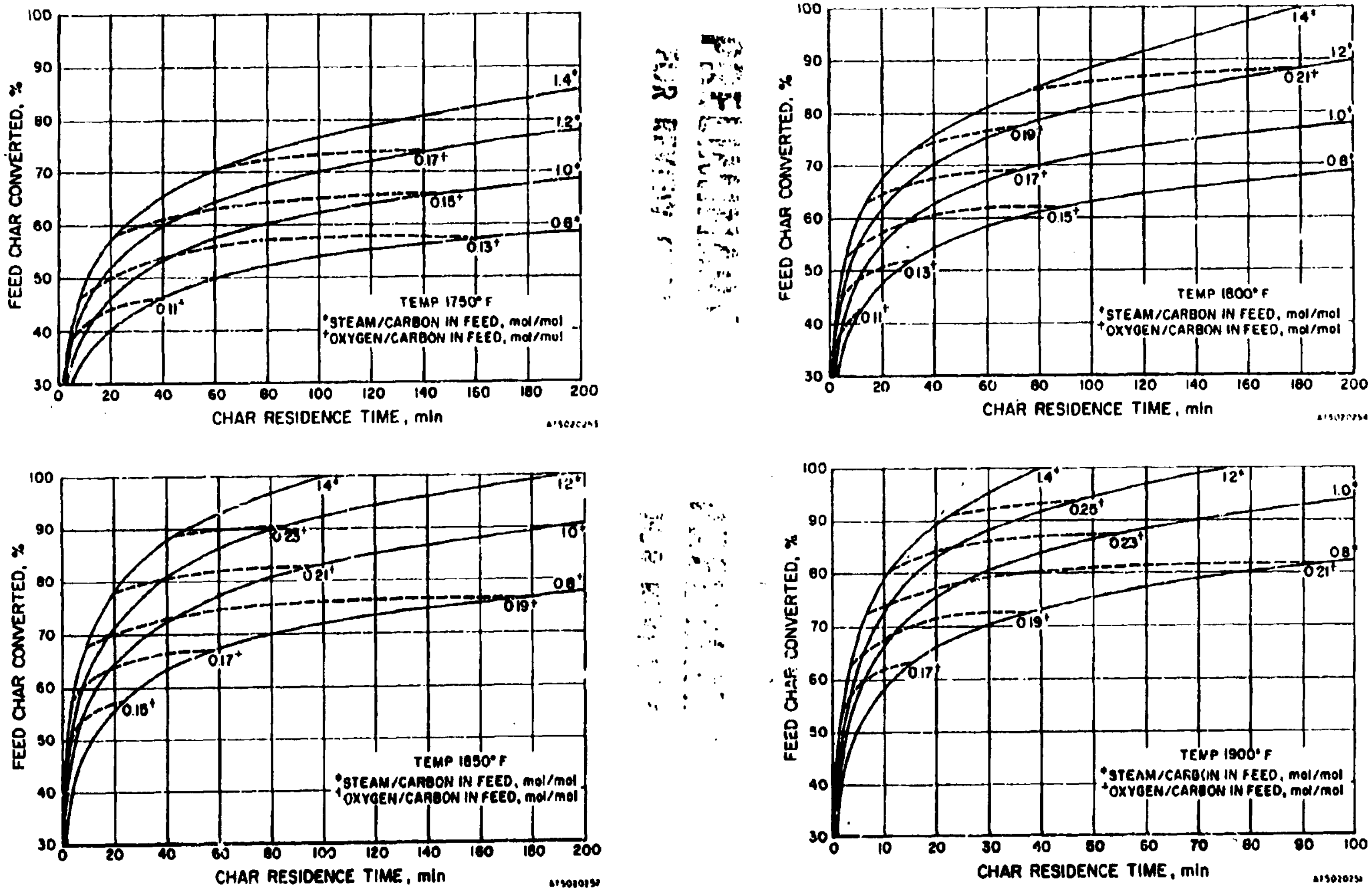

Figure 5. STEAM-OXYGEN GASIFICATION OF DEVOLATILIZED IRELAND MINE BITUMINOUS CHAR AT VARIOUS TEMPERATURES AND AT 70-atm PRESSURE

