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FIXED BED COAL GASIFICATION
FOR PRODUCTION OF
INDUSTRIAL FUEL GAS

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EXECUTIVE SUMMARY

This report summarizes the results of technical and economic evaluations of six commercially available fixed bed coal gasification processes for the production of industrial fuel gas. The study was performed for DOE and is intended to assist industrial companies in exploring the feasibility of producing gaseous fuels for both retrofit and new industrial plant situations.

Scope

This report includes a technical analysis of the physical configuration, performance capabilities, and commercial experience to-date for both air-blown and oxygen-blown fixed bed gasifiers.

The product gas from these gasifiers is analyzed economically for three different degrees of cleanliness: (1) hot raw gas, (2) dust-, tar-, and oil-free gas, and (3) dust-, tar-, oil-free and desulfurized gas. From these analyses, a coal consumer can calculate:

- Coal cost that will yield a desired product gas cost.
- Cost differences between low and high sulfur coals to yield a desired product gas cost.

A typical project schedule for installation of a commercially available fixed bed gasifier is also included.

Results and Conclusions

General

The evaluations indicate that low-Btu gases produced from fixed bed gasifiers constitute one of the most logical short-term solutions for helping ease the shortage of natural gas for industrial fuel applications because:

- The technology is well-proven and has been utilized on a commercial scale for several decades both in this country and overseas.
- Time from initiation of design to commercial operation is about two years.
- The technology is not complicated to construct, operate, or maintain.
- A reliable supply of product gas can be generated on-site.

- Low-Btu and medium-Btu gas can be substituted for natural gas in many industrial applications (HHV's: low-Btu gas from bituminous coal 150-180 Btu/scf; low-Btu gas from anthracite coal 125-156 Btu/scf; medium-Btu gas from bituminous 280-310 Btu/scf; medium-Btu gas from anthracite 240-280 Btu/scf).

Technical

The fixed bed gasification technology has many desirable features for industrial users because of physical configuration as well as performance capabilities. The major features are:

- The simple mechanical design results in relatively easy operation of the gasifier.
- Installation of a mechanical stirrer enables the single-stage gasifiers to handle highly caking coals.
- The simple start-up and shutdown procedures provide for ease of operation.
- Turndown capability is excellent (14-25% of maximum capacity).
- Steam required for the gasification can be generated in the gasifier water-jacket.
- The countercurrent mode of operation provides good thermal efficiency (88 to 94% for hot raw gas and 75-85% for desulfurized gas).
- The long residence time results in high carbon conversion.
- Solids carryover is low.
- Oxygen/air consumption is low.

Some less desirable features of the fixed bed gasification processes are:

- Two-stage gasifiers can only handle weakly caking coals.
- Coal must be sized and fines minimized.
- Tar, tar oil, NH_3, and phenols are produced due to the low product gas temperature.
- The low temperature and the presence of tars in the product gas restricts waste heat recovery.

Economic

The capital and operating costs for the fixed bed gasification are low compared with the high-Btu gasification because the system can be operated at low pressure and without the shift and methanation units. The average direct capital cost based on mid-1977 pricing for a 2.5 x 10^9 Btu/day (2.5 MM SCFD natural gas equivalent) capacity air-blown fixed bed gasification plant is estimated to be $2.210 MM for producing hot raw gas, $3.145 MM for dust-, tar-, and oil-free gas, and $4.585 MM for producing cold, dust-tar-oil-free and desulfurized gas. Fuel costs for low-Btu gas production were generated for varying coal costs at 8%, 10%, and 12% discounted cash flow (DCF) rates.

An example is shown at one of the DCF rates:

Coal Cost: $/Ton Delivered	Low-Btu Gas Cost at 10% DCF Rate (Without Investment Credit), $/MM Btu					
	50% Equity Capital			100% Equity Capital		
	(1)	(2)	(3)	(1)	(2)	(3)
20	-	-	2.63	-	-	2.91
30	2.25	2.69	3.19	2.40	2.90	3.48
40	2.69	3.11	3.76	2.84	3.32	4.06
50	3.12	3.75	-	3.28	3.96	-

(1) Hot Raw Gas
(2) Dust-, Tar-, and Oil-Free Gas
(3) Dust-Tar-Oil-Free and Desulfurized Gas

The hot raw gas and the dust-, tar-, and oil-free gas were obtained from 105 TPD and 126 TPD, respectively, of low sulfur Stockton, WV coal (HHV = 13,084 Btu/lb). The desulfurized gas was obtained from 135 TPD of high sulfur Belmont, OH coal (HHV = 12,473 Btu/lb).

The major financial parameters used in generating the fuel cost were 25 years plant life, 90% capacity factor, 16 years sum-of-the-years depreciation, and federal income tax rate of 48%. A payable period of 12 months was used for calculating interest during construction. An interest rate of 8.5% was used for the debt portion of the capital.

The capital charge represented approximately 14-18% of the hot raw gas cost and 22-29% of the desulfurized gas cost.

The gas cost based on 50% equity capital decreased the hot raw gas cost by \$0.15/MMBtu and the desulfurized gas cost by \$0.30/MMBtu compared with that based on 100% equity capital. With the investment tax credits such as 20% applied to the capital for the desulfurization unit and 10% for the rest of the plant, a further reduction of approximately \$0.06/MMBtu in the desulfurized gas cost can be realized.

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1.0 INTRODUCTION

Among the various energy consuming sectors, the industrial sector is the most energy intensive, accounting for more than 30% of total U.S. energy consumption in the form of natural gas and petroleum oil. Yet, industrial plants today are faced with the predicament of ever-dwindling supplies of natural gas which in the winter months may be completely cut-off.

Coal gasification is one of the prime candidate processes for supplying the alternate fuels for various industrial sectors. Among the coal gasification processes either being developed or commercially available, the fixed bed gasifier is one of the most flexible short-term solutions for providing a reliable supply of a gaseous fuel for industrial applications.

1.1 PURPOSE OF THE STUDY

The objective of the study was to perform technical and economic evaluations of six commercially available fixed bed gasifiers for the production of industrial gaseous fuels. Three single-stage gasifiers (McDowell-Wellman, Riley-Morgan, Wilputte) and three two-stage gasifiers (Woodall-Duckham, Wellman-Incandescent, Foster Wheeler Energy Corporation's FW-Stoic) were included in the evaluation. The study is intended to assist industrial companies in exploring the feasibility of producing gaseous fuels from fixed bed gasifiers for both retrofit and new industrial plant applications.

This study includes a technical evaluation of physical configurations of both air- and oxygen-blown gasifiers as well as their performance capabilities and commercial experience to-date. In the economic evaluation, a single averaged capital cost was applied to all gasifiers. A clarification was made, however, to indicate the scope of the system covered by the cost estimates. The cost data were then used to make an evaluation of utilizing low sulfur coal to produce a hot raw gas or a cold gas free of dust, tar, and oil, and utilizing high sulfur coal to produce a dust-, tar-, oil-free and desulfurized gas.

1.2 APPROACH TAKEN TO PERFORM STUDY

Considerable in-house data on the performance and costs of commercial fixed bed gasifiers, which were compiled from both literature and gasifier vendor contacts in conjunction with Gilbert's previous industrial projects, were reviewed. Additional data were obtained from organizations engaged in the testing of the fixed bed gasifiers, such as the Morgantown Energy Research Center (MERC).

From reviewing the available data, additional data needs were identified, and gasifier vendors were contacted to obtain the necessary information. Many of the missing data were obtained via these gasifier vendor contacts. In a very few instances, however, some of the vendors were unable to provide all the data Gilbert requested, and the missing data were either calculated on a theoretical basis or estimated by exercising engineering judgment based on Gilbert's previous experience with industrial gasification projects.

The report prepared by Gilbert was reviewed by both ERDA and the gasifier vendors. The review by each gasifier vendor of the data Gilbert presented for his particular gasifier was necessary to insure against divulging of proprietary information.

1.3 ORGANIZATION OF THE REPORT

The report consists of five sections and three appendices.

After the brief description of the purpose, scope, and study approach taken in Section 1.0, Section 2 gives a historical outline of the development of fixed bed gasifiers. Pertinent background materials on the chemistry of fixed bed coal gasification are also discussed in this section.

Section 3.0 presents a compilation and analysis of physical configuration, performance capabilities, operation, and commercial experience of the six gasifiers. Technical similarities and differences between single- and two-stage gasifiers are discussed. Advantages, disadvantages, problems, and potential for improvements in utilizing fixed bed gasifiers are also summarized.

Section 4.0 contains the results of the economic analysis including a detailed breakdown of capital and operating cost elements. A single "averaged" capital cost was applied to all gasifiers in generating the cost data. Fuel costs were generated using 8%, 10% and 12% discounted cash flow rates for three varying degree of gas cleanliness. A typical project schedule is also presented in this section.

Section 5.0 summarizes and discusses the results of both technical and economic evaluations of the six fixed bed gasifiers.

Appendix A presents a discussion of coal availability and characteristics pertinent to the chemistry of fixed bed coal gasification.

In Appendix B, the results of correlations made to relate the gasification rate and the higher heating value of product gas to the fixed carbon content of coal feed are presented.

Finally, Appendix C discusses the combustion characteristics of low- and medium-Btu gases and compares them with those of natural gas.

2.0 BACKGROUND

The term "fixed bed" is used in gasification to signify a fuel bed supported by a grate or by other means and maintained at a constant depth above the support. Thus, the upper and lower extremities of the bed are fixed in space, but within the bed fuel moves slowly from the top down through the gasification zone, and residue is discharged at the bottom.

2.1 EVOLUTION OF TECHNOLOGY

The basic science on which fixed bed coal gasification technology was first built dates back to 1670, when Reverend John Clayton, a Yorkshire clergyman, reported the generation of a luminous gas when coal was heated in a chemical retort. Technology lagged science by more than a century because it was not until 1792 that William Murdoch, a Scotsman, lighted his home with gas obtained by distilling coal in an iron retort. Thus was born the gas industry, more specifically, the producer-gas industry, the initial objective of which was to produce a illuminating gas and to sell the retort coke to domestic and other users. The gas retort method operated continuously except for charging coal and discharging coke; gas was stored in holders to take care of the variation in demand from day to night.

The first practical gas producer to serve the heating market was built by Bischof in Germany in 1839, followed by Ebelman in France in 1840, and Ekman of Sweden in 1845. The invention of the atmospheric gas burner by Bunsen in 1855 strengthened the industry's potential for growth in the heating market. In 1861, the first large industrial development in the use of gas producers was made when the two Siemens borthers of Germany patented their combined gas producer and regenerative furnace, thus opening up the field for the use of raw producer gas in heavy furnace work.

The gas industry further took advantage of the technological advance made by Lowe in 1875 when he developed the cyclic carbureted water gas process. In this process, hot coke is reacted with steam to produce water gas, a mixture of carbon monoxide and hydrogen. This gas is enriched by cracking oil in a downstream vessel filled with checker brick. Heat for the process is obtained by interrupting the gas-making period and blowing air through the coke bed. The introduction of this process enabled gas producers to be put on-stream and shut-down comparatively easily and were thus ideally suited for serving applications with variable loads. Also, there was no solid co-product to dispose of. The introduction of this process gave the industry an opportunity to optimize its physical plant through inplant use of retort coke to make water gas.

In the years 1879-1881 J. E. Downson, of England developed a producer gas cooling and cleaning plant, which extended the scope of application of producer gas to make possible its use in small furnaces and gas engines.

In 1889, Dr. Ludwig Mond showed how it had been possible during some preceding years to generate producer gas while simultaneously recovering by-products from the fuel in a chemical works in Cheshire, England, thereby pointing out during this early period that producer gas should not be considered only for its heat content, but also for its properties in regard to the recovery of certain products required in the chemical and agricultural industries.

The real innovations in coal gasification technology started around 1920 in Europe, where coal was the principal source of energy and where there was an incentive to develop process for making low-cost synthesis gas from coal for use in the production of ammonia and synthetic liquid fuels. During World War II, the German chemical industry succeeded in producing 4,500,000 tons per year of liquid fuels from coal. At the conclusion of World War II, the lack of natural gas in Europe helped promote the installation and use of coal gasification plants for the production of ammonia via oxygen-blown gasification of coal and subsequent catalyst synthesis.

In the United States, the early gasifiers were usually known by the name of their developers such as the Galusha, Wellman, Morgan, Chapman, Smythe, Wood, etc. The use of producer gas reached the height of its popularity in the 1920's. In 1926, there were about 12,000 gas producers in operation for production of low- and medium-Btu gases from coal. More than half of these fixed bed gasifiers were used for such metallurgical processes as annealing, billet heating, soaking pits and so forth. From this peak period on, however, producer gas began to diminish due to the competition from natural gas and oil which became increasingly available in the 1930's. It should be recognized nevertheless that during its long period of evolution, the producer-gas industry has been refining its technology and developing new technology to improve its day-to-day operations.

2.2 CHARACTERISTICS OF FIXED BED GASIFICATION

Fixed beds have several inherent characteristics that are advantageous in gasification processes. Flow of coal and residue is countercurrent to the gasification medium and products of gasification, and this leads to maximum heat economics. The countercurrent contacting permits both the coal and gaseous reactants to be preheated prior to gasification, thus increasing the overall efficiency of these reactions and ultimately the efficiency of the process. Also, increasing efficiency is the fact that this preheat can be supplied from the process itself rather than an external source which would require an additional expenditure of energy. Relatively long residence time of the fuel in the reaction vessel permits high carbon conversion. The long residence time reduces gasification rates but because of high carbon conversions, thermal efficiencies are high. Low gas exit temperatures result in lower oxygen or air consumption in the combustion zone. The product gas is not contaminated with solids to any great extent, and plug flow of solids minimizes loss of ungasified fuel in the residue.

The fuel bed is characterized by zones of different temperature and the processes taking place in them. These may be designated as:

1. Drying Zone - This zone is at the top of the gasifier where raw coal is dried and preheated by the hot gases flowing from below.

2. Devolatilization Zone - Here the coal is distilled to remove volatile matter in the feed to render a caking coal noncaking and recover the methane, oil and tars in the coal.

3. Gasification Zone - Here the coal is contacted with steam and carbon dioxide to form hydrogen and carbon monoxide.

4. Combustion Zone - Here the remaining carbon in the coal is burned with oxygen to supply the heat required in the upper zones.

Figure 2.2-1 shows the typical arrangement of the four zones in a fixed bed gasifier. It also depicts the basic difference between the single-stage gasifier and the two-stage gasifier. In single-stage gasifiers, drying/devolatilization of volatile matter and gasification/combustion of coal take place in the same overall bed with comingling of the distilled gas with the producer gas. In the two-stage gasifier, there is a separation of the processes with the gases coming off more or less separately.

2.3 CHEMISTRY OF FIXED BED GASIFICATION

In normal operations of a fixed bed gasifier, the four zones described above often overlap and no discrete separation exists. However, the chemical reactions and temperature ranges which can occur in each zone are presented below, individually:

Drying Zone - In this zone the raw coal comes in contact with hot product gas to dry and preheat it. Depending on the coal and gasifier selected, the temperature in this zone can run from 200-400°F for two-stage and 700-1100°F for single-stage gasifiers. Two-stage gasifiers will operate at the lower temperature range to permit gradual controlled drying and devolatilization and thus prevent cracking of the tar and oils. Since the removal of moisture absorbs heat, a coal with a high moisture content would require longer residence time in this zone. Similarly, the added moisture would lower the final hot product gas heating value and decrease overall thermal efficiency.

Devolatilization Zone - Drying and devolatilization generally occur simultaneously depending on the temperature. Additional moisture is removed as the coal heats up, but low molecular weight gases, oils and tars also begin distilling out.