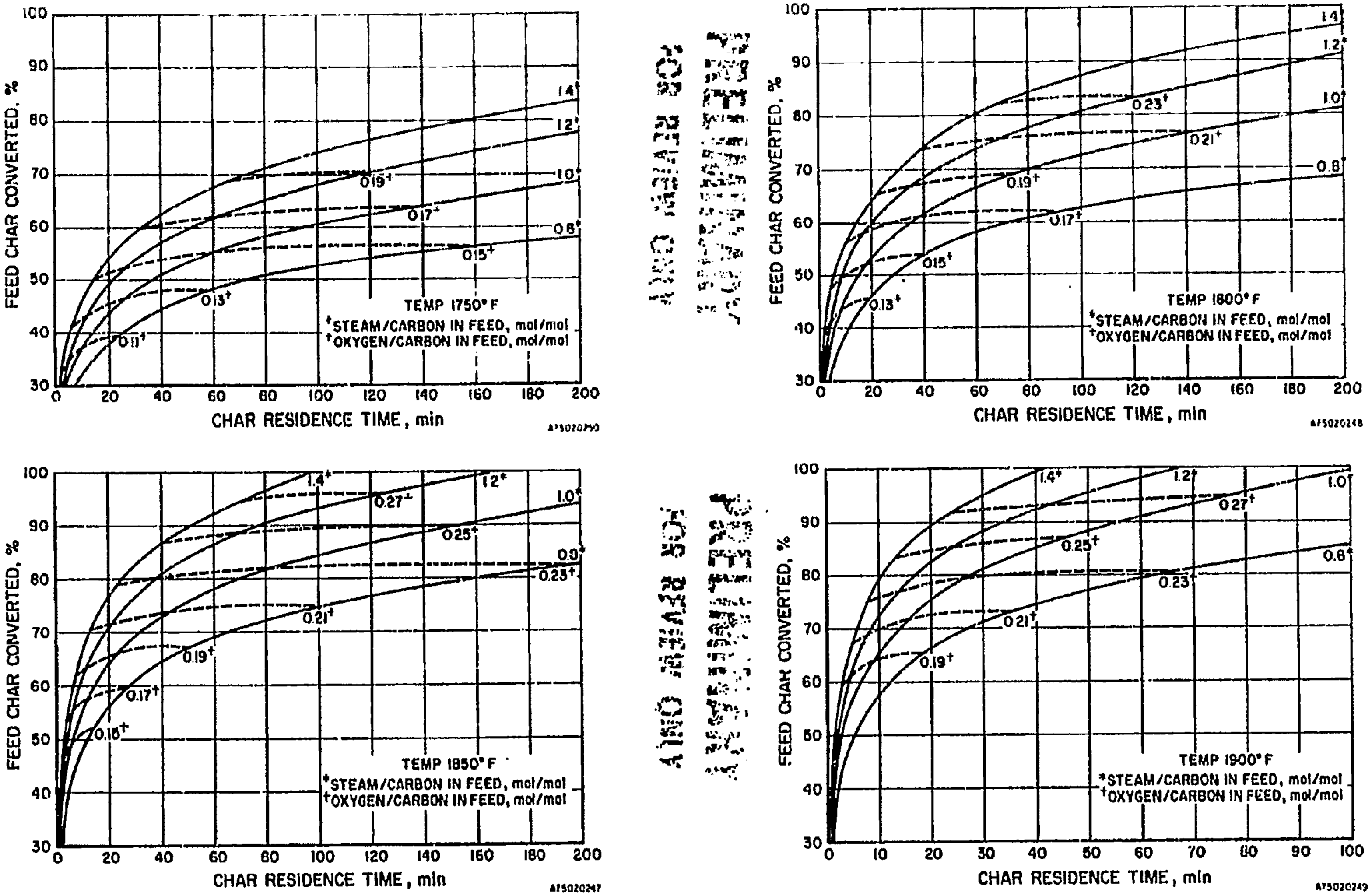

Figure 6. STEAM-OXYGEN GASIFICATION OF DEVOLATILIZED IRELAND MINE BITUMINOUS CHAR AT VARIOUS TEMPERARES AND AT 15-atm PRESSURE

4. The feed to the reactor is devolatilized char. (That is, all volatile matter is removed and none of the fixed carbon of the original coal has been gasified.)
5. The water-gas shift reaction is at equilibrium at the reactor operating temperature.
6. The reactor is adiabatic, and there are no heat losses.

This model can be extended to the case where the solids are in plug flow, with the aid of Figure 7. Here, the multiplication factor R, to convert the residence time for "backmixed solids" model to that for the "plug flow solids" model, is plotted as a function of initial and final carbon conversion of the char.

Another correction chart, to account for the fact that the initial fixed carbon conversion of the feed char may not be equal to zero,* is being prepared.

The calculations for the gas compositions as a function of various operating variables are completed. These additional charts and the details of computations will be presented in next month's report.

Reference Cited

1. Johnson, J. L., "Kinetics of Bituminous Coal Char Gasification With Gases Containing Steam and Hydrogen," in Coal Gasification, ACS Advances in Chemistry Series No. 131, 145-78 (1974).

C. FLUIDIZATION

Available data on minimum fluidization velocities (U_{mf}) for coal and other solids pertinent to coal conversion processes were collected. A number of U_{mf} correlations are being evaluated for their ability to predict the minimum fluidization velocities for these materials.

The information collected is presented below. The evaluation of correlations will be presented next month.

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* That is, the feed may be a partially gasified, devolatilized char.

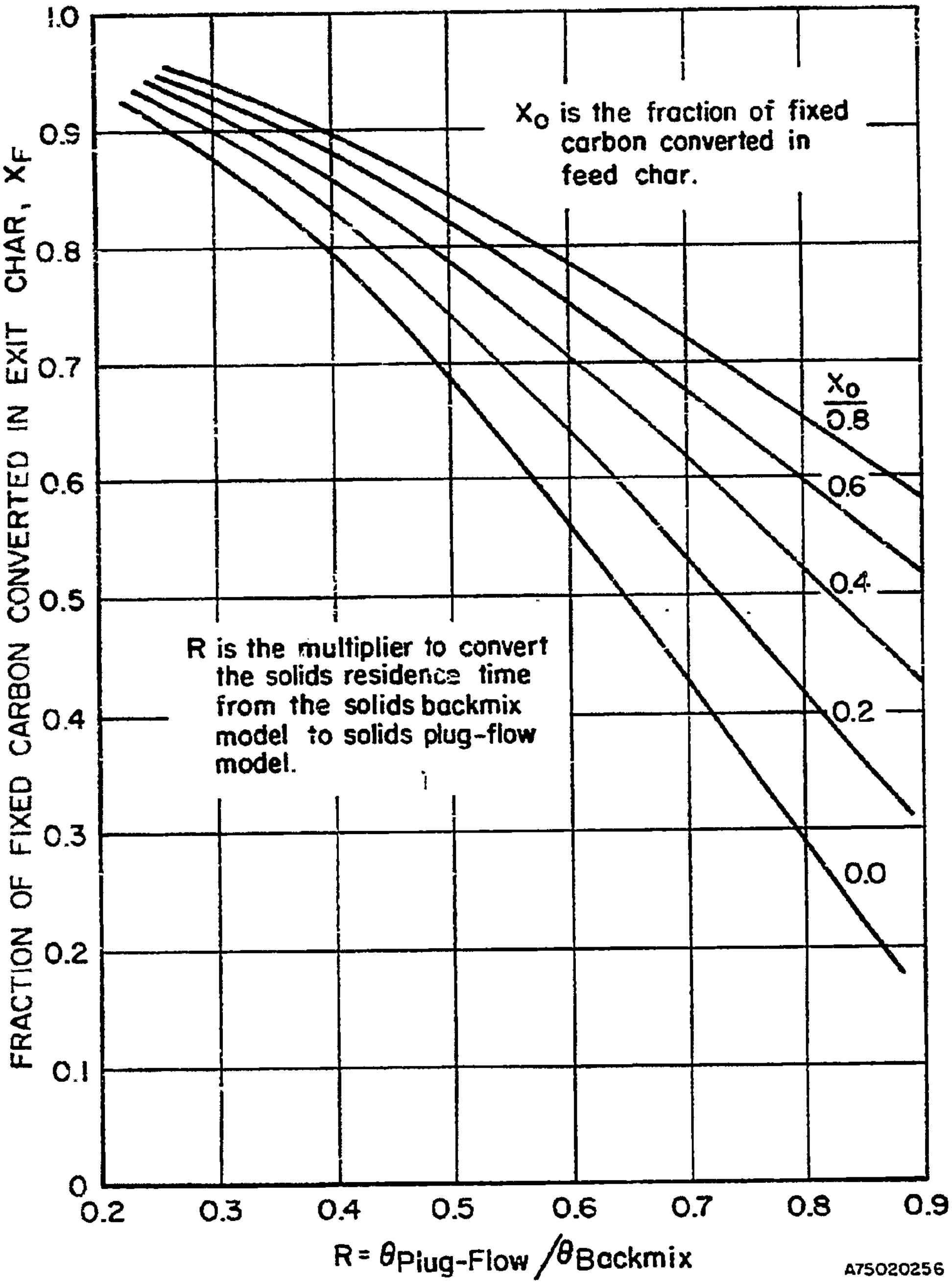

Figure 7. CONVERSION FACTOR FOR PLUG-FLOW MODEL

PRELIMINARY
FOR REVIEW ONLY

Minimum Fluidization Velocity

Although the definition of minimum or incipient fluidization velocity is subject to varying interpretations, it continues to be a fundamental measure of fluidization. In the design of fluidized beds, it is essential to determine the gas flow rate at which a given material begins to fluidize, and this, in general, corresponds to the conditions when the specific bed weight equals the pressure drop across the bed. The entire mathematical procedure of two-phase theory to predict the performance of fluidized beds is based on a measure of the minimum fluidization conditions. The minimum fluidization velocity is closely related to defining the desirable purge velocity in stand pipes.

At low pressures and with dense materials, only a fraction of the bed will appear to approach fluidization at the minimum fluidization velocity, while the remaining volume remains undisturbed. Consequently, parameters like "complete" or "fully supported" fluidization and "minimum bubble velocity" are being used in the literature to characterize total transition from a fixed to a fluidized bed. Because these alternative measures of fluidization are still being described qualitatively, the published correlations to estimate the minimum fluidization velocity continue to be indispenable in the design and operation of fluidized beds.

The evaluation of published correlations is extensively discussed in the literature.[8, 10, 15] Some of the generally used correlations, shown in Table 2, were used to calculate the minimum fluidization velocity of coals and related materials. Table 3 is a summary of the sources of experimental data used to compare with the calculated values. A comparison of the relative accuracy of the various correlations is being prepared.

Nomenclature (for Table 2)

D_f = Particle Diameter of Sieved Fraction, ft

D_p = Average Particle Diameter, ft $= \frac{1}{\Sigma\ (X/D_f)}$

g = Gravitational Constant, ft/s^2

Table 2. SOME PUBLISHED CORRELATIONS TO PREDICT MINIMUM FLUIDIZATION VELOCITY

Investigators	Bed Diameter, inches	Fluidized Solids	Particle Diameter, inches	Fluidizing Medium	Proposed Correlation
Leva [8]	2, 5 and 4	Sand, anthracite coal, iron catalyst	0,002 to 0,04	He, air, CO_2	$U_{mf} = \frac{0,00088\ D_p^{1,82} (\rho_s - \rho_g)^{0,94}\ g}{\rho_g^{0,06}\ \mu^{0,88}}$
Zenz [14]	--	--	--	--	Graphical Correlation (Figure 1)
Wen and Yu [13]	4	Sand and steel balls	0,08-0,25	Water	$U_{mf} = \left(\frac{\mu}{\rho_g \cdot D_p} \right) \left\{ \left[(33,7)^2 + \frac{0,0408}{\mu^2} \cdot D_p^3\ \rho_g\ (\rho_s - \rho_g)\ g \right]^{1/2} - 33,7 \right\}$
Frantz [4]	2, 4, and 6	Sand and catalysts	0,002 to 0,012	Air	$U_{mf} = 0,001065\ g \cdot D_p^2\ (\rho_s - \rho_g)/\mu$
Kunii and Levenspiel [7]	--	--	--	--	$U_{mf} = \frac{(\phi\ .\ D_p)^2}{150} \cdot \frac{\rho_s - \rho_g}{\mu}\ .\ g \left(\frac{\epsilon_{mf}^3}{1 - \epsilon_{mf}} \right)$ for $Re_p < 20$ $U_{mf} = \left[\frac{\phi\ .\ D_p}{1,75} \cdot \frac{\rho_s - \rho_g}{\rho_g}\ .\ g\ .\ \epsilon_{mf}^3 \right]^{1/2}$ for $Re_p > 1000$ $\frac{1,75\ D_p\ \rho_g}{\phi\ \epsilon_{mf}^3}\ U_{mf}^2 + \frac{150\ (1 - \epsilon_{mf})}{\phi^2\ \epsilon_{mf}^3}\ U_{mf} = \frac{D_p^2\ (\rho_s - \rho_g)\ g}{\mu}$ for $20 < Re_p < 1000$

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Table 3. SOURCES OF FLUIDIZATION DATA FOR COALS AND RELATED MATERIALS

Investigators	Bed Diameter, in.	Fluidized Solids	Particle Diameter, in.	Particle Density, lb/cu ft	Shape Factor	Fluidizing Medium	Operating Temperature, °F	Operating Pressure, psig
Agarwal and Storrow[1]	1.64	Coal	0.0124-0.022	82-83	0.67	Air	70-80	0
Lova *et al.*[9]	4.0	Anthracite	0.002-0.04	122-123	--	He, air	70-80	0
van Heerden *et al.*[12]	3.35	Coke, iron oxide (Fe_3O_4)	0.0037-0.0026	112-323	--	H_2, air, CO_2, Ar	70-80	0
Jones *et al.*[5]	3	Coal, char	0.0055-0.0189	71-80	--	CO + H_2, steam	70-80	2-5
Curran and Gorin[2]	1, 2	Lignite, char, dolomite, periclase	0.0028-0.0173	51-122	--	N_2, H_2, CO_2	70-80	0
Feldmann *et al.*[3]	3.69	Char	0.0052-0.113	16-23	--	CO_2	70-80	0
Tarman *et al.*[11]	2.5	Iron ore	0.0048-0.0053	245	0.74	Air, CO_2, H_2, Freon	70-80	0-100
Knowlton[6]	11.5	Coal, char, lignite, siderite	0.0096-0.0113	73-245	--	N_2	70-80	0-1000