Coal contains certain occluded gases such as carbon dioxide and methane and inherent moisture. When the coal is heated the occluded carbon dioxide and methane are first driven off, their removal being more or

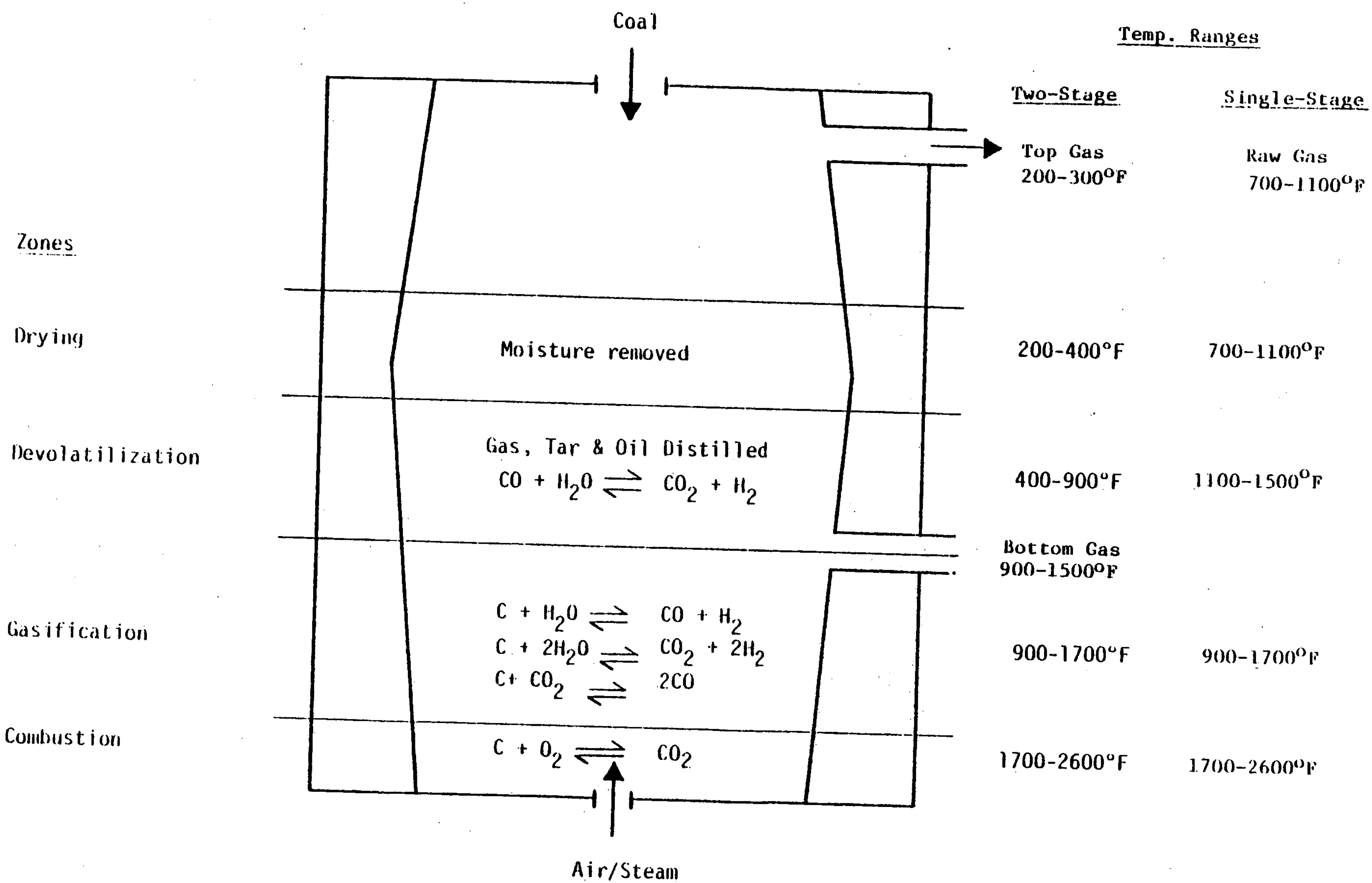


Figure 2.2-1 Typical Location and Chemical Reactions in a Fixed Bed Gasifier

less complete at about 400°F. Above this temperature a certain amount of internal condensation occurs in the molecules comprising the essential coal substance; this is accomplished by the evolution of carbon dioxide and water vapor. The extent of these reactions increases with decreasing coal rank.

In the temperature range 400°-900°F the organic sulfur compounds of coal decompose to hydrogen sulfide and other organic sulfur compounds. Decomposition of the nitrogenous compounds begins with the evolution of nitrogen and ammonia. In this temperature range, decomposition of the essential coal substance begins, resulting in the evolution of methane and its higher olefins; the bulk, but not all, of the combined oxygen is also released and appears in the evolved gases mainly as water and oxides of carbon.

The expulsion of oils from coal begins at about 550° to 750°F, the yield of tar usually increasing to a maximum at 900° to 1000°F. With light oil and tar there is usually an increase in aromaticity with increasing temperature. Thus, the liquids produced from coal at the lower temperatures consist mainly of cyclic hydroaromatic compounds and smaller quantities of higher olefins and paraffin hydrocarbons with very little aromatic compounds of the benzene series, while higher temperature tars contain quite high proportions of aromatic hydrocarbons.

The quality and composition of gases and tars produced from coal vary with the type of coal and the temperature. The yield of tar and gas increases with temperature and decreasing coal rank. The composition of the gas also changes, the carbon dioxide and methane content increasing and the hydrogen content decreasing with decreasing rank.

<u>Gasification Zone</u> - The devolatilized coal (now referred to as char) from above contacts steam and combustion gases rising up from the combustion zone and they react to form the bulk of the fuel gas produced in a fixed bed gasifier. Figure 2.2-1 shows three carbon reactions which can occur. The degree to which each reaches equilibrium is dependent on the temperature in the bed.

The carbon dioxide rising from the combustion zone reacts with carbon resulting in the production of carbon monoxide via the endothermic reaction[1]:

$$C + CO_2 \rightleftharpoons 2\,CO - 74{,}197 \text{ Btu/lb-mole C}$$

The extent to which the reaction occurs depends on the temperature and on the solid residence time. To set up equilibrium conditions may require a long residence time, depending on the rate of reaction. Since the rate of reactions increases with temperature, these equilibrium values are difficult to obtain at lower temperatures.

The steam introduced also reacts with carbon in the gasification zone via the two endothermic reactions:

$$C + H_2O \rightleftharpoons CO + H_2 - 56,488 \text{ Btu/lb-mole C}$$

$$C + 2\ H_2O \rightleftharpoons CO_2 + 2\ H_2 - 38,779 \text{ Btu/lb-mole C}$$

The first reaction occurs almost exclusively at and above 1800°F and the second reaction at 1100°F. Between these two temperatures both reactions occur to reach some equilibrium concentration. A high gasification temperature is desirable to avoid the production of carbon dioxide.

The rate of the steam-carbon reactions is also influenced by the quantity of steam present. It is important that as much of the steam as possible be converted into carbon monoxide and hydrogen.

The endothermic carbon-steam reactions which occur during gasification are highly temperature dependent. High temperatures favor carbon and steam equilibrium conversion to produce more fuel gas. The necessary endothermic heat of reaction to promote the carbon-steam reaction is provided wholly by the exothermic combustion of carbon and oxygen. In addition to the steam/carbon dioxide/carbon reactions, the sulfur will also react endothermically with hydrogen and carbon monoxide and will be reduced to hydrogen sulfide and trace quantities of carbon disulfide and carbonyl sulfide. Approximately 90% of the sulfur in the coal will appear as hydrogen sulfide[2].

Combustion Zone - This zone consists of a layer of gasified char supported by a layer of dry ash. The remaining carbon in the char is reacted with oxygen to generate heat required for the subsequent endothermic gasification reactions and for the distillation and drying zones. The combustion proceeds via the following exothermic reaction[1]:

$$C + O_2 \rightleftharpoons CO_2 + 169,293 \text{ Btu/lb-mole C}$$

The ash layer in the combustion zone serves two purposes. The first is to distribute the oxygen and steam feed evenly across the fuel bed and the second, and more importantly, is to recover sensible heat in the hot ash for improved efficiency and reaction rate in the gasification zone by preheating the oxygen and steam mixture.

2.4 REFERENCES

1. Perry, J. H., "Chemical Engineers Handbook," Fourth Edition, pp. 134-141, McGraw-Hill Book Company, New York (1963).

2. Gilbert Associates, Inc., "Feasibility of Reducing Fuel Gas Clean-Up Needs," ERDA Contract No. (49-18)-1236 (June 20, 1976).

3.0 TECHNICAL ANALYSIS OF GASIFIERS

Technical data compiled for physical configuration, performance capabilities, operation and maintenance, and commercial experience of the six fixed bed gasifiers are discussed in this section.

3.1 PHYSICAL SYSTEM

Single-stage and two-stage fixed bed gasifiers are designed to operate at atmospheric pressure. In both types of gasifiers coal is charged from the top and the air blast (or oxygen blast) saturated with moisture enters at the bottom. Ash is removed from the bottom. Coal is charged by gravity flow using either drum feeders or lock hoppers.

The single-stage gasifier and the two-stage gasifier differ in their gas off-take configurations. In a single-stage gasifier the producer gas is taken from one point, whereas in a two-stage gasifier part of the gas is taken from the top (distillation zone) and the remaining gas from a location below the top of the gasifier (gasification zone). A single-stage gasifier can be equipped with an agitator, whereas a two-stage gasifier is unavailable commercially with an agitator. Bed height of a single-stage gasifier is 5 to 6 ft while a two-stage gasifier can be 17 to 18 ft deep. The gasification shell is cylindrical for both types. For a single-stage gasifier, the shell can be either brick-lined or water-jacketed. A two-stage gasifier is always brick-lined in the retort section.

Generally, both types of gasifier have a fixed shell and a rotating grate. This is not so in the case of Riley-Morgan (single-stage) gasifier which has a revolving shell and no grate.

3.1.1 Single-Stage Gasifiers

The single-stage fixed bed gasifiers consist of a cylindrical shell provided with a system for feeding coal from the top, air-steam or oxygen-steam blast from the bottom, and an ash removal system at the bottom. Thus, the coal is fed downward and the moist air (or oxygen) flows upward through an ash zone to the combustion zone.

In some single-stage gasifiers such as Wilputte, the ash plow is stationary and the grate and ash pan rotate. In such a gasifier ash removal is intermittent, and three or four inches of ash are removed each revolution. Riley-Morgan (R-M) has a rotating shell but no grate, and the ash bed performs the function of a grate. In the McDowell-Wellman (M-W), the shell is stationary and the grate rotates to discharge ash continuously into a conical hopper, from which it is removed periodically.

The gasifier shell can be brick-lined (R-M, Wilputte) or water-jacketed (M-W). In the former type, steam has to be raised either in a waste heat boiler or obtained from an external source. Water-jacketed gasifiers are self-sufficient in their steam requirements. In the M-W gasifier air is blown over the jacket water, where it picks up the required moisture before entering the gasifier. The amount of steam going into the gasifier is controlled by regulating the supply of jacket water. In the R-M gasifier, metered steam is mixed with the air blast before it enters the gasifier. The Wilputte gasifier can be adapted to either mode of operation.

All the single-stage gasifiers are fitted with agitators which permit gasification of highly caking coals and increase the gas production.

There are several variations in the mode of feeding the single-stage gasifiers. The Wilputte gasifier uses a Chapman drum feeder; the Riley-Morgan gasifier uses a drum feeder coupled with lock hopper; and the McDowell-Wellman gasifier uses a two-compartment coal feed bin which continuously feeds the gasifier by gravity through two pipes connecting the bin and the gasifier.

3.1.1.1 McDowell-Wellman Gasifier [1] [2] [3]

Standard Gasifier

The gasifier has a continuous automatic gravity coal feeding system, a revolving grate, and an elevated ash pit. The schematic diagram of a standard McDowell-Wellman (M-W) gasifier is shown in Figure 3.1-1.

A two-compartment coal bin forms the top of the gasifier. The upper section serves as a storage bin, fed by any suitable device (such as a bucket elevator) for coal handling. The lower compartment is separated from the upper section by disc valves through which coal is fed. Similar valves cover the entrance to each of the feed pipes connecting the lower bin with the fire chamber. Coal from the lower bin flows continuously through these feed pipes to fill the fire chamber, and revolving grates discharge the ash from below the fire at the same rate at which it is formed.

The coal feed pipe valves are normally open, but for brief intervals they are closed, during which time the upper valves in the lower compartment are opened to fill the feeding compartment with coal. A simple interlocking mechanism prevents the opening of the upper valves unless all lower valves are tightly closed. It also prevents opening any lower valves while any top valve is open. An optional power device is available to open and close the coal feed valves.

The gas-making chamber is completely water-jacketed. The inner wall is made of one-inch thick steel plate and requires no brick lining. Waste heat in the water jacket generates the required steam.

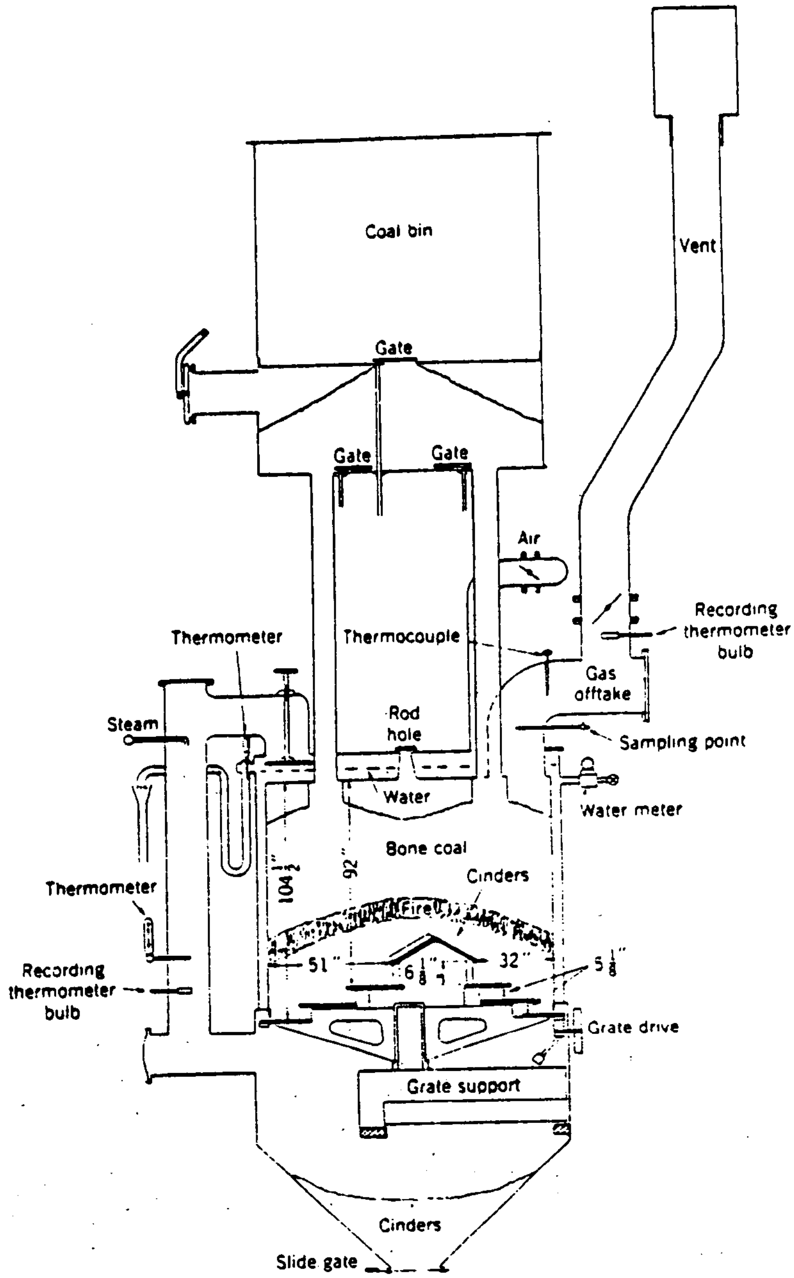


Figure 3.1-1 McDowell-Wellman Standard Type Gasifier

A direct-driven fan supplies air to the gasifier. This air acquires moisture on its way to the fire bed by passing over the steaming water at the top of the jacket. Saturation is automatically controlled by regulating the rate of supply of jacket water to maintain the desired saturation temperature.

Intersecting girders at the first floor level of the M-W gasification plan support a cast steel grate bearing. The grates are made of circular heavy steel plate rings that are flat and without perforations. They are set on top of each other, with edges overlapping so that the ash cannot escape unless pushed horizontally through the vertical space between the stepped plates.

The grates are eccentric with the center support, and the entire assembly is rotated very slowly. Due to this eccentricity, the space between the grate plates and the shell of the gasifier varies constantly as the grates revolve. As the space increases, it fills with ash; as the space decreases, the ash is forced over the inner edge of the grate platforms. In the area of least space, the ash is crushed and is thoroughly broken up. This action occurs progressively throughout the entire grate area, delivering a constant stream of loose, readily flowing ash to the hopper below. The grates have no perforations through which coal can be lost. The elimination of water seals makes it possible to carry higher pressures.

The cone-shaped ash hopper is sufficiently elevated to allow a truck, railroad car or conveyor to be placed under the discharge gate. The free flowing ash can be quickly and conveniently discharged for disposal. No interruption of operation is involved.

M-W units are available with water jacket or with brick lining. Brick-lined gasifiers range from 1-1/2 ft to 5 ft in diameter. Water-jacketed series covers the diameter range from 3-1/2 ft to 10 ft.

With Agitator

The physical configuration of the M-W gasifier with an agitator is the same as that of a standard type gasifier. As shown in Figure 3.1-2 a slowly revolving horizontal arm, which also spirals vertically below the surface of the coal bed, is installed in the stirred M-W gasifier to retard channeling and to maintain a uniform coal bed for the maximum gas production. The agitator arm and its vertical drive shaft are made of heavy, water-cooled steel tubing, with the wearing parts protected by heat and wear resistant castings. The arm can be revolved at varying speeds, and its position within the coal bed may be changed as desired for different coals and operating conditions. The agitated gasifier can gasify about 25% more anthracite or coke of the same size than the standard unit.