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Re_p = Particle Reynold's Number = $(D_p \cdot U_{mf} \cdot \rho_g / \mu)$

U_{mf} = Minimum Fluidization Velocity, ft/s

X = Weight Fraction of Sieved Particles

ϵ_{mf} = Voidage of Minimum Fluidized Bed

ϕ = Shape Factor

ρ_g = Density of Fluidizing Gas, lb/CF

ρ_s = Particle Density of Fluidizing Solids, lb/cu ft

μ = Viscosity of Fluidizing Gas, lb/ft-s

References Cited

1. Agarwal, O. P. and Storrow, J. A., "Pressure Drop in Fluidized Beds – Part I," *Chem. Ind. (London)*, 278-86 (1951) April 14.

2. Curran, G. P. and Gorin, E., "Studies on Mechanics of Fluo-Solids Systems," prepared for Office of Coal Research, *Contract No. 14-01-0001-415*, *Interim Report* No. *8*, Book 1. Washington, D. C., 1970.

3. Feldmann, H. F., Kiang, K. and Yavorsky, P.," Fluidization Properties of Coal Char," Symposium on Gasification of Coal 162nd National Meeting, *ACS Division of Fuel Chemistry Preprints 15*, (3), 62-76 (1971) September.

4. Frantz, J. F., "Minimum Fluidization Velocities and Pressure Drop in Fluidized Beds," *Chem. Eng. Progr. Symp. Ser.* *62*, 21-31 (1966).

5. Jones, J. F., Eddinger, R. T. and Seglin, L., "Pyrolysis of Agglomerating Coals in Multiple Fluidized-Bed Reactors," in *Proceedings of the International Symposium on Fluidization*. Amsterdam: Netherlands Univ. Press, 1967.

6. Knowlton, T. M., "High-Pressure Fluidization Characteristics of Several Particulate Solids: Primarily Coal and Coal-Derived Materials." *Paper* No. *9b*, presented at the 67th Annual Meeting of the A. I. Ch. E., Washington, D. C., December 1-5, 1974.

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12. van Heerden, C., Nobel, A. P. P. and van Krevelen, D. W., "Studies on Fluidization I — The Critical Mass Velocity," Chem. Eng. Sci. 1, No. 1, 37-49 (1951).

13. Wen, C. Y. and Yu, Y. H., "Mechanics of Fluidization," Chem. Eng. Progr. Symp. Ser. 62, 100-11 (1966).

14. Zenz, F. A., "Calculate Fluidization Rates," Pet. Refiner 36, No. 8, 147-55 (1957).

15. Zenz, F. A. and Othmer, D. F., Fluidization and Fluid Particle Systems, New York: Reinhold, 1960.

D. COMBUSTION

Low-Temperature (Fluidized-Bed) Combustion

Heat Transfer in Fluidized Beds

The heat-transfer coefficient, h, between a fluidized bed and a submerged surface increases rapidly as the gas velocity (U_g) is increased from the minimum fluidization velocity until a maximum value of h is reached at U_{max}. The heat-transfer coefficient then remains practically constant before dropping off after about 3 U_{max}. There are insufficient data at higher flow rates to permit general definition of the velocity at which h falls off significantly. But this may reflect regions of operation that are of little interest.

The velocity at which h reaches h_{max} appears to depend primarily on the solid and gas properties and can be described through two dimensionless variables, the Reynold's number (Re) at U_{max} —

$$(Re)_{max} = \rho_g U_{max} d_p / \mu_g \qquad (1)$$

and the Archimedes' number (Ar) —

$$\mathrm{Ar} = g(\rho_s - \rho_g)\ \rho_g\, d_p^{\ 3} / \mu_g^{\ 2} \qquad (2)$$

where —

ρ_s is the density of the solid particles.

ρ_g is the density of the gas phase.

μ_g is the viscosity of the gas.

d_p is the effective diameter of the particles.

g is the acceleration due to gravity.

In Figure 8 the relation between these parameters is presented based on data[3,5,6] covering the following ranges with air or combustion products:

d_p: 0.0055 to 0.37 inch (0.14 to 9.5 mm)

ρ_s: 125 to 500 lb/cu ft (2000 to 8000 kg/m^3)

Temperature: 77° to 1922°F (25° to 1050°C)

For comparison, the Reynold's number at minimum fluidization (based on a void fraction of 0.43 at that condition) is also shown.

The gas velocity range at which less than h_{max} occurs is negligible at high values of Ar. For a typical fluidized-bed combustion system, Ar $\simeq$600 to 4000. The gas velocity may be varied by a factor of 2 to 4 between minimum fluidization and achieving h_{max}. But in reported practice, with loadings of 10^6 Btu/ft^2-hr (3 MW/m^2), the gas velocities are in excess of U_{max}.

In the region between U_{mf} and U_{max}, the heat-transfer coefficient increases rapidly from a value similar to forced convection (~5 Btu/hr-ft^2-°F; 30 W/m^2-K) to the high values characteristic of fluidized beds. Many correlations, dependent on the characteristics of the fluidized bed, have been offered, but as shown in Bright and Smith's [2] analysis, the precision is not adequate for design use. These correlations require bed-expansion data the lack of which may be a major limitation in their application. A correlation based on minimum fluidization velocities, U_{max}, and h_{max} may be more useful and could not be much worse than those analyzed by Bright and Smith.

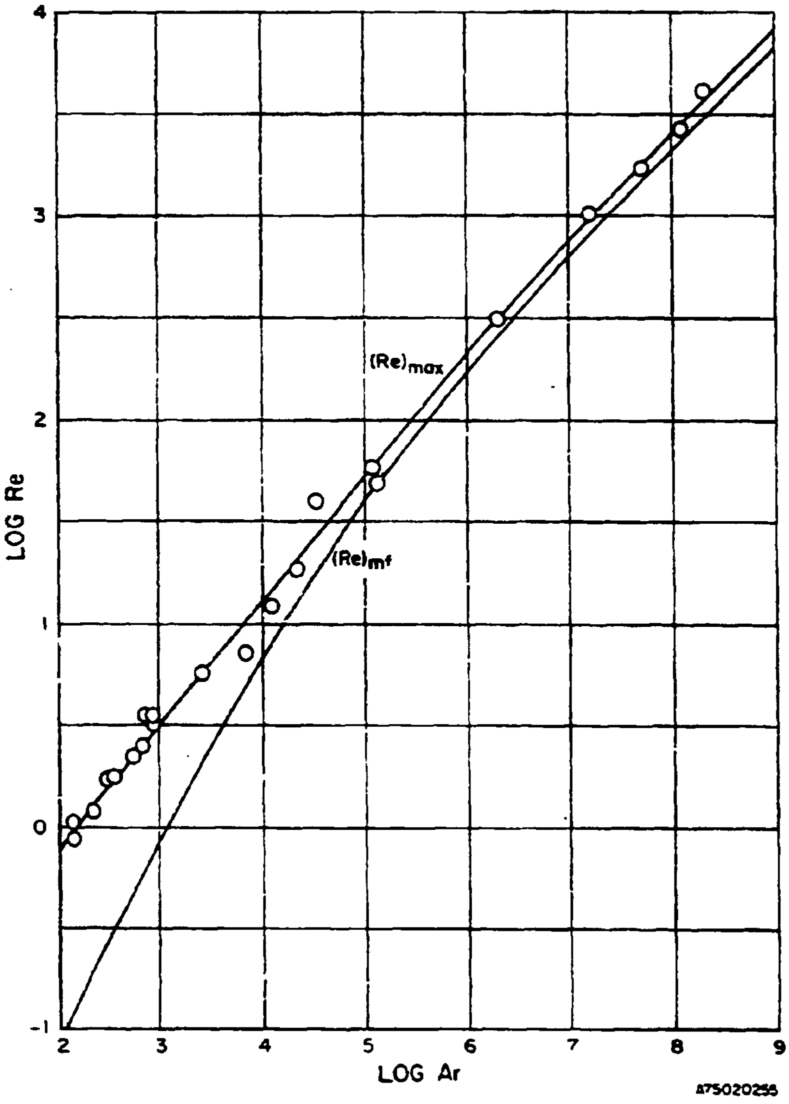

Figure 8. CORRELATION BETWEEN THE REYNOLD'S NUMBER AT WHICH THE HEAT-TRANSFER COEFFICIENT ACHIEVES A MAXIMUM AND THE ARCHIMEDES' NUMBER

The general estimation of h_{max} from gas and solid properties was examined. Proposed correlations based solely on Ar [3] proved unsatisfactory for smaller particles and for high-temperature systems. The correlation given by Zabrodsky[8] relates the h_{max} to —

$$\rho_s^{0.2}\ k_g^{0.6}\ d_p^{-0.36} \qquad (3)$$

This function, emphasizing the gas thermal conductivity, k_g , and de-emphasizing the viscosity and density terms in Ar, is much more successful in extreme cases such as hydrogen fluidized systems. In Figure 9, Zabrodsky's correlation, somewhat modified from his strict proportionality, is shown for conditions covering the ranges[5, 9] —

ρ_s: 55.9 to 435.4 lb/cu ft (900 to 7000 kg/m^3)

k_g: 0.015 to 0.1076 Btu/ft^2-hr-°F/ft (0.026 to 0.186 W/m^2-K/Ar)

d_p: 0.00236 to 0.06535 inch (0.06 to 1.66 mm)

Temperature: 77° to 1922°F (25° to 1050°C)

For large particles, a different heat-transfer mechanism becomes dominant, and this correlation is no longer appropriate. This correlation does not apply if —

$$\left.\begin{array}{l} \rho_s^{0.2}\ k_g^{0.6}\ d_p^{-0.36} < 7 \text{ (SI units)} \\ \text{and} \\ d_p \le 1.5 \text{ mm.} \end{array}\right\} \qquad (4)$$

As seen in Figure 9, there appears two rather distinct correlating lines. In each group, wide-temperature and particle-size ranges are involved. A tentative suggestion is that the lower values of h_{max} appear to be associated with the more porous particles. In any case, the discrepancy, corresponding to a factor of 0.74, seems to be real.

The lines drawn in Figure 9 correspond to the equations —

a. $h_{max} = 28.0\,(\rho_s^{0.2}\ k_g^{0.6}\ d_p^{-0.36})^{1.12}$ (SI units)

$h_{max} = 21.4\,(\rho_s^{0.2}\ k_g^{0.6}\ d_p^{-0.36})^{1.12}$ (British units)