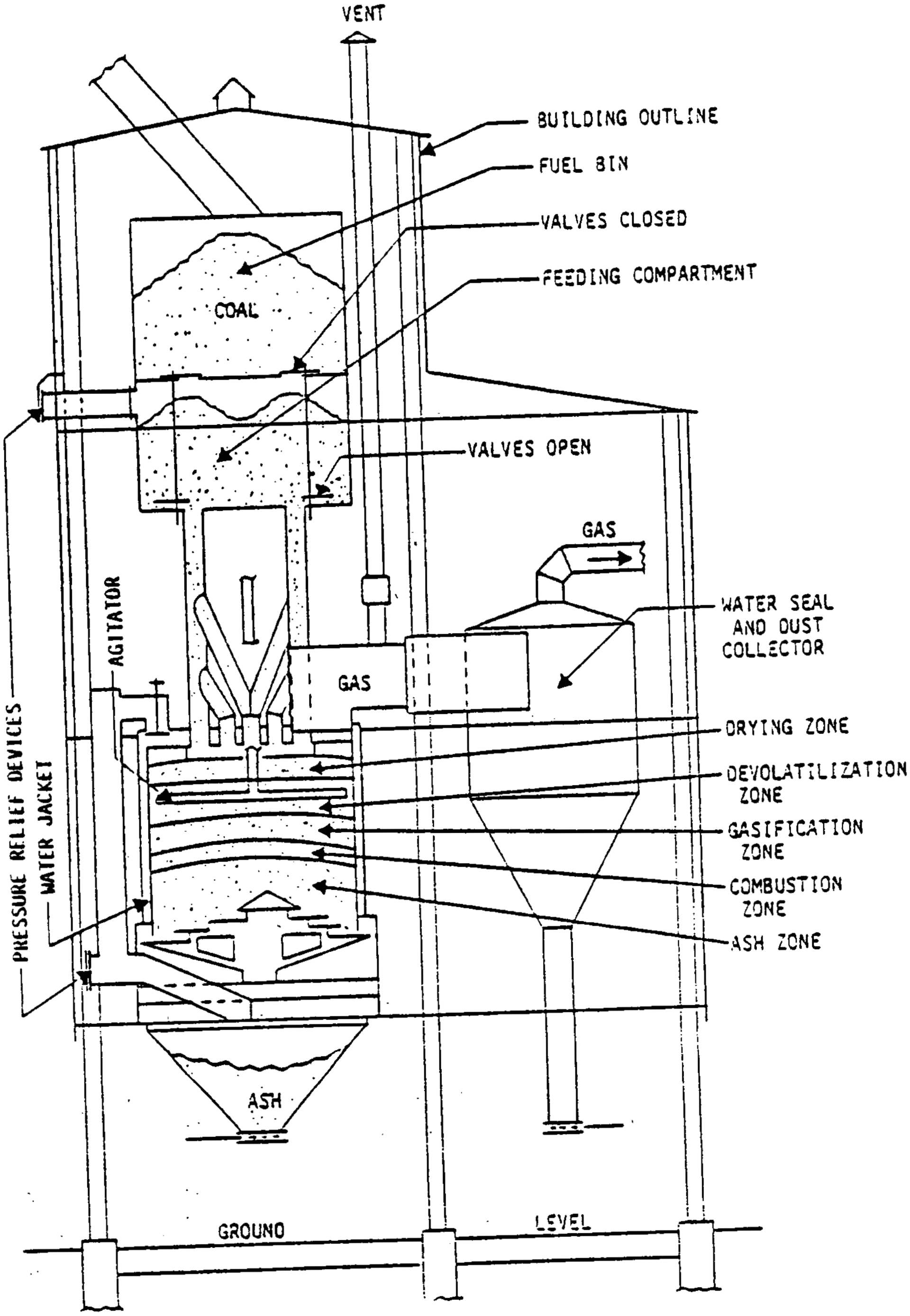


FIGURE 3.1-2 MC DOWELL-WELLMAN GASIFIER WITH AGITATOR

All M-W gasifiers equipped with stirrers are water-jacketed. Standard sizes of 6-1/2 and 10 ft are available for the stirred gasifier.

A summary of the physical system for the M-W gasifier and its advantages, disadvantages, maintenance areas, and potential for improvement is presented in Table 3.1-1.

3.1.1.2 Wilputte Gasifier(4) (5) (6)

The Wilputte gasifier, as shown in Figure 3.1-3, is used for the gasification of various types of coal by partial combustion with air or oxygen at atmospheric pressure. For the gasification of bituminous coal, the gasifier shell is brick-lined and is equipped with a Chapman drum feeder and agitator assembly.

Supported under the shell, riding on three sets of rollers and guided by rollers, is the Koller-type revolving grate and ash pan. The grate and ash pan are constructed of cast iron with spiral ribs in the grate to shear the bottom of the fuel bed and force the ashes into the ash pan.

The tuyere and ash table are mounted in a pan which is filled with water to form a seal with the seal ring attached to the gasifier shell. The whole assembly is mounted on a heavy gear ring, attached to a circular rail track which, in turn, rides on the supporting rollers. The grate is driven by a variable speed drive. A stationary ash plow removes the ash from the revolving pan so as to discharge the ash into the ash hopper.

For gasifying coke or anthracite coal, the Chapman feeder and agitator assembly is replaced by a cyclic batch feeder. The gasifier shell is also water-jacketed and equipped with a steam drum and boiler accessories designed for production of 15 psig steam. This steam is used as process steam to saturate the air going to the gasifier.

Steam from the water jacket or from an outside source is admitted to saturate the air going to the gasifier. The amount of steam is controlled by the saturation temperature, and the amount of air is controlled by the gas demand.

The Wilputte gasifier is available in two standard sizes: 9 ft-2 in and 10 ft-4 in diameter. The height of both units is 16 ft-5 in.

A summary of the physical system for the Wilputte gasifier and its advantages, disadvantages, maintenance areas, and potential for improvements is presented in Table 3.1-2.

Table 3.1-1

Summary of Physical Systems of McDowell-Wellman Gasifier

Physical Components	
Coal Feeding System	o Continuous automatic gravity coal feeding o Two compartment fuel bin
Gasifier	o Coal feed from top o Ash discharged to bottom o Stirrer available to handle caking coals o Completely water-jacketed o 1" thick inner wall steel plate
Ash Withdrawal System	o Rotating grates o Continuous discharge o Elevated ash pit
Air/Oxygen Feeding System	o Direct driven fan blast o Saturated with steam from jacket
Steam Feeding System	o Steam generation with waste heat in water jacket
Inside Diameter	o Brick-lined: 1'-6", 1'-10", 2', 3', 4', 5' o Jacketed: 6'-6", 8', 10'
Advantages	
Coal Feeding System	o No moving parts - minimum abrasive effects o Simple design and operation
Gasifier	o No brick lined inner wall for some gasifier provide low maintenance cost o Stirrer can handle caking coals of high FSI
Air/O_2 Feeding System	o Air/O_2 saturation temperature controlled easily by controlling jacket water supply
Disadvantages	o Gas leakage from the feed system o Unsuitable feed system at elevated pressure o Poking required to determine ash level
Maintenance Areas	o Wear bars on agitator blade o Disc valves in coal feeding system
Potential for Improvement	o Elimination of gas leakage problems by addition of air lock in the feed system o Elimination of poking o Automatic control of ash withdrawal rate

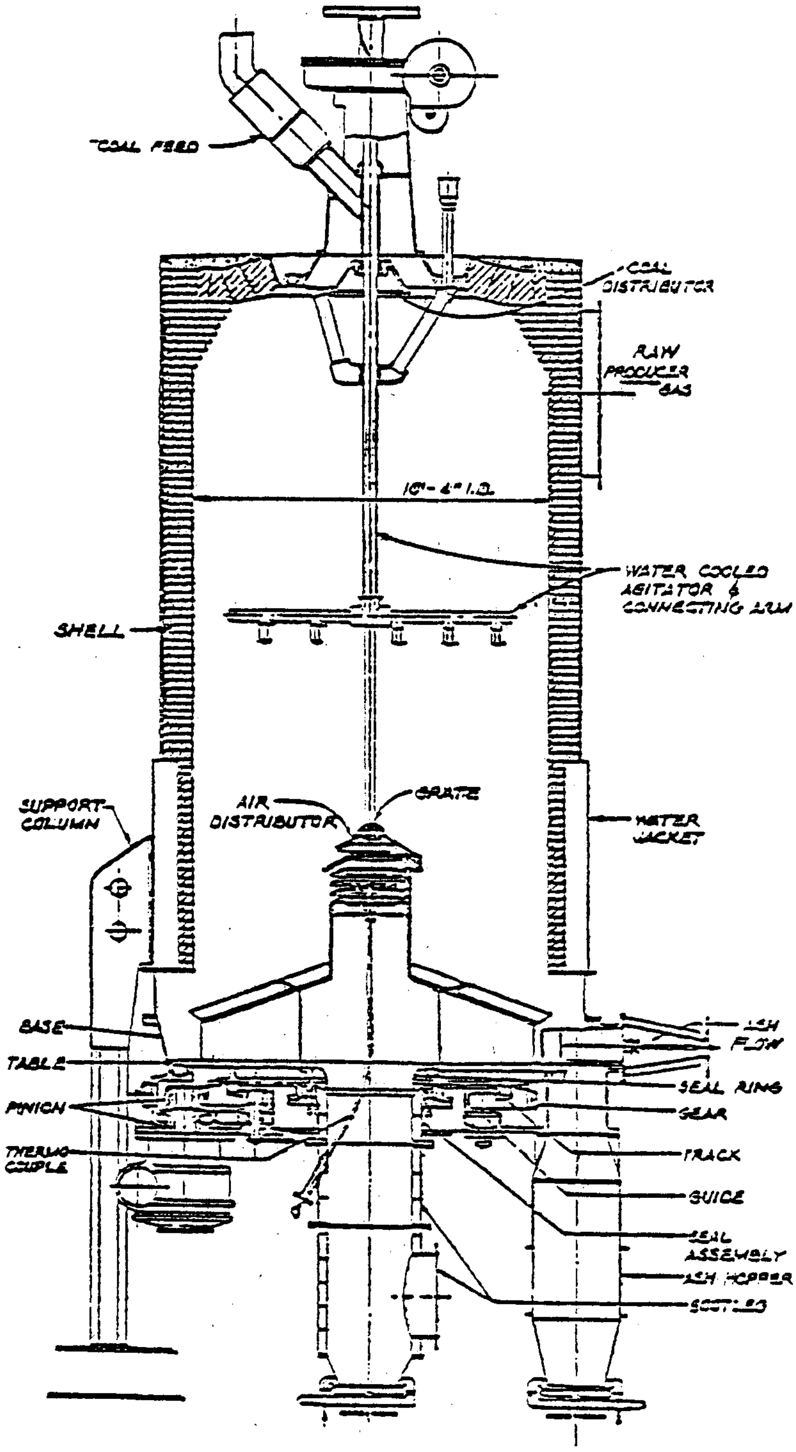


FIGURE 3.1-3 WILPUTTE GASIFIER

Table 3.1-2

Summary of Physical Systems of Wilputte Gasifier

Physical Components	
Coal Feeding System	o Chapman drum feeder for bituminous coal o Magazine for anthracite and coke
Gasifier	o Coal from top and ash from bottom o Chapman agitator o Coal distribution o Water-filled ash pan forms seal o Water-jacketed shell for anthracite coal o Brick-lined shell for bituminous coal
Ash Withdrawal System	o Rotating grate, stationary ash plow and rotating ash pan
Air/Oxygen Feeding System	o F. D. blast mixed with steam from the jacket or external source
Steam Feeding System	o For coke and anthracite: 15 psig steam from water jacket for use with air saturation o For bituminous coals: steam from waste heat boiler or outside source
Inside Diameter	o 9'-2", 10'-4"
Height	o 16'-5", 16'-5"
Advantages	
Coal Feeding System Gasifier	o No gas leakage from the coal feed system o For anthracite and coke: self sufficient steam
Air/O_2 Feeding System	o Control of air feeding rate by air saturation temperature
Disadvantages	o No steam generation for bituminous coal gasifier
Maintenance Areas	o Possible increase in maintenance for brick-lined gasifier. o Gradual erosion of agitator blade and grate
Potential for Improvement	o Adaption of anthracite gasifier for bituminous coal o Elimination of poking o Automatic control of ash withdrawal rate

3.1.1.3 Riley-Morgan Gasifier (7) (8) (9) (10) (11)

Figure 3.1-4 shows a sketch of the Riley-Morgan (R-M) gas producer and Figure 3.1-5 a schematic of the R-M gasification system. A typical commercial size gasifier is housed in a 72-foot tall building. The top half of the building houses a 60-ton coal bunker and the lower half contains the gasifier. A control room is at the rear of the building, and an enclosed flare stack is mounted above the roof.

Coal is unloaded into the truck hopper, then elevated to the bunker from which it flows to a standard Riley-Stoker Drum Feeder. This volumetric device feeds coal to a lock hopper system. The metered coal then drops into a twin lock hopper arrangement designed so that the coal gates do not close against a head of coal. The discharge of the lock hopper is governed by a count from the feeder. Coal enters the fixed top portion of the R-M gasifier and is spread evenly on top of the bed by the rotating barrel and pivoting leveller arms. As coal is consumed by the gasification process, the level at the top of the bed is automatically restored by coal feed.

Air enters the system via the forced draft fan as shown in the lower right of Figure 3.1-5. Metered steam is added downstream of the air flow meter, and the mixture enters the bottom of the rotating ash pan through a blast hood. There is no grate in the system -- the ash bed functions as a grate. The air-steam mixture moves countercurrent to the descending coal, first through the oxidizing zone, and then through the reducing and devolatilization zones.

The producer gas exits the building through a 36 inch I.D. refractory-lined duct to a cyclone dust drop, and then to consumption or further processing, as shown in Figure 3.1-5.

Ash is removed by means of a helical plow located in the ash pan. As coal is consumed, the remaining ash builds up. To maintain a level, ash is removed according to a calculated schedule in conjunction with leveller arm position. Ash is moved radially outward and over the tip of the pan where the plow is engaged. From there it is discharged through a water seal and conveyed to disposal.

The R-M gasifier has not been commercialized. However, the development gasifier is 10.5 ft in diameter which can be used as a commercial scale gasifier. R-M claims that technology and fabrication techniques are available to fabricate a 18-ft diameter unit.

A summary of physical system for the R-M gasifier and its advantages, disadvantages, maintenance areas, and potential for improvement is presented in Table 3.1-3.

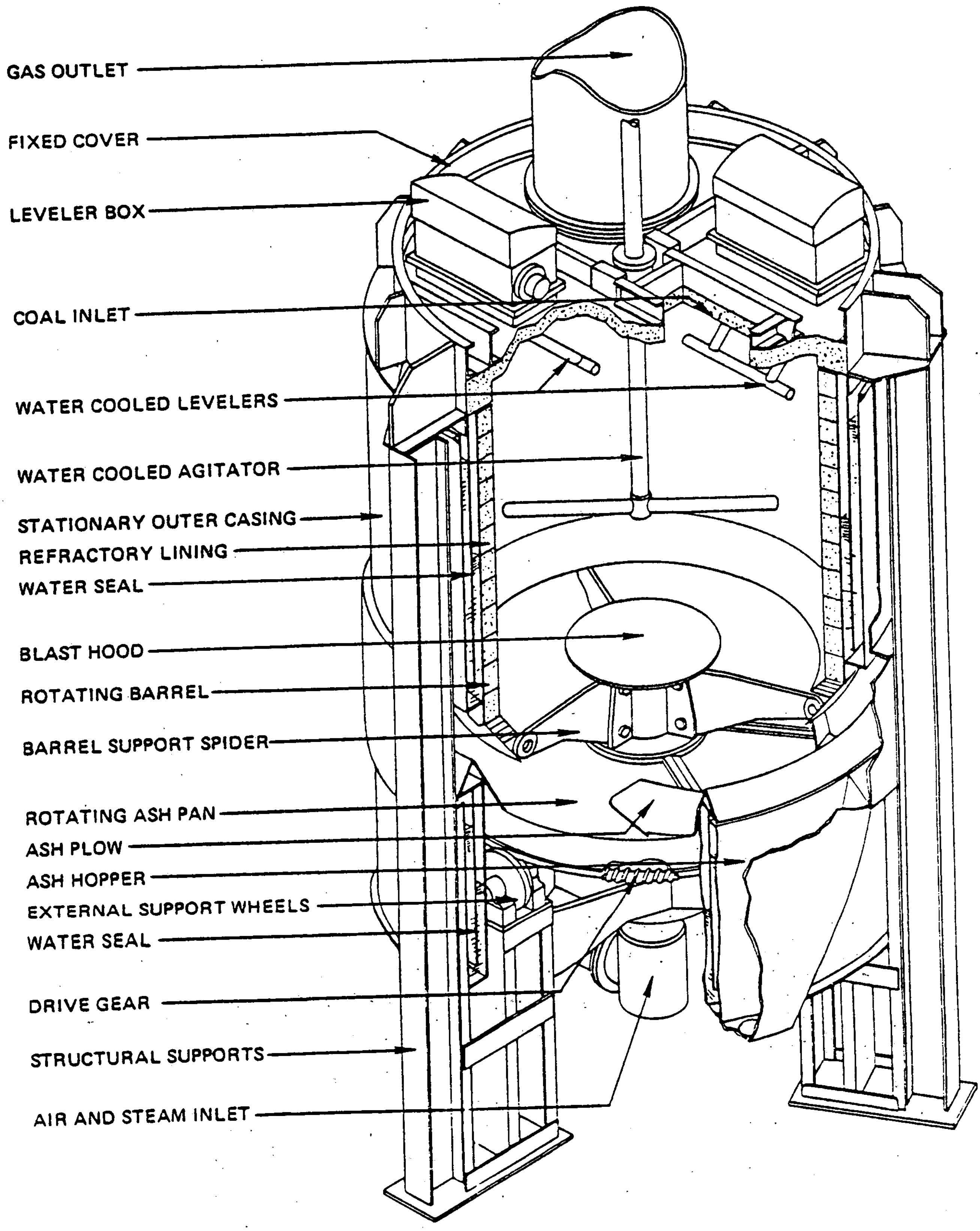


Figure 3.1-4 Riley-Morgan Gasifier

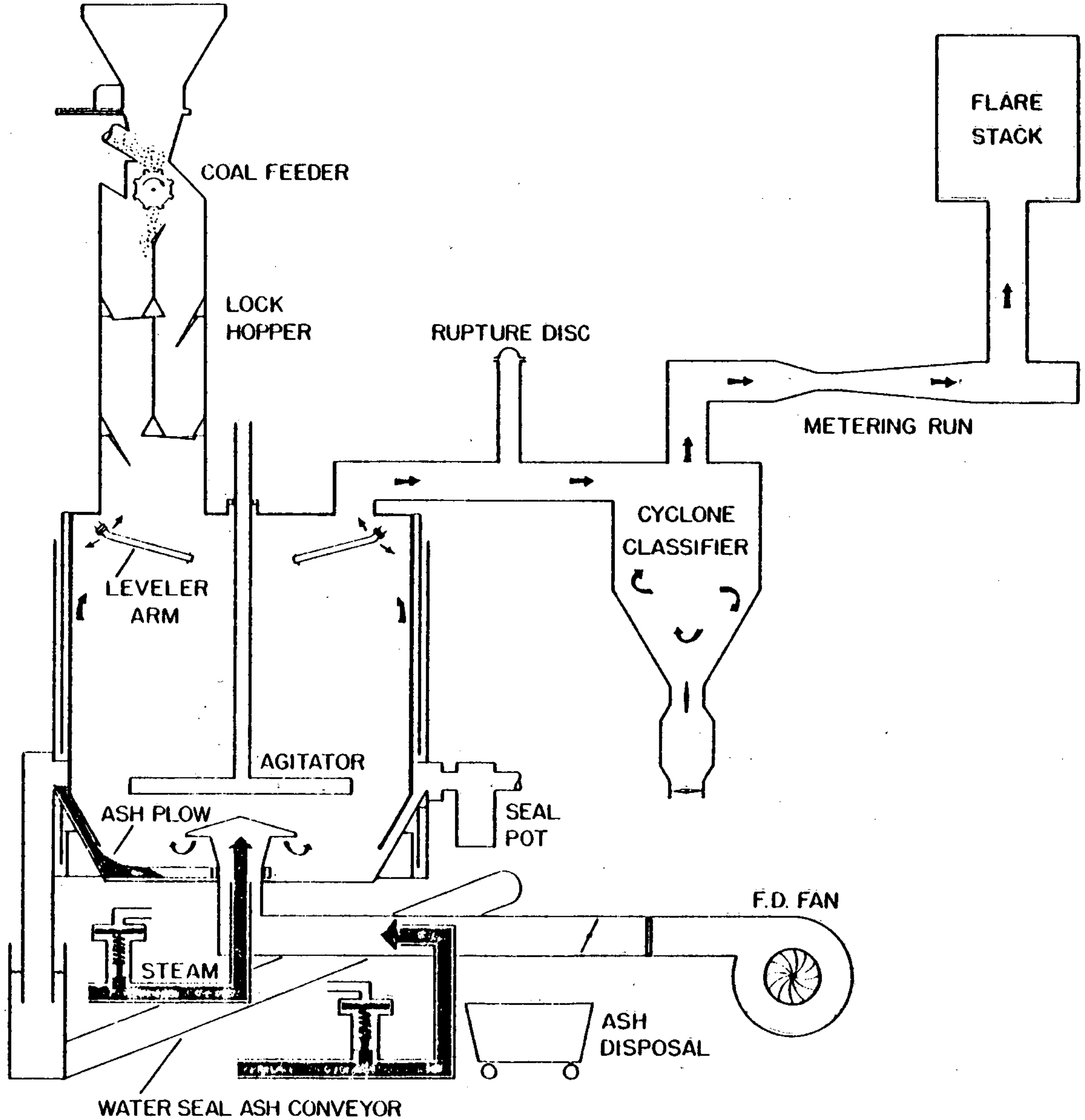


Figure 3.1-5 Schematic of Riley-Morgan Gasification System

Table 3.1-3

Summary of Physical Systems of Riley Morgan Gasifier

Physical Components	
Coal Feeding System	o Continuous automatic drum feeder and lock hopper
Gasifier	o Coal from top ash from bottom o Leveler arm to ensure uniform coal distribution across gasifier o Water-cooled rotating cylindrical gasifier shell o Water cooled agitators o Refractory lining
Ash Withdrawal System	o Intermittent removal by means of ash plow o Ash plow stationary, gasifier shell revolving o No grate
Air/Oxygen Feeding System	o F. D. fan blast o Blast hood to ensure uniform distribution o Air and steam both metered
Steam Feeding System	o Metered steam from external source
Inside Diameter	o 10'-6", 18'
Advantages	
Coal Feeding System	o No gas leakage from the feed system
Gasifier	o Rotating cylindrical shell surrounded by stationary dust hood for clean deashing
Air/O_2 Feeding System	o Air and steam streams metered
Disadvantages	o Steam from an outside source
Maintenance Areas	o High maintenance requirement due to rotating pan, barrel and charge.
Potential of Improvement	o Elimination or automation of poking o Relating ash withdrawal rate with coal feed rate

3.1.2 Two-Stage Gasifiers

The principle of the two-stage coal gasification process was originally developed by Il Gas Integrale of Milan, Italy, and has been successfully applied to the production of industrial fuel gases for over 30 years. (13) (14) (15) (16) The term "two-stage" refers to independent control of the distillation of the volatile matter and the gasification of the carbon in the coal. The two-stage gasifiers currently marketed in the United States by Woodall-Duckham (WD/GI gasifier), Applied Technology Corporation (ATC/ Wellman-Incandescent gasifier), and Foster Wheeler Energy Corporation (FW-Stoic gasifier) are designed on the same principle and, therefore, share many common mechanical features.

The two-stage gasifier is of the counterflow type primarily designed for low temperature distillation and gasification of high-volatile, weakly caking coals. The gasifier is of vertical cylindrical construction and consists of two distinct sections: (1) the refractory-lined, drying/distillation retort, and (2) the water-jacketed, gasification section.

Distillation Retort

As shown schematically in Figure 3.1-6, the distillation retort stands above the relatively short gasification section, and is nearly filled with coal. In contrast to single-stage gasifiers, the gas produced in a two-stage gasifier is withdrawn at two levels, one at the top of the retort and one at a lower level of the gasifier shell proper. A portion of the gas formed in the gasification section flows through the annular passage in the refractory wall and is withdrawn from the lower outlet. This gas stream is called the bottom gas (ATC/WI and FW-Stoic) or the clear gas (WD/GI), and is normally withdrawn at about 1100 to 1200°F. The remainder of the gas passes through the retort section and is withdrawn from the upper outlet(s). This gas is termed the top gas, and it is a mixture of the gas formed in the gasification zone and the distillation products of coal. The flow of top gas, and hence the amount of heat applied to drying and distilling, is regulated by controlling the flow of gas leaving the bottom gas outlet. As the bottom gas flow is reduced by closing a butterfly valve, the hot gas is forced to flow up through the retort section, thereby increasing the top gas temperature.

Since no mechanical stirrer is used in two-stage gasifiers, the inner refractory wall of the retort section is designed to have a slight taper toward the top to prevent bridging of difficult caking coal. In a smaller gasifier (the smallest available size is 4.5 ft I.D.), the brick lining forms a simple circular shape. In larger diameter units (the largest available size is 12.5 ft I.D.), however, the cross section of the retort is divided into four compartments by means of vertical walls which join at the center to form a cruciform. (14) (17) This arrangement prevents channelling and brings about better distribution of the gas passing upward.

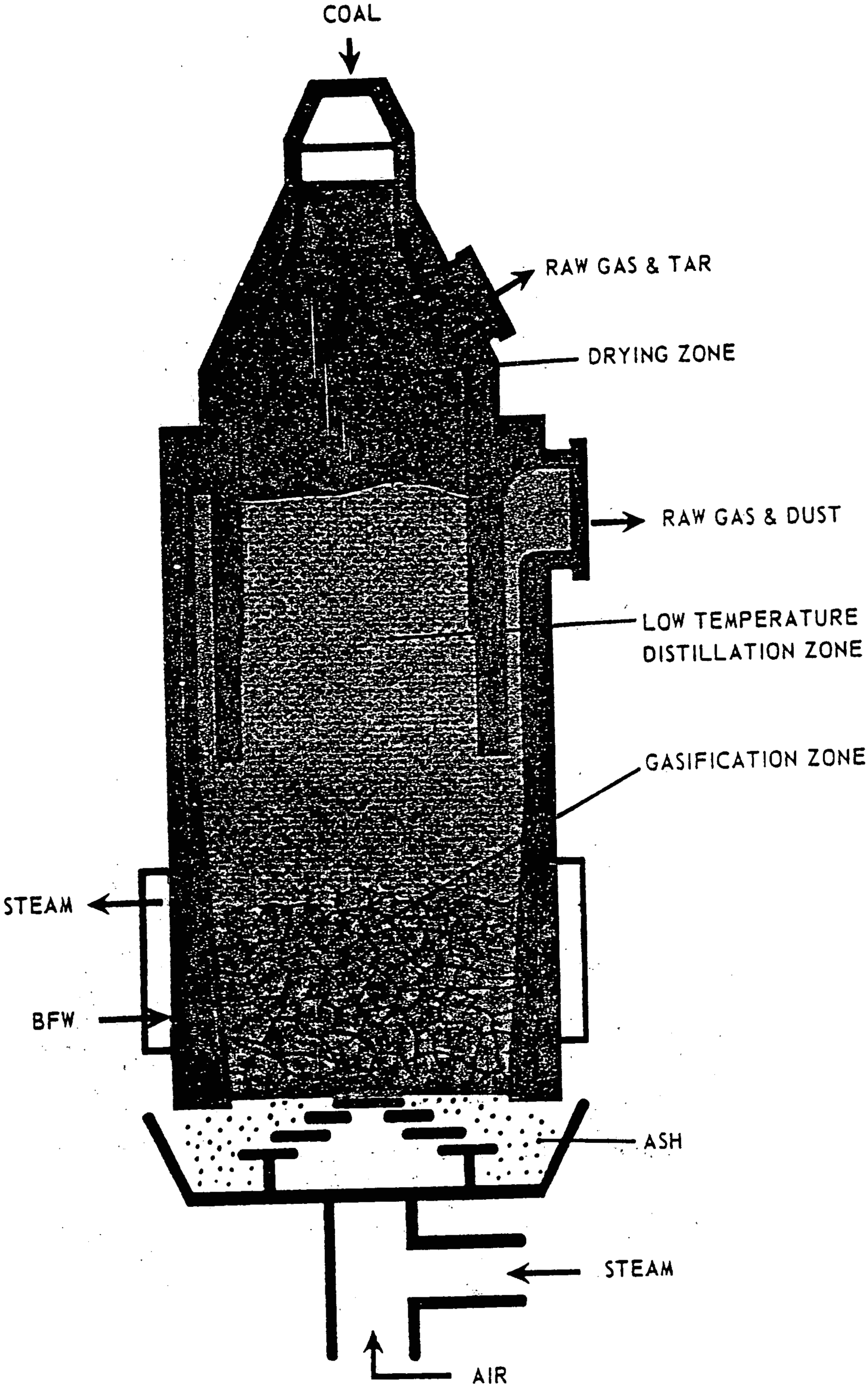


Figure 3.1-6 Typical Two-Stage Gasifier

The circular wall as well as the vertical partitions are made of hollow refractory bricks that allow passage of the bottom gas. Heat can thus be extracted from the bottom gas and imparted to the coal by means of conduction. The descending coal is therefore heated in two ways: first, by the hot gas that is rising through the bed and second, by indirect heat conduction.

An advantage of surmounting a tall retort above the main shell of the gasifier is that the raw coal is not exposed suddenly to a high gas offtake temperature. When the coal is fed over the top of the retort section via a drum feeder (ATC/WI, WD/GI, and FW-Stoic) or lock hopper (WD/GI) it meets the departing top gas at a temperature no higher than 300^{o}F. As the coal begins its slow descent, it first loses the water content, then evolves gases. Since a piece of coal takes as long as 4 to 8 hours (18) (19) to pass through the retort, oils and tars are progressively distilled off at moderate temperatures long before the coal is converted to semi-coke or char at the bottom of the retort. The released tars and oils are thus not subjected to high temperature radiation and, consequently, cracking and polymerization to pitch or soot are largely avoided.

Gasification Section

The gasification section at the lower half of the gasifier is a water-jacketed cylindrical reactor fitted with a rotating grate at the open bottom. The grate is composed of a series of circular steel rings used to remove ash as well as to distribute the incoming steam/air (or steam/oxygen) mixture. The purpose of water-jacketing is to generate the low pressure steam (or water vapor) required for the gasification reaction and at the same time to cool the reactor shell. The ash can be withdrawn either by use of lock hoppers (WD) or through a water-sealed ash pan (WI, WD, and FW-Stoic).

Air saturated with steam is introduced from the bottom of the grate. The steam-air mixture is preheated when it passes through the hot bed of ash which is proportionately cooled prior to its removal. The steam-air mixture then ascends to the fire or combustion zone where it meets the remains of semi-coke or char that has descended from the retort. Here, partial oxidation reactions take place at temperatures close to (but below) the ash fusion point, producing CO, some CO_2, and the heat required for the balance of the gasification reactions to take place above the fire zone. In the gasification zone, steam is decomposed with this heat to yield hydrogen, and more CO is produced by the accompanying reactions. The gas generated in the gasification zone is ultimately withdrawn in two streams (top gas stream and bottom gas stream) in the manner described earlier. Since the bottom gas leaves the gasification section directly through the hollow annular space in the refractory wall, it is relatively free of tar but dust-laden. The top gas stream, on the other hand, is forced to pass through the bed of coal in the retort section which acts as a filter. Furthermore, there is minimal free falling coal at the top of the retort. The top gas is therefore oil/tar-laden but relatively free of dust.

The difference in the nature of the two gas streams necessitates two separate trains of gas cleanup equipment. In the simplest arrangement, the top gas leaving the gasifier is passed through a tar cyclone which operates above the dew point of the gas. The bottom gas is dedusted in a separate cyclone. The two streams of gas are then combined to form a product gas called the "hot raw" gas. Other more elaborate arrangements involving electrostatic precipitators, spray coolers, and/ or indirect heat exchangers yield two other types of product gas commonly termed the "hot detarred" gas and the "cold, clean" gas, plus tar and oil as by-products. These will be described in more detail in a later section (Sec. 3.2.2.).

All two-stage gasifiers marketed in the United States today share the basic physical features described above (see Table 3.1-4 for a summary). To the extent information is disclosed, some differences can be found in coal feeding and ash removal systems, available standard sizes, and the degree of automation in control and instrumentation. The more notable differences are discussed below for each of the gasifiers.

3.1.2.1 Woodall-Duckham Two-Stage Gasifier

The WD two-stage gasifier (see Figure 3.1-7) is essentially the Gas Integrale gasifier originally developed for producing water gas by cyclic blasting of air and superheated steam. (14) It has been used as a continuous air-blown fuel gas generator since 1942. Currently, the WD gasifier is available in two standard sizes: a 10-ft diameter gasifier and a 12-ft diameter gasifier. (16) The empty weight of the 10-ft gasifier is approximately 100 tons, and the operating weight approximately 140 tons. The empty weight of the 12-ft gasifier is approximately 150 tons, and the operating weight is approximately 200 tons. In a 10-ft diameter unit, the height of the retort section and that of the water-jacketed section are approximately 17 ft and 8 ft, respectively.

Sized coal is typically transported from a storage to the top of the gasifier by a bucket elevator. The coal feeding system used in the WD gasifier consists of a lock hopper, a feed buffer hopper, and a flooded-feed coal distributor. (20) The coal is charged automatically to the upper hopper and its release is controlled by the level of the coal inside the distillation retort.