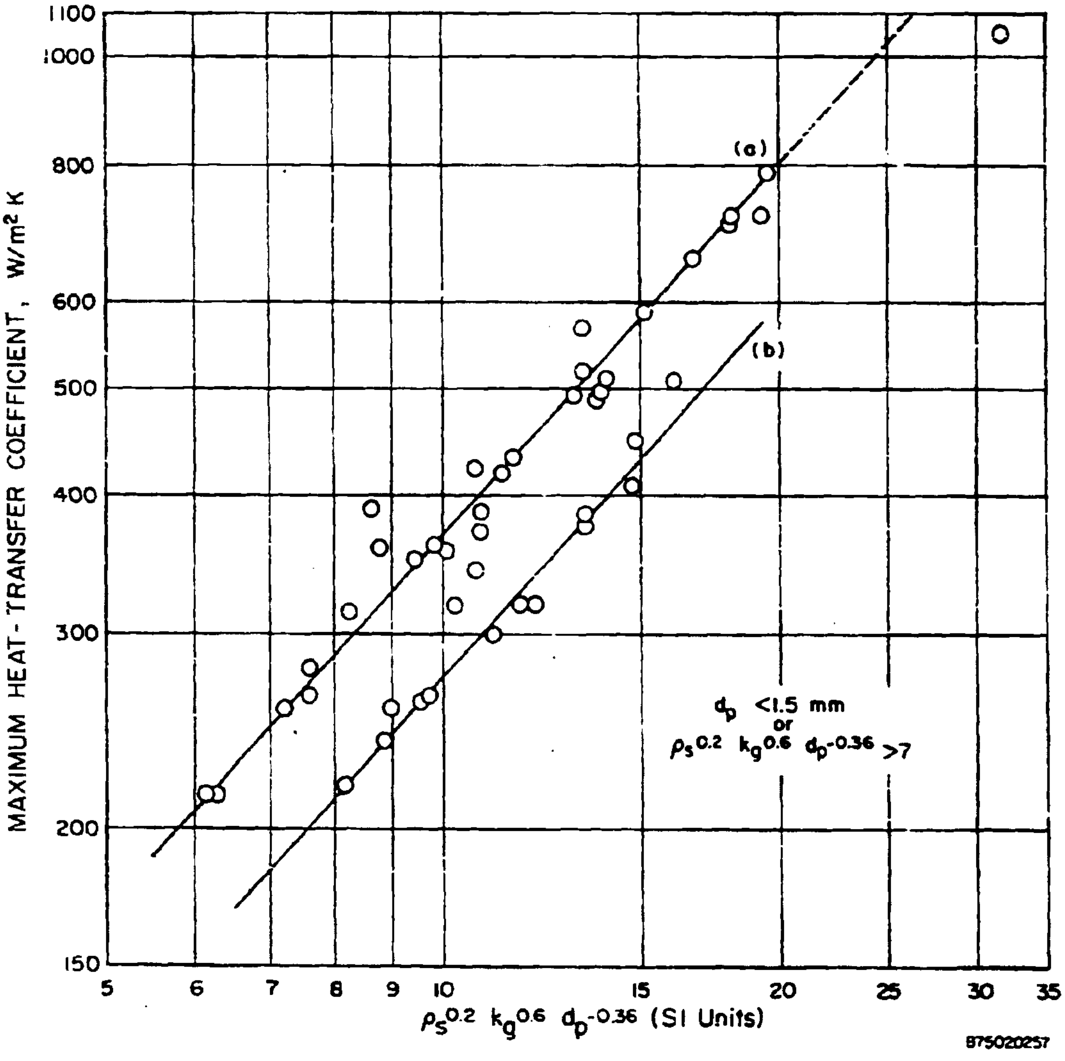

Figure 9. CORRELATION OF THE MAXIMUM HEAT-TRANSFER COEFFICIENT WITH ZABRODSKY'S PROPOSED FUNCTION FOR SMALLER PARTICLES

b. $h_{max} = 20.7 (\rho_s^{0.2} k_g^{0.6} d_p^{-0.36})^{1.12}$ (SI units)

$h_{max} = 15.8 (\rho_s^{0.2} k_g^{0.6} d_p^{-0.36})^{1.12}$ (British units)

The highest point shown corresponds to hydrogen as fluidizing gas and leaves uncertain the linearity at these extreme cases.

For larger particles, with a smaller available data base,[6,9] the maximum particle Nusselt number has been shown to relate to Ar, but over the small range of gases studied, Zabrodsky's function could do just as well. For the range of conditions –

ρ_s = 59.1 to 702.8 lb/cu ft (950 to 11,300 kg/m^3)
d_p = 0.05906 to 0.5079 inch (1.5 to 12.9 mm)
Temperature = 77° to 302°F (25° to 150°C)

the following equation describes h_{max} with a precision of 5% for the range constrained by (4):

$h_{max} = 1.86 \times 10^4 \rho_s^{0.36} k_g^{1.78} d_p^{0.15}$ (SI units)

$h_{max} = 1.97 \times 10^4 \rho_s^{0.36} k_g^{1.78} d_p^{0.15}$ (British units)

The dependence on thermal conductivity was assigned from only two conditions in this heat-exchange region.

The data base for the above correlating procedures is very limited. The effect of pressure is not included. Low-density gases such as hot flue products and hydrogen appear to work. Liquid fluidized beds appear to behave as if in the large particle region described above. Thus, it is possible that with increasing pressure and volume heat capacity of the fluid, the boundary between the two regions may be displaced to lower particle diameters.

The data also overwhelmingly are based on narrow particle-size ranges, probably on only a two- to fourfold variation at most.

The bulk of these data was taken under conditions where the heat exchange did not affect the flow patterns. There are many studies that used more realistic heat-exchanger elements or systems. Such information has not been utilized directly in developing the correlation presented here because of inadequate definition of system properties or of gas-velocity dependence. Tube bundles that tend to baffle and restrict the fluidizing bed tend to lower the heat-transfer coefficient, the effect being dependent on spacing and orientation. Where the bed is maintained in a fluidized state, the heat-transfer coefficient is affected by less than 20% with tube spacings comparable to tube diameters.[1,3] There is some confusion on the effect of tube orientation (for example, vertical versus horizontal) as discussed by Archer.[1] An arrangement that causes channeling or defluidization would have major consequences on the state of the bed and the heat transfer.

The work of BCURA Laboratories[4,7] on fluidized-bed combustion was carried out in reactors containing practical exchangers and approaching industrially acceptable loadings; this work reports experimental heat-transfer coefficients. They correlate their values in terms of the sum of a convective coefficient and a radiation coefficient. The latter is computed with the assumption of blackbody radiation exchange between the bed and the heated surface.

To compare these data with those of the correlation presented in Figure 9, the total h was recalculated from their correlating curve[4] for the convective term and the radiation term for the 1500°F and 5-atm system studied. For the higher temperature systems,[7] the total values were reported. In Table 4 the values obtained from the BCURA work are compared with those estimated from curves (a) and (b) in Figure 9.

For these calculations, a particle density of 1960 kg/m^3 was used. A reported bed density of about 850 kg/m^3, if it refers to a nonfludized state, would indicate a much lower density and a significantly porous solid. The estimated values with curve (b) are in good agreement with the measured values. The one bad point ($dp = 0.25$ mm) disagrees with BCURA's correlation. If there is a misreported value, it would have to be the average particle diameter to account for the discrepancy.

These results appear to substantiate the use of curve (b) in the correlation for fluidized-bed combustion systems up to pressures of at least 5 atm and for realistic heat-exchanger tube configurations.