For ash removal, either a dry grate or a wet grate can be used. However, the dry grate gasifier is normally considered to be the more viable option for larger plant sizes. (16) In dry removal, gritty

Table 3.1-4

Summary of Physical Systems of Two-Stage Gasifier

Physical Components	
Coal Feeding System	o Lock hopper, buffer hopper (WD) o Drum feeder (WI, WD, and FW-Stoic)
Gasifier	o Coal from top, ash discharged to bottom o Refractory-lined distillation retort surmounts water-jacketed gasification section o No stirrer o Two levels of gas withdrawal o Retort may be compartmentized
Ash Withdrawal System	o Rotating grate o Dry ash removal - ash hoppers (WD) o Wet ash removal - water-sealed ash pan (WI, WD, and FW-Stoic)
Air/O_2 Feeding System	o Air saturated with steam introduced from the base of grate
Steam Generating System	o Gasification steam generated in gasifier jacket
Inside Diameter	o 4'-6" to 12'-6"
Advantages	
Coal Feeding System	o Minimum free-falling of coal o No dust carry-over (top gas)
Gasifier	o Gradual heating of coal o Separate control of distillation and gasification (consistent gas quality) o High quality by-product tars o Efficient oil and tar recovery systems
Air/O_2 Feeding System	o Blast saturation temperature control
Steam Generating System	o Self-sufficient steam generation by water-jacketing
Disadvantages	o No stirrer - can not handle high FSI coals
Maintenance Areas	o Possible gas leak from coal feeder or poke holes
Potential for Improvements	o Addition of stirrer for handling higher swelling coals o Increased slope at the retort wall for handling high FSI coals o Automated poking

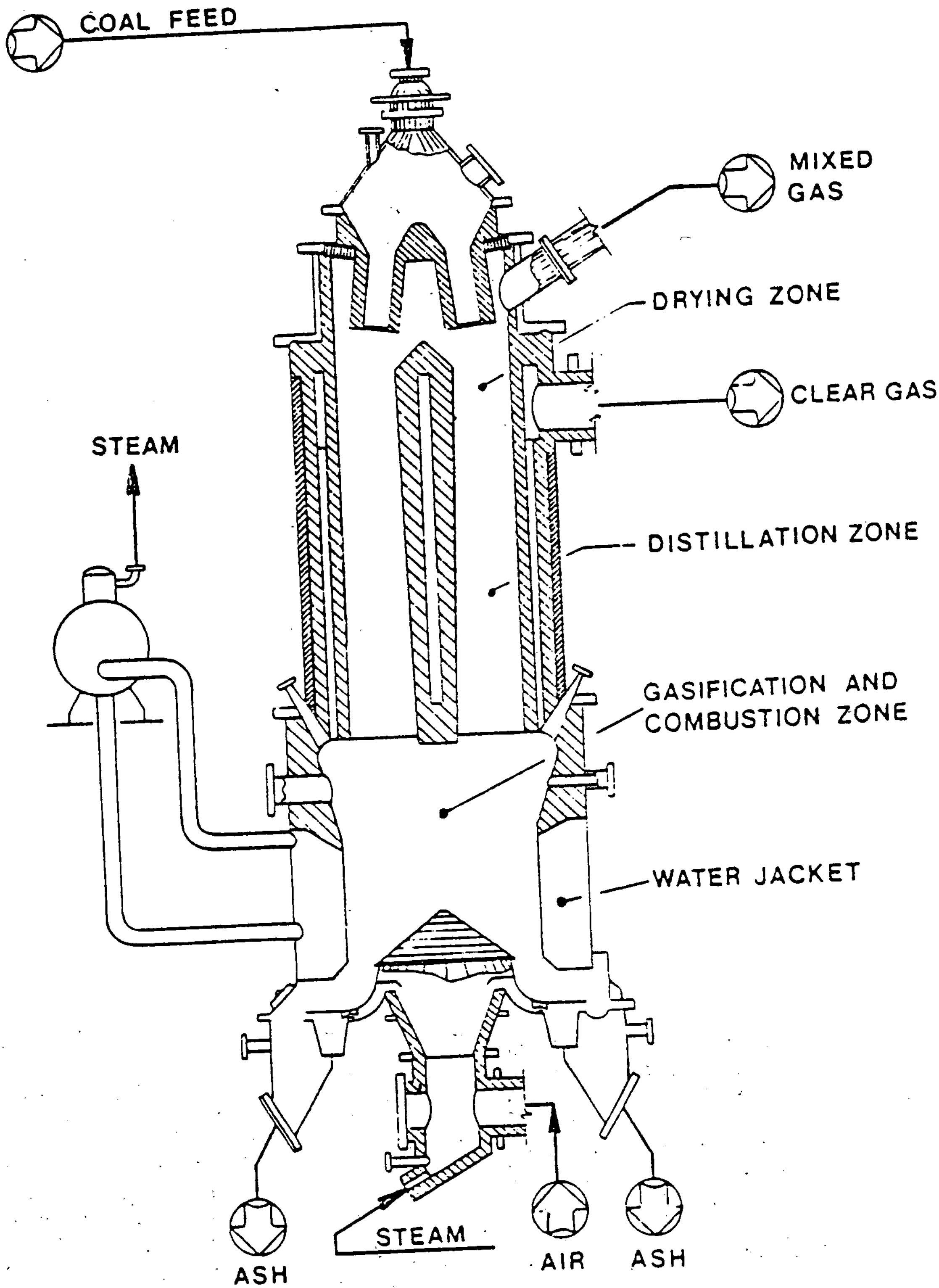


Figure 3.1-7 WD/GI Two-Stage Gasifier

ash (clinker) is released to two ash hoppers diametrically opposed and located at the bottom of the gasifier.

3.1.2.2 Wellman-Incandescent Two-Stage Gasifier

The WI two-stage gasifier is marketed in the United States by Applied Technology Corp. of Houston under exclusive license from Wellman-Incandescent, Ltd. of England. Mechanically, the WI gasifier is nearly identical to the IFE two-stage gasifier that was commercially available until the late 1950's from the International Furnace Equipment Co., Ltd. (13) (19) The WI gasifiers are currently available in seven standard sizes: 4.50, 5.50, 6.50, 8.50, 10.00, 10.75, and 12.00 ft I.D. These units can furnish fuel gas in amounts from 2 million to 100 million Btu/hr; for larger needs, multiple unit systems are used.

Figure 3.1-8 is the schematic diagram of the WI two-stage gasifier. (21) Coal supply to the bunker above the gasifier is typically by a bucket elevator. Coal feed to the retort is done by a drum type rotary feeder driven by a gear motor and is automatically activated by a dipstick mechanism which monitors the level of coal in the retort. When the charged drum rotates to discharge the coal through its open port, it seals off the gasifier at the same time so that the top gas does not escape during coal charging. The drum then resets to take another charge from the coal bunker located above, and advances a revolution counter which, together with the known capacity of the drum, gives a measurement of the coal feed rate.

In the WI gasifier, the ash is removed wet. A skirt attached to the lower edge of the water jacket is extended down into a water seal retained by an ash pan which rotates with the grate. Ash is removed by stationary ploughs which extend down into the pan at an angle to scoop up the ash and let it run over and drop into ash hoppers at the side of the pan. The integrated ash pan and grate is usually rotated by a hydraulic drive and rachet mechanism.

3.1.2.3 FW-Stoic Two-Stage Gasifier

The FW-Stoic two-stage gasifier is designed by Stoic Combustion Pty Ltd. of Johannesburg, South Africa and is marketed in the United States by Foster Wheeler Energy Corporation. (18) Currently, the gasifier is available in four sizes: 6.50, 8.50, 10.00, and 12.50 ft I.D. The 6.50-ft diameter unit handles approximately 1.3 tons per hour of coal and the 12.50-ft diameter unit approximately 4.5 tons per hour. A typical 10-ft diameter gasifier module with its associated equipments (from coal feeding to ash removal systems) can be erected on a platform 25 ft wide by 30 ft long for a structure about 80 ft high. Figure 3.1-9 shows the scale model of such a gasification plant or module. Coal supply to the bunker above the gasifier is by a bucket elevator. Fines are removed by a vibrating screen at ground level.

ATC/WELLMAN TWO-STAGE COAL GASIFIER

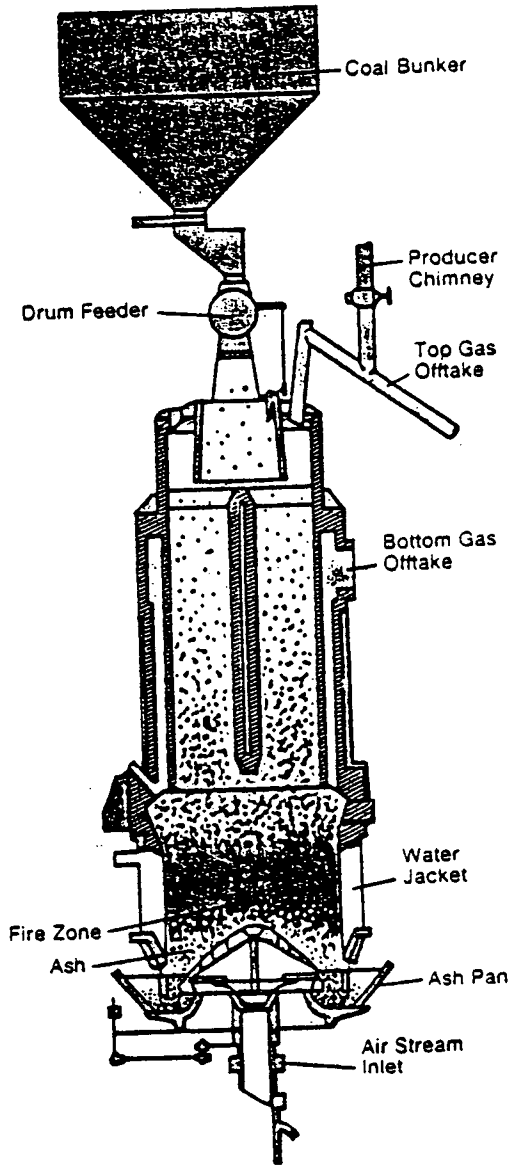


Figure 3.1-8 WI Two-Stage Gasifier

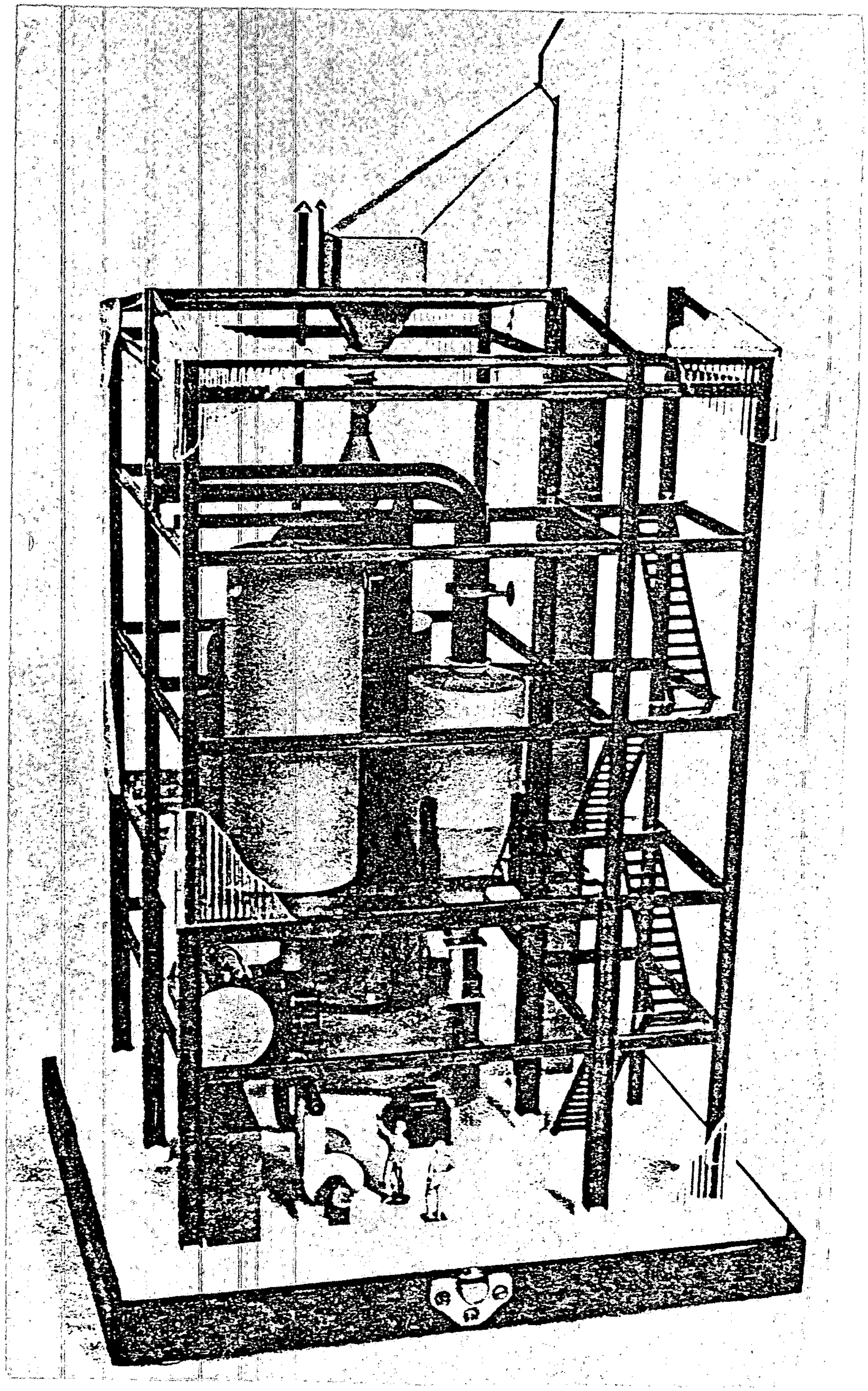


Figure 3.1-9 Scale Model of Stoic Gasification Module

Internals of the FW-Stoic gasifier are shown in Figure 3.1-10. The coal feeder is of the rotary drum type. The levels of coal in the top of both the bunker and the retort are maintained automatically.

The ash in the Stoic gasifier is removed damp. The water seal and ash removal facilities rotate to drive the ash through the water seal on to the ash conveyors.

3.2 PERFORMANCE CAPABILITIES

The performance capabilities of single- and two-stage gasifiers are similar in some aspects and different in others. Both single- and two-stage gasifiers are capable of producing two or three different types of product gas. A single-stage gasifier can produce a hot raw gas or a cold clean gas. In a two-stage, air-blown unit, a third type of product gas, i.e., the hot detarred gas, can be obtained. The product gas, however, has a comparable composition, heating value, and thermal efficiency within its type whether it is produced in a single-stage or a two-stage unit. Operating pressure in both types of gasifier is essentially atmospheric.

However, there are basic differences in the method of distillation of the coal and the properties of the distillation product. In a two-stage unit, the distillation gas is obtained by slow and steady increase in temperature of the coal in the tall retort section. The released tars and oils can therefore be removed from the gas as high quality by-products.

On the other hand, none of the two-stage gasifiers are equipped with mechanical stirrers. As a consequence, a two-stage gasifier can handle only non-caking or weakly caking coals, whereas a single-stage gasifier can handle all types of strongly caking coal as well as non-caking coals. A coal that is low in volatile matter content is also not suitable to be gasified in a two-stage unit because the advantage of its distillation process is greatly reduced.

3.2.1 Single-Stage Gasifier

In this section, the performance capabilities of the three single-stage gasifiers are discussed in terms of coal feed, product gas characteristics, and operating conditions.

3.2.1.1 McDowell-Wellman Gasifier (1)(2)(3)(12)

Coal Feed

The McDowell-Wellman (M-W) gasifier can be used for the gasification of bituminous or anthracite coal, and coke. Graded feed of uniform size with fines up to 30% is acceptable. Typical sizes of coal feed

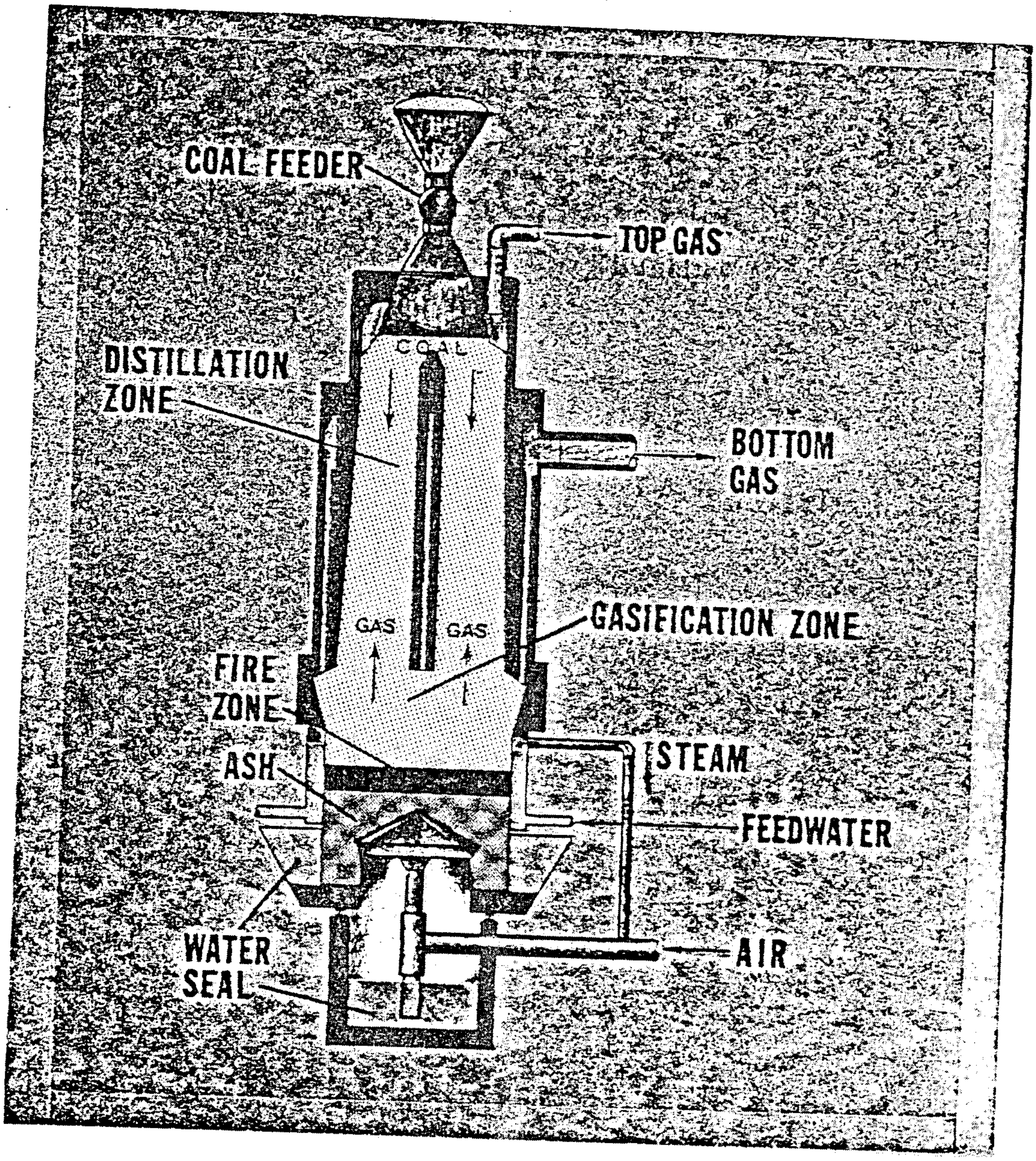


Figure 3.1-10 FW-Stoic Two-Stage Gasifier

are 1-1/4 to 2 inches for bituminous, 3/16 to 9/16 inch for anthracite, and 1/4 to 5/8 inch for coke. The M-W unit has handled successfully coal with FSI ≤ 9 in the agitated units. Minimum ash fusion temperature is $2100^{o}F$.

M-W makes both brick-lined (sizes 1-1/2 to 5 ft I.D.) as well as water-jacketed units (sizes 6-1/2 to 10 ft I.D.). Water-jacketed gasifiers can be with or without an agitator. Throughputs for varying gasifier diameters are presented in Table 3.2-1 for bituminous, anthracite and coke feeds. A typical coal feed rate to a 10-ft diameter gasifier with agitators is 84 tons per day bituminous coal or 27.6 tons/day anthracite. Typical proximate analyses of various coals which can be used in the M-W gasifier are also presented in Table 3.2-1.

Product Gas

Gas generated from a M-W gasifier can be utilized in any one of the three forms: hot raw gas and cold clean gas with or without desulfurization. The process diagram for producing these forms of gas from a M-W gasifier is shown in Figure 3.2-1.

The gas leaving the M-W gasifier at about $900-1200^{o}F$ is first passed through a refractory-lined cyclone to remove most of the particulates. Gas leaving the cyclone is hot raw gas and can be used directly. The heating value of this gas ranges from 160-210 Btu/SCF with a thermal efficiency of about 93%.

After the cyclone, the gas exchanges heat with cold, desulfurized gas and is then quenched with water in a quench drum to condense the tar and oil vapor present in the hot raw gas. The gas from the quench drum passes through an electrostatic precipitator to remove traces of particulates and a gas cooler to remove traces of oil. The gas leaving the cooler is cold clean gas. The tar, oil and water containing ammonia and other traces of impurities is sent to a tar/oil gravity separator. The heavy tars and solids settle to the bottom and are sent to a tar/oil storage tank. The aqueous layer containing oil is taken to a second settling tank and the oil layer is decanted to the tar/oil storage tank. The aqueous effluent containing ammonia and phenol is steam stripped, and the purified water is recycled for use in the gasifier jacket, the quench, and cooling units. Cold clean gas leaves the gas cooler at about $120^{o}F$ having a heating value of 146-170 Btu/SCF. Thermal efficiency ranges from 71.6 to 85.6%, depending upon the type of coal used. The cold clean gas can be used as is or can be desulfurized in a Stretford unit if sulfur content is too high.

The process scheme shown in Figure 3.2-1 uses cold desulfurized gas leaving the Stretford unit as a cooling medium in a heat exchanger for recovering heat from the hot raw gas. A waste heat boiler can be used

Table 3.2-1

Typical Coal Feed Characteristics for Single-Stage McDowell-Wellman Gasifier

Size	• 3/16" to 9/16" for anthracite		
	• 1-1/4" to 2" for bituminous coal		
	• 1/4" to 5/8" for coke charcoal		
	• Fines not more than 30%		
FSI	No limit		
Ash Fusion Temp.	>2100°F		
Typical Coals			
Proximate Analysis, %	Anthracite	Coke	Bituminous
Moisture	4.2	5.0	1.4
Volatile Matter	4.4	-	30.1
Fixed Carbon	80.7	83.1	58.5
Ash	10.7	11.9	10.0
Total	100.0	100.0	100.0
Sulfur Content, wt %	0.6	0.6	3.2
HHV, Btu/lb	12,700	16,000	13,400
Feed Rate (Air-blown), TPD			
Diameter, ft			
3.5 Standard	2.6	2.9	-
6.5 Standard	9.2	10.0	-
6.5 Agitator	11.5	12.4	34.8
8.0 Standard	13.8	15.0	-
10.0 Standard	22.1	24.0	-
10.0 Agitator	27.6	30.0	84.0

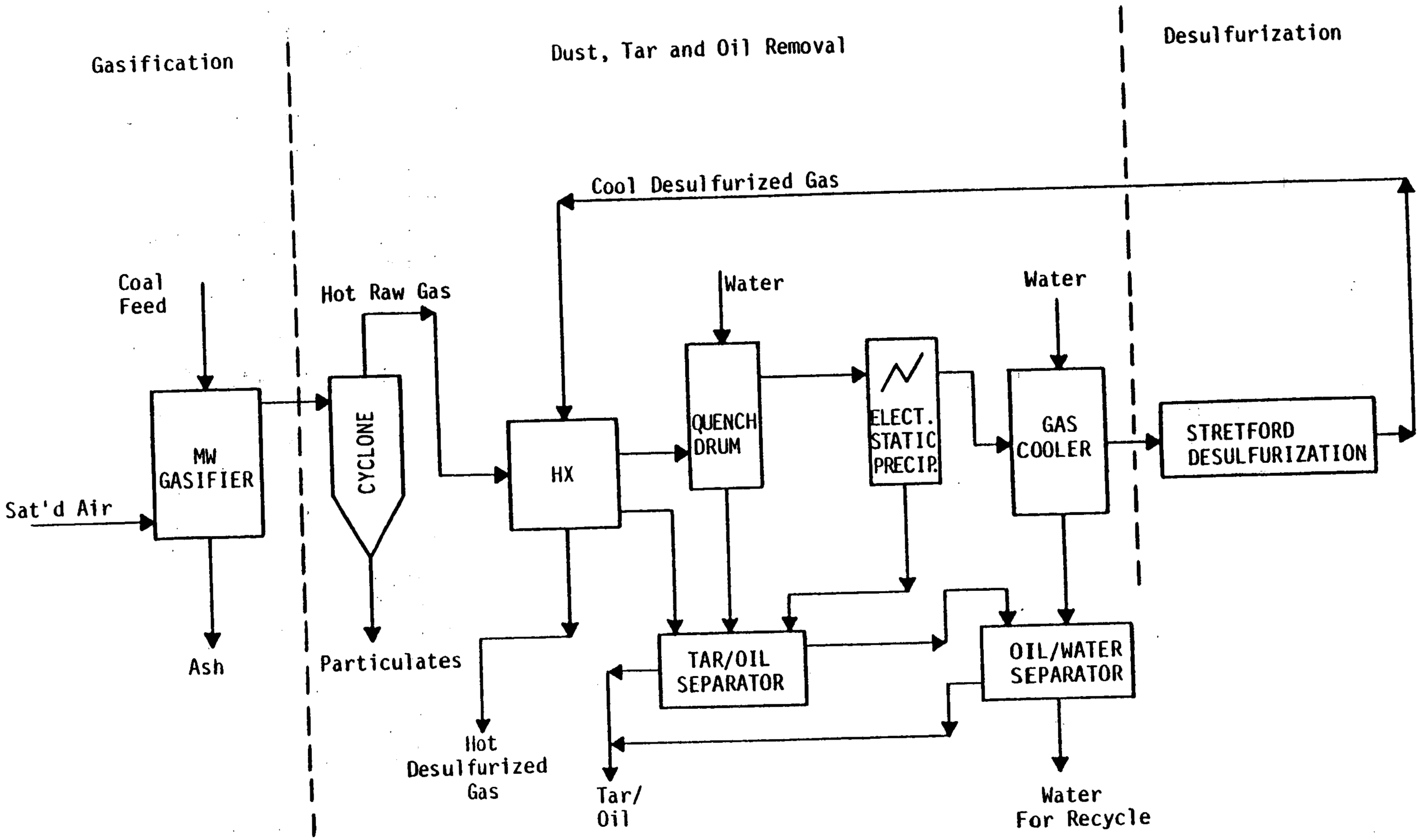


FIGURE 3.2-1 MC DOWELL-WELLMAN FUEL GAS PROCESS FLOW DIAGRAM

in place of the heat exchanger to produce steam for use in the plant. In addition to low-Btu gas, the M-W can also produce medium-Btu gas by using oxygen instead of air. Typical product gas characteristics obtainable from the M-W gasifier are given in Table 3.2-2.

Operating Conditions

In a typical air-blown, M-W gasifier, 3.12 lb of air/lb of coal and 0.5 lb of steam/lb of coal are utilized. This corresponds to a blast saturation temperature of 141°F for the air-steam mixture entering the gasifier. Depending upon the ash fusion temperature of coal, the air-steam ratio is regulated to avoid formation of clinkers (insufficient steam) or dry powdery ash bed (too much steam). The gas leaves the gasifier at 800-1200°F depending upon the coal type and is at a pressure of 5 to 6 inches of water. The M-W gasifier can be turned down from 100% throughput to about 8% without affecting its efficiency adversely.

A summary of operating conditions of the M-W gasifier is presented below:

. Oxidant, lb/lb coal	3.21 for air and 0.8 for oxygen
. Steam, lb/lb coal	0.5
. Combustion zone temperature, °F	2400
. Pressure at gas outlet, inches W.G.	5-6
. Turndown capability	13 to 1

3.2.1.2 Wilputte Gasifier (4)(5)(6)

Coal Feed

Bituminous coal, subbituminous coal, anthracite, and coke have been gasified in the Wilputte gasifier. Typical coal size is 3-4 inches for all coal types, but 1-3/8 to 4 inches can also be used with up to 10% fines. The highest FSI of coal used is 6 and ash fusion temperatures must be greater than 2300°F. Coal feed requirements for Wilputte gasifier are summarized in Table 3.2-3 along with the typical characteristics of bituminous coal used in the Wilputte unit. A 10 ft-4 in air-blown Wilputte unit can gasify 60 TPD of bituminous coal.

Product Gas

Figure 3.2-2 shows a schematic of the Wilputte gasification system to produce three different product streams of hot raw gas; dust, tar-, and oil-free gas; and dust-, tar-, oil-free and desulfurized gas. The

Table 3.2-2

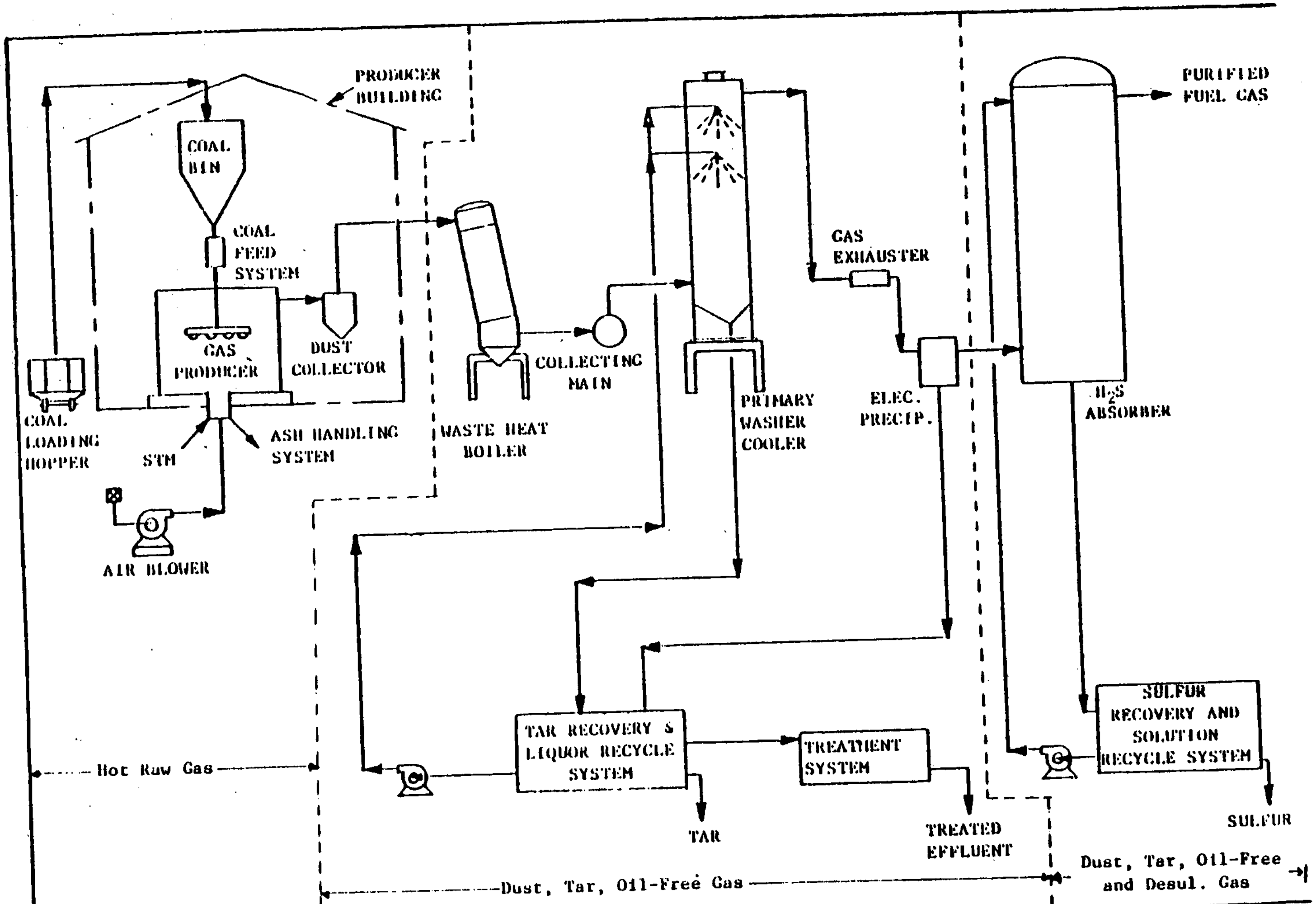
Typical Product Gas Characteristics Available from Single-Stage McDowell-Wellman Gasifier

	Low-Btu Gas	Medium-Btu Gas
Composition, Vol. %		
H_2	18.7	36.25
CO	24.9	47.05
CO_2	6.2	13.90
CH_4	0.6	0.65
N_2	49.3	2.05
Others	0.3	0.10
Total	100.0	100.00
HHV, Btu/SCF		
Hot raw gas	160-210	
Cold clean gas	146-170	258-270
Temperature, ^{o}F		
Hot raw gas	800-1200	-
Cold clean gas	120	120
Thermal efficiency, %		
Hot raw gas	93	-
Cold clean gas	71.6-85.6	-
Gas product rate, SCF/lb coal	50-75	-
By-product rate		
tar/oil, lb/lb coal	0.06	-

Table 3.2-3

Typical Coal Feed Characteristics for Single-Stage Wilputte Gasifier

Size		3"-4"
		Fines up to 10% acceptable
FSI		up to 6
Ash Fusion Temp., °F		>2300
Typical Coal		Bituminous
Proximate Analysis, %		
Moisture		3.28
Volatile Matter		35.31
Fixed Carbon		55.87
Ash		5.54
	Total	100.00
Sulfur, wt %		0.47
HHV, Btu/lb		13,200
Feed Rate, TPD		60 for 10'-4" dia. air-blown gasifier



Wilputte CORPORATION

REVISION		DRAWN	DATE
BY	DATE	Cuevas	5/12/77
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FIGURE 3.2-2 WILPUTTE FUEL GAS PROCESS FLOW DIAGRAM

SK-12897-L

gas from the gasifier is passed through a dust collector to produce hot raw gas. The gas has a higher heating value of 207 Btu/SCF and a thermal efficiency of 90% including the sensible heat and the heating values of tar and oil. The hot raw gas from the dust collector goes to a waste heat boiler. The dust-free gas is sent to water scrubbing to condense tar and oil. The tar is separated from the scrubbing liquor in a decanter which is provided with a slow moving rake to remove settled solids. The product tar is continuously removed from the decanter as pumpable tar and used as a fuel. An electrostatic precipitator is used to remove traces of tar and oil from the scrubbed gas. The scrubbing liquor is continuously recycled through spiral exchange coolers to control the temperature. An exhauster is used to pass the gas through the sulfur removal equipment.