Table 4. HEAT-TRANSFER COEFFICIENTS FOR FLUIDIZED-BED COMBUSTION FROM BCURA LABORATORIES

				Estimated	
Reference	U_g/U_{max}	d_p, mm	h, W/m^2-K	h_{max} (a)	h_{max} (b)
4	3.8	0.3	450	660	490
4	2.6	0.5	410	550	410
4	2.0	0.7	370	500	370
4	1.2	1.3	285	375	275
7	3	0.5-0.6	420	570	420
7	3	0.25	385	770	570
7	3	0.45	395	590	440

References Cited

1. Archer, D. H. et al., Evaluation of Fluidized-Bed Combustion Process, Vol. II, 109. Springfield, VA: National Technical Information Service, 1970. (PB 212960)

2. Bright, A. and Smith, K. A., "Heat Transfer in Fluidized Beds," Final Report prepared for the National Air Pollution Control Administration, Contract No. CPA-22-69-44. Cambridge, Mass.: Massachusetts Institute of Technology, Department of Chemical Engineering, October 1970.

3. Gelperin, N. I. and Einstein, V. G., "Heat Transfer in Fluidized Beds," in Davidson, J. F. and Harrison, D., Eds., Fluidization, Chapter 10, 471-540. New York: Academic Press, 1971.

4. Hoy, H. R. and Roberts, A. G., "Fluidized Combustion of Coal at High Pressures," A.I.Ch.E. Symposium Series No. 126, 68, 225 (1972).

5. Kharchenko, M. V. and Makhorin, K. E., "The Rate of Heat Transfer Between a Fluidized Bed and an Immersed Body at High Temperature," Int. Chem. Eng. 4, 650-54 (1964).

6. Masbaev, V. K. and Baskakov, A. P., "Features of External Heat Transfer in a Fluidized Bed of Coarse Particles," Int. Chem. Eng. 14, 80-83 (1974).

7. National Research Development Corp., "Pressured Fluidised-Bed Combustion," prepared for Office of Coal Research, Contract No. 14-32-0001-1511. London, n. d.

8. Zabrodsky, S. S., Hydrodynamics and Heat Transfer in Fluidized Beds, 296. Cambridge, Mass.: M.I.T. Press, 1966.

9. Ibid., pp. 257, 271, 278.

High-Temperature (MHD) Combustion

A large number of reports on coal-fired MHD power plants have been collected.

E. COAL, CHAR, AND OIL SHALE PROPERTIES

We are investigating the scope and progress of work on coal that is being carried out at Pennsylvania State University under an OCR contract. Our understanding is that the following properties (listed in Table 5) are being determined on all or some of its PSOC series of samples.

Table 5. PROPERTIES DETERMINED ON PENN STATE PSOC SAMPLES

Proximate Analysis
Ultimate Analysis
Chlorine Content
Equilibrium Moisture
Free-Swelling Index
Forms of Sulfur
Hardgrove Grindability Index
Microhardness
Surface Area
Porosity
Ash-Softening Point
Elemental Ash Analysis
Mineralogical Analysis of Mineral Matter
Size and Shape of Mineral Matter Grains
Gray-King Assay
Batch Liquefaction Yield

A recent (1974) breakdown of Penn State's sampling indicates a total of 314 samples at 157 different seams or locations. Except for Alaska, all important coal-producing states are represented; that is, reserves of states not represented amount to only 0.1 % of the total. The more important producing states appear to be better represented than others; about 50 % of the different seams or locations are from the five highest producing states, according to 1971 production data.

For our compilation of basic data on coal samples from important deposits, we need to establish —

1. How adequately does the Penn State sample series, as it now exists, represent the important coal deposits of the United States? in several year's time?
2. How much of the data being obtained on the present collection is available now or will be available in the near future?
3. What changes, if any, should be made in the listed properties as proposed in Table 2 of the 8964 December 1974 Status Report?

A conference with coal-property investigators at Penn State is being arranged to consider these questions.

Comments on our list of coal properties to be considered (Table 1 in the 8964 December 1974 Status Report) were solicited from the Illinois State Geological Survey. In addition to some helpful comments on organization and nomenclature, the following additional categories were suggested:

- Water-soluble chlorine
- Coal strength
- Freezing and thawing characteristics
- Caking during handling and shipping
- Washability
  Coal-mineral matter intergrowth
  Float-sink data

F. MISCELLANEOUS

1. Filing System

A procedure has been defined to create a central filing system of all the collected material. A number of articles in different areas of coal conversion processes have been indexed.

2. Data Book Index

Many suggestions were received about the published outline in last month's report. The modified outline is again given in the Appendix. The additions have been identified by an asterisk (*).

3. MPC Phase 1 Meeting

Dr. Al Talwalkar attended the Phase 1 meeting of the Material Properties Council on January 16, 1975.

4. Gasification Data Meeting

A meeting was held with IGT people active in the coal gasification area to review the progress of gasification data collection and presentation. It was decided to contact, as soon as possible, various other people involved in gasification studies for kinetic or other data that they may have that can be included in the data book in a suitable format.

A draft letter, along with a sample of presentation of IGT data, is being completed and will soon be sent out.

5. Technical Advisory Committee

We plan to form an advisory committee of persons active in the coal conversion field to review and comment on the content and format of the data prepared for inclusion in the data book. A draft letter, inviting potential members to join the advisory committee, is being prepared.

IV. Patent Status

The work performed during January is not considered patentable.

V. Future Work

Data collection and correlation will be continued in the selected high-priority areas.