The gas leaving the electrostatic precipitator is dust-, tar-, and oil-free. This gas has a heating value of 170 Btu/SCF and yields a thermal efficiency of 80%. If necessary, the detarred gas can be desulfurized in a Holmes-Stretford process, as shown in Figure 3.2-2.

Typical product gas characteristics obtained from a Wilputte gasifier are given in Table 3.2-4.

Operating Conditions

For an air-blown, Wilputte gasifier, the amount of air required varies from 3.31 to 3.67 lb/lb coal, and the amount of steam is 0.53 lb/lb coal. The air and steam rates are controlled to provide a blast saturation temperature of 138 to 141^{o}F. The gas leaving the gasifier is at 1200^{o}F and at a pressure of 2 to 4 inches water when a bituminous coal is used. The turndown capability of Wilputte gasifier is 10:1 based on maximum capacity.

A summary of operating conditions of the Wilputte gasifier is given below:

. Air, lb/lb coal	3.31-3.67
. Steam, lb/lb coal	0.53
. Temperature profile, ^{o}F	
Devolatilization	1200-1500
Gasification	1500-1850
Combustion	2200-2300
. Pressure at gas outlet, inches water	10-20
. Turndown capability	10 to 1

Table 3.2-4

Typical Product Gas Characteristics Available from Single-Stage Wilputte Gasifier

		Low Btu Gas
Composition, Vol. %		
H_2		16.6
CO		22.7
CO_2		5.9
CH_4		3.6
N_2		50.9
Others		0.3
	Total	100.0
HHV, Btu/SCF		
Hot raw gas		207
Cold clean gas		170
Temperature, ^oF		
Hot raw gas		1200
Cold clean gas		120
Thermal efficiency, %		
Hot raw gas		90
Cold clean gas		80
Gas product rate, SCF/lb coal		57.3
By-product rate, lb/lb coal		
Tar		0.1
Oil		0.2

3.2.1.3 Riley-Morgan Gasifier (7)(8)(9)(10)(11)

Coal Feed

The typical coal feed sizes used in a Riley-Morgan gasifier are 3/8 to 5/8 inches for anthracite, 1-1/4 to 2 inches for bituminous coal, and 3/4 to 1-1/2 inches for coke. Fines up to 10% are acceptable. Riley-Morgan specifies that the ash fusion temperature should not be less than 2700°F for anthracite and 2400°F for bituminous coal. R-M can handle coal of FSI $\leq$ 8-1/2. Typical coal feed characteristics for R-M gasifiers are summarized in Table 3.2-5.

The typical coal feed rates to a 10-1/2 ft diameter R-M gasifier are 90 and 156 TPD, respectively, for air-blown and oxygen-blown units.

Product Gas

The process schematic diagram of the Riley-Morgan gasification system is shown in Figure 3.2-3 to produce three product streams of hot raw gas; dust-, tar-, and oil-free gas; and dust-, tar-, oil-free and desulfurized gas. The gas leaving the R-M gasifier passes through a dust collector where particulates are removed. The gas leaving the dust collector (hot raw gas) is at a temperature of 1100°F and at 40 inches of water pressure. It has a heating value of 185-201 Btu/SCF for air-blown and 262-305 Btu/SCF for oxygen-blown gasifiers. Thermal efficiency of 88-90% is obtained for air-blown gasifier. Wide ranges of heating value of product gas and thermal efficiencies are due to the use of various coal types.

The hot raw gas is then cleaned and cooled to remove heavy tars in the direct quench and the lighter tars in the indirect cooler. This is followed by the electrostatic precipitator to remove the last trace of tar droplets. The light oils are removed in light oil absorber. The detarred gas yields a heating value of 138-163 Btu/SCF and a thermal efficiency of 70.5 to 78.3%, depending upon coal types used.

Gas leaving the light oil absorber is fed to a Stretford desulfurization unit for removal of H_2S and for production of dust-, tar-, oil-free and desulfurized gas.

Typical product gas characteristics obtained from the R-M gasifier are summarized in Table 3.2-6.

Operating Conditions

For air-blown, R-M gasifier, the air requirement ranges from 2.98 to 3.44 lb/lb coal, and the steam requirement is 0.56 lb/lb coal, giving a blast saturation temperature of 142-147°F for the air-steam mixture entering the gasifier. The hot raw gas leaves the gasifier at 1080-1100°F

Table 3.2-5

Typical Coal Feed Characteristics for Single-Stage Riley-Morgan Gasifier

Size	• 3/8" to 5/8" for anthracite
	• 1-1/4" to 2" for bituminous coal
	• 3/4" to 1-1/2" for coke
	• Up to 10% fines acceptable
FSI	up to 8-1/2
Ash Fusion Temp., °F	• Bituminous - 2400
	• Anthracite - 2700

Typical Coals

Proximate Analysis, %	Anthracite	Coke	Bituminous
Moisture	3.95	9.2	3.43
Volatile Matter	4.45	1.0	30.93
Fixed Carbon	81.70	81.2	53.81
Ash	9.90	8.6	11.83
Total	100.00	100.0	100.00
Sulfur, wt %	0.7	1.0	0.9
HHV, Btu/lb	12,700	16,000	13,400
Feed Rate (10'-6" dia.), TPD			
Air-blown	36-48	50.4	90
Oxygen-blown	61-82	85.2	156

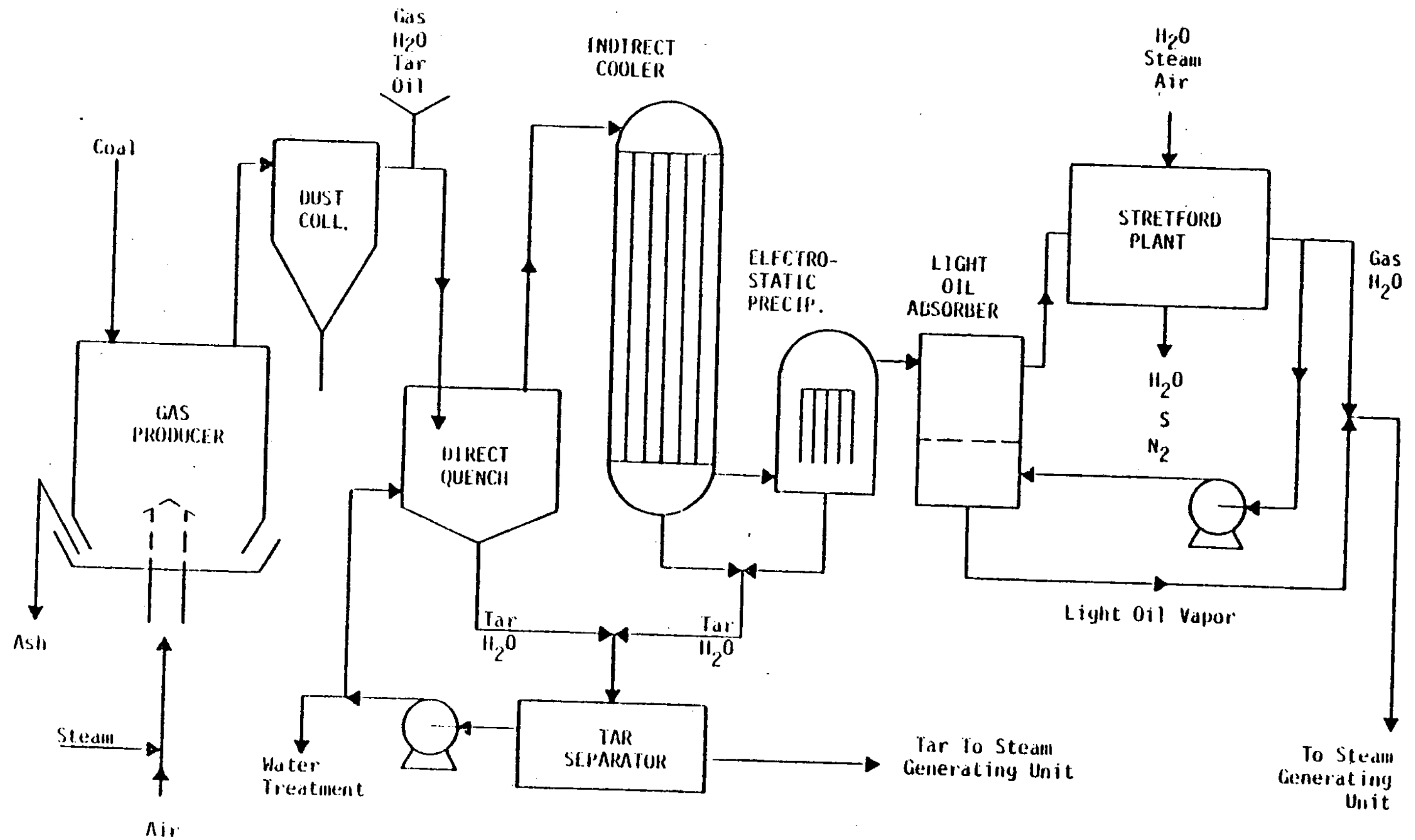

Figure 3.2-3 Riley-Morgan Low-Btu Gas Plant Flow Diagram

Table 3.2-6

Typical Product Gas Characteristics Available from Single-Stage Riley-Morgan Gasifier

	Low-Btu Gas	Medium-Btu Gas
Composition, Vol. %		
H_2	18.7	39.2
CO	24.9	41.3
CO_2	6.2	17.5
CH_4	0.6	1.4
N_2	49.3	0.6
Others	0.3	-
Total	100.0	100.0
HHV, Btu/SCF		
Hot raw gas	185-201	
Hot detarred gas	165-179	
Cold clean gas	138-163	262-305
Temperature, ^{o}F		
Hot raw gas	1080-1100	1100
Cold clean gas	120	120
Thermal efficiency, %		
Hot raw gas	88-89.9	
Cold clean gas	70.6-78.3	75.0
Gas product rate, SCF/lb coal	58-63	28
By-product rate, lb/lb coal		
Tar	.078	0.078
Oil	.009	0.009

and under a pressure of about 40 inches of water. Turndown capability is 10:1 based on maximum capacity. Data on operating conditions for a 10-1/2 ft diameter R-M gasifier are summarized below:

	Low-Btu Gas (Air)	Medium-Btu Gas (O_2)
Air or O_2, lb/lb coal	2.98-3.44	0.6-0.7
Steam, lb/lb coal	0.56	1.3-1.5
Temperature profile, ^oF		
Devolatilization	1200-1500	1200-1500
Gasification	1600-1800	1600-1800
Combustion	2000-2100	2000-2100
Pressure at gas outlet, inches in water	40	40
Turndown capability	10 to 1	10 to 1

3.2.2 Two-Stage Gasifier

Performance capabilities of all two-stage gasifiers are very similar. All can operate only with a weak-caking coal because there is no stirrer in two-stage gasifiers to break up agglomerations. All require sized feed coal and removal of fines, as fines may plug the deep coal bed in the tall retort section and severely hinder uniform flow of ascending gas. In air-blown operation, the two-stage systems can produce two or three different types of product gas (hot raw gas, hot detarred gas or cold clean gas) having comparable heating values and thermal conversion efficiencies. Operating temperature and pressure are nearly identical in all gasifiers. For recovery of byproduct tar and oils, all utilize electrostatic precipitators and coolers.

However, there are some differences in the process configurations for producing the final product gas. Only WD offers an oxygen-blown system for producing medium-Btu gas. Considerations as to which coal type or types are suitable for use in the two-stage gasification process also appear to differ among manufacturers. In the following discussion, performance capabilities of Woodall-Duckham, Wellman-Incandescent, and Stoic two-stage gasifiers are detailed in three categories -- coal feed, product gas, and operating conditions.

3.2.2.1 Woodall-Duckham Two-Stage Gasifier

Coal Feed

The WD two-stage gasifier can be operated with a range of coal feed from lignite through subbituminous to bituminous coal. The gasifier can also operate on an anthracite coal; however, an anthracite feed is not normally considered to be an economical alternative because of its relatively low volatile content.(16) In general, the feed coal should have an FSI of less than 2-1/2 or 3 and should be graded in the typical size range of 3/8 to 1 inch, 1/2 to 1-1/2 inches or 3/4 to 2 inches (16) for satisfactory operation of the gasifier. Fines must be removed by double screening. However, predrying of feed coal is normally not required. The ash fusion temperature of coal should ideally be greater than 2200°F but a coal with an ash fusion as low as 2050°F may be used. With a change in the ash fusion point, the temperature in the gasification/fire zone is varied by varying the steam/air ratio so as to maintain the proper gritty ash condition for easy dry removal.

The coal feed rate to a 10-ft diameter WD gasifier is approximately 3 to 3.5 tons per hour (72 to 84 TPD); and the capacity for a 12-ft unit is approximately 3.5 to 4.5 tons per hour (84 to 108 TPD). Table 3.2-7 summarizes the requirements for coal feed, along with the proximate analysis of a typical bituminous coal that can be used in the WD gasifier.

Product Gas

Two basic types of product gas are obtained with air-blown operation in the WD gasification plant. To produce a hot raw gas, the top gas (250°F) is passed through a tar cyclone to remove large droplets of tar, and the clear gas (i.e., the bottom gas at 1200°F) flows through a dust cyclone to remove entrained dust (Figure 3.2-4). The gases are then combined, and the heat in the clear gas revaporizes the tar and oil mist in the top gas. The resultant gas is called the hot raw gas and, because of its relatively high temperature (600 to 700°F), it can be distributed in insulated mains without deposition over distances up to 1500 ft.(12) The thermal conversion efficiency is approximately 88 to 92%. The effective heating value of hot raw gas is 200 to 210 Btu/SCF when the sensible heat as well as the heating values of tar and oil are included.

To produce a cold clean gas, the top gas is passed through a tar precipitator without cooling, as shown in Figure 3.2-5. The precipitator operates above the gas dewpoint, and consequently, no more than 1% water is contained in the recovered tar. The tar is fluid (pumpable) because of the gentle distillation process used, as described in Section 3.1.2. The detarred gas is then cooled in a heat exchanger and passed through a second precipitator to remove both oil and water

Table 3.2-7

Coal Feed Characteristics for WD Two-Stage Gasifier

Size	• Must be fairly uniform; typical size range: 3/8" to 1", 1/2" to 1-1/2", or 3/4" to 2"
	• Can accept only a limited quantity of fines
FSI	• <1-1/2 ideally, but could use coals with FSI up to 2-1/2 or 3
Ash Fusion Point	• >2200°F ideally, but may be as low as 2050°F
Typical Bituminous Coals	
Proximate Analysis, %	
Moisture	3.02
Volatile Matter	31.96
Fixed Carbon	56.64
Ash	8.38
Total	100.00
Sulfur content (dry, wt %)	3.89
HHV, Btu/SCF	13,000
Feed Rate, TPD (10-ft dia. unit)	72 - 84