Approved WW Bodle
W. W. Bodle, Director,
Process Analysis

Signed ATalwalkar
A. Talwalkar, Coordinator,
Process Data

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APPENDIX. Data Book Outline

Volume 1. Properties of Raw Materials, Intermediates, Products, and Related Processing Materials*

A. Properties of Coals, Coal Chars, and Oil Shales

- Proximate Analysis
  - Moisture
  - Ash
  - Volatile Matter
  - Fixed Carbon
- Ultimate Analysis
  - Carbon
  - Hydrogen
  - Nitrogen
  - Sulfur
  - Ash
  - Oxygen
- Petrographic Properties
  - Maceral Analysis
    - Vitrinite
    - Exinite
    - Resinite
    - Micrinite
    - Semifusinite
    - Fusinite
  - Vitrinite Reflectance
- Calorific Value
- Forms of Sulfur
  - Pyritic
  - Sulfate
  - Organic
- Chlorine Content
  - Water-Soluble Chlorine*
- Rank Classification
  - Rank
  - Fixed Carbon, Dry, mm-Free

  - Equilibrium Moisture
  - Calorific Value, Moist, mm-Free
- Structure
  - Porosity
  - Pore-Size Distribution
  - Surface Area
  - True Density
- Mineral Matter Characteristics
  - Elemental Composition
    - SiO_2
    - Al_2O_3
    - Fe_2O_3, etc.
  - Mineralogical Properties
    - Composition
      - Kaolinite
      - Quartz, etc.
    - Size and Shape of Grains
  - Ash Fusibility*
  - Trace Elements
- Grinding and Handling Characteristics
  - Abrasiveness
  - Angle of Repose
  - Bulk Density
  - Apparent (Particle) Density
  - Caking*
  - Flow Properties
  - Freezing and Thawing Characteristics*
  - Friability
  - Hardgrove Grindability Index
  - Microhardness
  - Slacking
  - Rate of Oxidation (Spontaneous Combustion)
- Washability*
  - Coal-Mineral Matter Intergrowth*
  - Float-Sink Data*

- Miscellaneous Properties
  - Compressibility
  - Dielectric Constant
  - Elasticity
  - Electrical Resistivity
  - Heat Capacity
  - Permeability
  - Thermal Conductivity
  - Thermal Diffusivity
  - Thermal Expansion
- Caking and Carbonization Properties
  - Free-Swelling Index
  - Agglomeration Index
  - Gray-King Assay
  - Low-Temperature Carbonization Assay (BM) Yield:
    - Char
    - Tar
    - Light Oil
    - Gas
    - Water
- Geiseler Plastometer Test
  - Initial Softening Temperature
  - Fusion Temperature
  - Temperature of Maximum Fluidity
  - Solidification Temperature
- Audibert-Arnu Dilatometer Test
- Liquefaction Properties
  - Yield by Batch Autoclave Test
- Gasification Properties
  - Johnson Reactivity Factor

B. Properties of Intermediates* and Conversion Products

- General Properties
  - Molecular Weight
  - Melting Point
  - Boiling Point

- Temperature of Transformations
- Density or Specific Gravity
  - True
  - Bulk
- Thermal Expansion Coefficient
- Solubilities
- Surface Tension
- Critical Properties
- Transport Properties
  - Heat Capacity
  - Viscosity
  - Thermal Conductivity
  - Diffusivity
  - C_p/C_v
  - Prandtl No.
  - Diffusion Coefficient
  - Electrical Conductivity
  - Emissivity
  - Absorptivity
  - Permeability
- Thermodynamic Properties
  - Heat of Formation
  - Enthalpy
  - Free Energy of Formation
  - Equilibrium Constant of Formation
  - Heat of Fusion
  - Heat of Vaporization
  - Heat of Transition
  - Heat of Combustion
  - Heat of Solution
  - Activity Coefficient
  - Fugacity Coefficient
  - Heats of Reactions of Selected Reactions
  - Equilibrium Constants of Selected Reactions

- Vapor-Liquid Equilibria
  - Critical Properties
  - K-Factor
  - V/L Equilibrium
  - PVT and Phase Behavior

C. Properties of Related Processing Materials

For Example, Catalysts, Reagents, and Treating Agents

Volume 2. Solids Storage, Preparation, and Pretreatment

- Sampling of Coal
- Projecting Data From Samples
- Coal Characteristics and Their Relationship to Utilization
- Raw-Coal Handling
- Breaking and Crushing
- Screening
- Wet Concentration of Coal
  - Coarse Coal
    - Dense-Medium Separation
    - Hydraulic Separation
  - Fine Coal
    - Dense-Medium Separation
    - Hydraulic Concentration
    - Froth Flotation
- Dry Concentration
- Mechanical Dewatering
- Thermal Dewatering
- Coal Storage and Loading
- Dry Coal Feed Systems*
  - Mechanical Feeders*
  - Lock Hoppers*
- Refuse Removal and Disposal
- Coal Pretreatment

Volume 3. Conversion Fundamentals

A. Gasification

- Fluid Bed
    - Steam-O_2
    - Steam-Air
    - Steam-H_2
    - Steam-H_2-CO-CO_2-N_2
- Dilute Phase
    - Entrained
        - Steam-O_2
        - Steam-Air
    - Texaco-Type
        - Steam-O_2
        - Steam-Air
- Fixed Bed
    - Steam-O_2
    - Steam-Air
- Molten Bed
    - Steam-O_2
- Spouting Bed
- *In Situ* Gasification*

B. Liquefaction

- Catalytic With H_2
    - Ebullating Bed
    - Fixed Bed
    - Others
- Catalytic Without H_2
    - Ebullating Bed
    - Fixed Bed
    - Others
- Noncatalytic
    - With H_2
    - Without H_2

- C. Pyrolysis
  - Low-Temperature
  - High-Temperature
- D. Fluid-Bed Combustion
- E. Advanced Power Generation*
  - MHD*
  - Fuel Cells*

Volume 4. Design Procedures (Unit Operations)

- A. Conversion Tables and Numerical Constants*
- B. Fluidization
  - Fluid-Bed
  - Solid Transport
- C. Fluid Flow
  - Single-Phase
  - Multiphase
- D. Heat Transfer

Volume 5. Supporting Processes

- A. Gas Treating
- B. Methanation
- C. Environmental Control
  - Gas Effluents
  - Liquid Effluents
  - Solid Effluents
- D. Hydrogen Production
  - Electrothermal
  - Steam-Iron
  - Other

Volume 6. Miscellaneous Products

- A. Methanol
- B. Acetylene
- C. Ammonia

Volume 7. Materials of Construction

- A. Refractories
  - Properties
  - Corrosion/Abrasion Data
- B. Ceramics
  - Properties
  - Corrosion/Abrasion Data
- C. Metals and Alloys
  - Properties
  - Corrosion/Abrasion Data
- D. Plastics
  - Properties

Volume 8. Equipment Specifications

Volume 9. Cost Data and Costing Procedures

Volume 10. Process Flow Sheets*

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* Modifications to the initial outline.

IGT-MPR--4

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