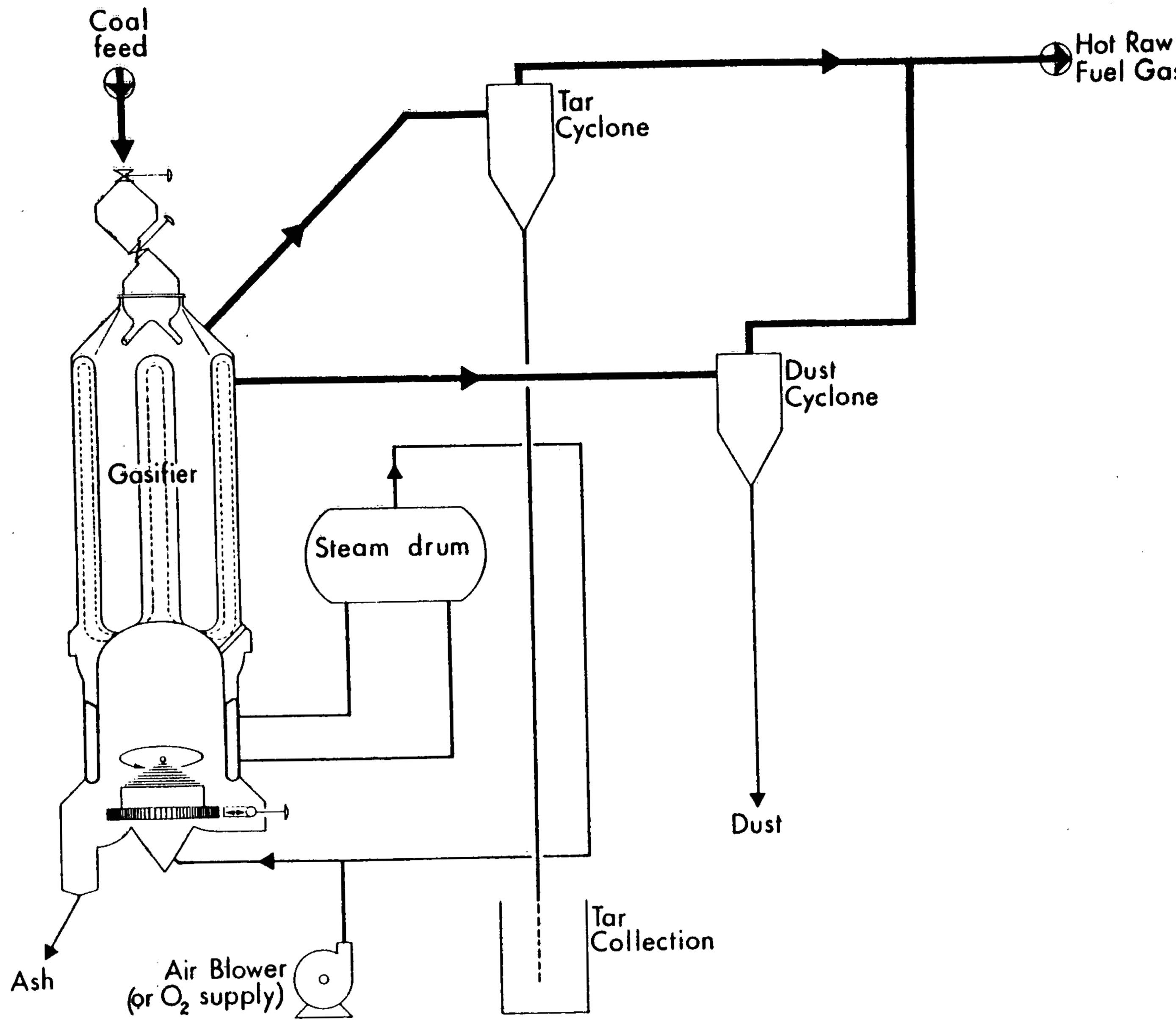

Figure 3.2-4 WD/GI Process for Hot Raw Gas

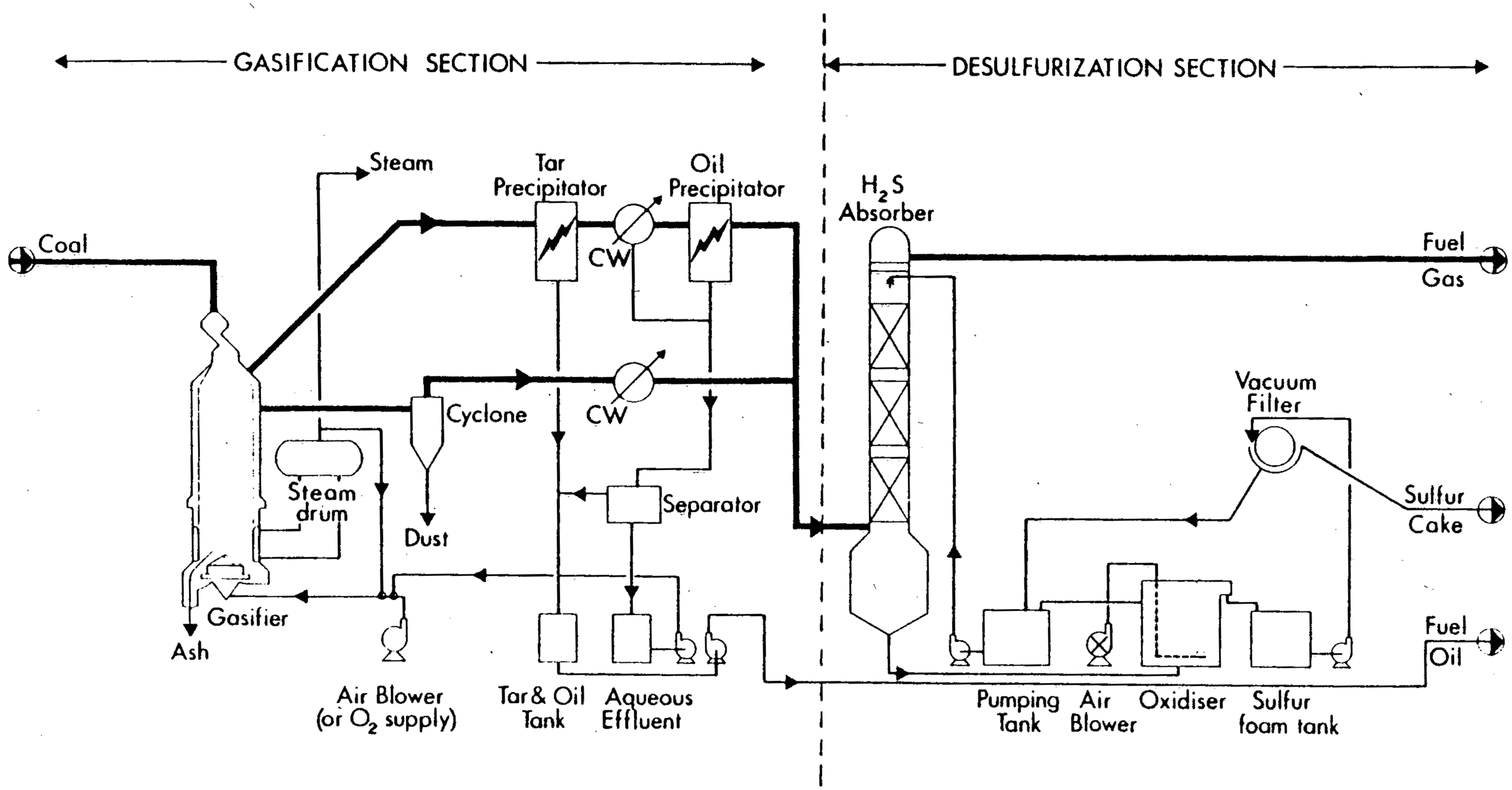

Figure 3.2-5 WD/GI Process for Desulfurized Cold Clean Gas

droplets. The oil, however, is easily separated from water as a by-product. The clear gas leaving the gasifier, on the other hand, is dedusted in a cyclone, cooled in a heat exchanger, and finally mixed with the cleaned top gas. The resultant product gas is the cold clean gas (120°F), having a heating value of approximately 176 Btu/SCF. The thermal efficiency is about 74 to 76%. This gas is suitable for feeding to a low temperature desulfurization process (e.g., Stretford) if the sulfur content is too high.

In addition to the above two types of low-Btu gas, the WD gasifier has also been used to produce medium-Btu gases by substituting oxygen for air, or by cyclic operation with air and superheated steam.[(14)(16)] Typical product gas compositions obtainable from WD gasifiers are given in Table 3.2-8 which also summarizes other pertinent performance characteristics.[(20)(22)(25)]

Operating Conditions

In a typical air-blown operation, the air requirement is approximately 2.3 lb/lb coal and the steam requirement approximately 0.25 lb/lb coal.[(12)] This results in a normal blast saturation temperature of about 128°F for the steam-air mixture entering the gasifier from the bottom. With a change in the ash fusion point of coal, however, the actual steam/air ratio may be modulated to vary the gasification/fire zone temperature in the range of 2000 to 2500°F. The top gas temperature is normally regulated in the range of 220 to 250°F while the clear gas may leave the gasifier in the range of 900 to 1500°F.

The pressure in the gasifier is essentially atmospheric. In a dry grate gasifier, the inlet pressure is 40 to 60 inch w.g. and the outlet pressure is about 30 to 40 inch w.g. In a wet grate gasifier, the inlet and the outlet pressures are, respectively, 20-30 inch w.g. and 15-20 inch w.g.

A single WD gasifier can be turned down to about 30% of design capacity. On plants involving multiple units it is possible to achieve a further turndown.[(11)] The product gas heating value will be reduced slightly during the period the gasification plant is turned down.[(16)]

A summary of operating conditions described above and other pertinent data relative to the operation of the WD gasifier[(12)(16)] is presented below:

Table 3.2-8

Product Gas Types Available from WD Two-Stage Process

	Med.-Btu Gas		Low-Btu Gas	
	Cyclic	O_2-blown	Hot raw	Cold clean
Composition, male % (moisture, tar, tar oil free)				
H_2	52.2	38.4	17.0	17.0
CO	28.5	37.5	28.2	28.2
CO_2	8.0	18.0	4.5	4.5
CH_4	6.5	3.5	2.7	2.7
N_2	4.2	2.2	47.1	47.1
Others (H_2S, COS, NH_3)	0.6	0.4	0.5	0.5
	100.0	100.0	100.0	100.0
Tar and Tar Oil, lb/lb coal	Not Available	Not Available	0.075-0.12	-
Temperature, °F	-	-	600-700	120
Sp. gr. (Air = 1)	0.52	0.73	-	0.83
Wobbe No.	465	334	-	193
Thermal efficiency, %	-	89-93	88-92	74-76
Gas prod. rate, SCF/lb coal	-	-	-	50-53

Temperature, °F		
Gasification Zone	2000-2500	
Bottom Gas Offtake	900-1500	
Top Gas Offtake	220-250	
Pressure, inch w.g.	Dry Grate	Wet Grate
Gasifier Inlet	40-60	20-30
Gasifier Outlet	30-40	15-20
Air/Steam Requirements		
Air, lb/lb coal	2.3	
Steam, lb/lb coal	0.25	
Turndown Capability	25-30%	

3.2.2.2 Wellman-Incandescent Two-Stage Gasifier

Coal Feed

The WI two-stage gasifier has been operated on a wide range of brown and bituminous coals. In general, the feed coal must be fairly uniformly graded in the size range of 2 to 3 inches; however, up to 10% by weight of undersize (smaller than 2 inch but larger than 5/16 inch) and up to 15% of fines less than 5/16 inch are considered acceptable.[21] Alternate size ranges are 1-1/2 to 2-1/2 inches and 3/4 to 1-1/2 inches. The coal should have an FSI of 1 to 3, and the ash fusion temperature must be at least greater than 2200°F for satisfactory operation of the two-stage gasifier. Other desirable coal properties are summarized in Table 3.2-9 along with the proximate analysis of a typical bituminous coal that can be used in the WI gasifier. Nominal coal consumption rates for various standard size WI gasifiers are given in Table 3.2-10.[23] The nominal thermal output from an individual unit ranges from 0.25 to 2.2 billion Btu/day.

Product Gas

Depending on the process application three different types of product gas can be manufactured in the same basic WI gasifier.

Table 3.2-9

Desirable Feed Coal Properties for WI Gasifier

Free Swelling Index	1 to 3
Ash Fusion Temperature	greater than 2200°F
Coal Size	2" to 3", 1-1/2" to 2-1/2", or 3/4" to 1-1/2"
Allowable Undersize	
Max. 10% by wt.	5/16" to 2"
Max. 15% by wt.	fines less than 5/16"
Max. Moisture Content	15 wt %
Hardgrove Index	40 to 70
Typical Bituminous Coal	
Moisture	4.65 %
Volatile Matter	34.24
Fixed Carbon	52.33
Ash	8.78
	100.00%
HHV	12,470 Btu/lb
Sulfur content	3.87%

Table 3.2-10

Coal Feed Rate, Thermal Output Rate and Efficiency on WI Two-Stage Gasifiers

Gasifier Diameter, Feet	Coal Feed Rate, TPD	Thermal Output, 10^9 Btu/day			Thermal Efficiency, %[a]		
		Hot Raw Gas	Hot Detarred Gas	Cold Clean Gas	Hot Raw Gas	Hot Detarred Gas	Cold Clean Gas
4.50	13.92	0.30	0.28	0.25	89.8	83.3	76.2
5.50	20.40	0.44	0.41	0.37	90.2	83.8	76.0
6.50	29.40	0.64	0.59	0.54	90.1	84.0	75.9
8.50	51.90	1.12	1.05	0.95	90.2	84.0	75.9
10.00	71.40	1.54	1.45	1.30	90.1	84.9	76.1
10.75	82.56	1.79	1.67	1.51	90.5	84.3	76.3
12.00	103.20	2.23	2.08	1.88	90.1	84.0	76.0

(a) Based on 12,00 Btu/lb coal.

As shown in Figure 3.2-6, a hot raw gas is produced with minor cleanup steps on the top gas and the bottom gas streams. Large droplets of tar in the top gas (240°F) are removed in a tar cyclone without cooling. The bottom gas (1170°F) is dedusted in a separate cyclone. When two streams are combined, tar and oil mist remaining in the top gas is revaporized by the sensible heat of the hot, tar-free bottom gas. The resulting hot raw gas (690°F) has a heating value of approximately 200 Btu/SCF, when the heating values of tar and oil as well as sensible heat are included. The thermal efficiency is about 90 to 93%.

To produce a hot detarred gas, the top gas from the tar cyclone passes through an electrostatic detarrer which removes all tar mist (Figure 3.2-7). The gas temperature in the precipitator is maintained high enough so that moisture-free tar is recoverable as high quality liquid fuel. Because of the absence of dust and because of the gentle distillation process described earlier, the tar flows freely from the collecting electrodes, allowing low power consumption of the precipitator. The detarred gas is then mixed with the separately dedusted bottom gas to yield the final hot detarred gas. The thermal efficiency of this process is about 84% and the heating value of gas is approximately 185 Btu/SCF.

To produce a cold clean gas, the top gas is first passed through a hydraulic seal vessel (Figure 3.2-8). It then flows to an electrostatic precipitator where it is detarred at a temperature above the dewpoint of the gas. The bottom gas from the lower gas offtake is quenched directly in a spray column. Both gas streams are subsequently mixed in an indirect tubular cooler from which the mixture flows to a second electrostatic precipitator for recovery of oils free of the tars removed earlier. Beyond the second precipitator, the cold clean gas (100-120°F) can be compressed in a normal manner for distribution. The thermal efficiency of this configuration is about 76% for bituminous coal. Heating value of gas is approximately 172-175 Btu/SCF since both the sensible heat of gas and the heating values of the tar/oil constituents are lost.

Table 3.2-11 shows the gas conditions found in producing a hot raw gas from a typical bituminous coal containing 2% sulfur.[21] It can be seen that the methane content is much higher in the top gas than that in the bottom gas. Thus, the methane found in the mixed gas is largely a product of the distillation process, not the gasification process.

Characteristics of by-products (tar and oils) obtainable from the cold clean gas process are given in Table 3.2-12 and Table 3.2-13.[19][21]

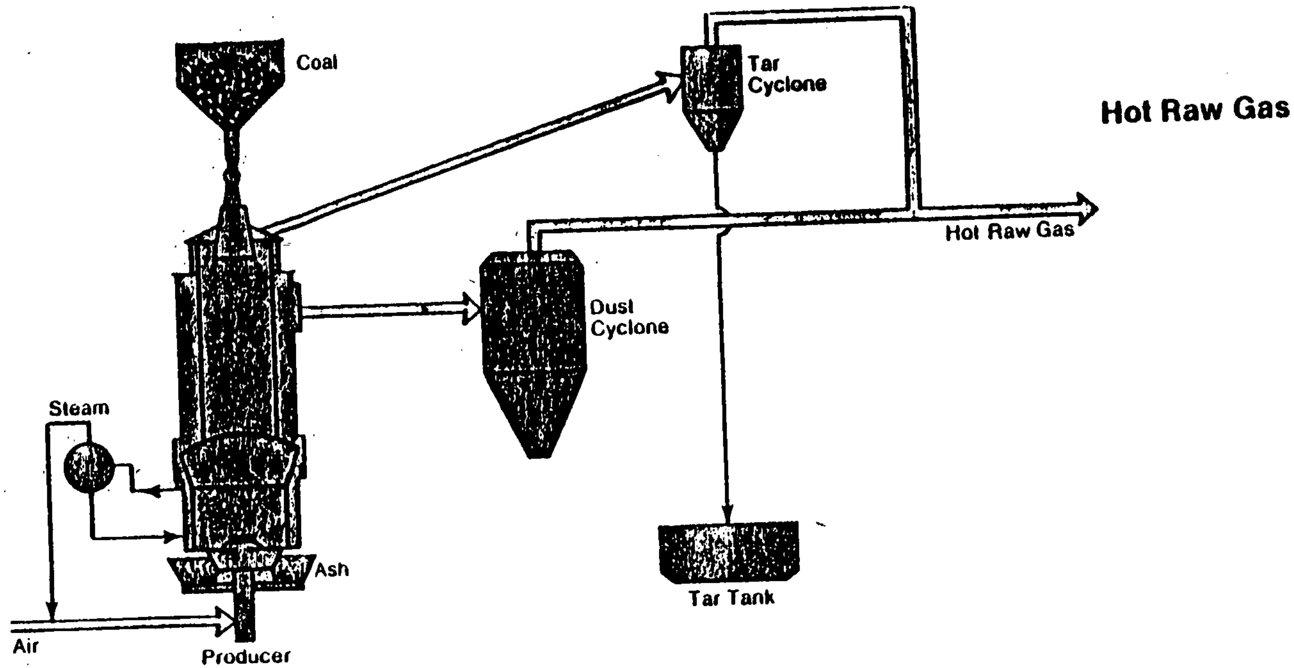

Figure 3.2-6 . WI Process for Hot Raw Gas

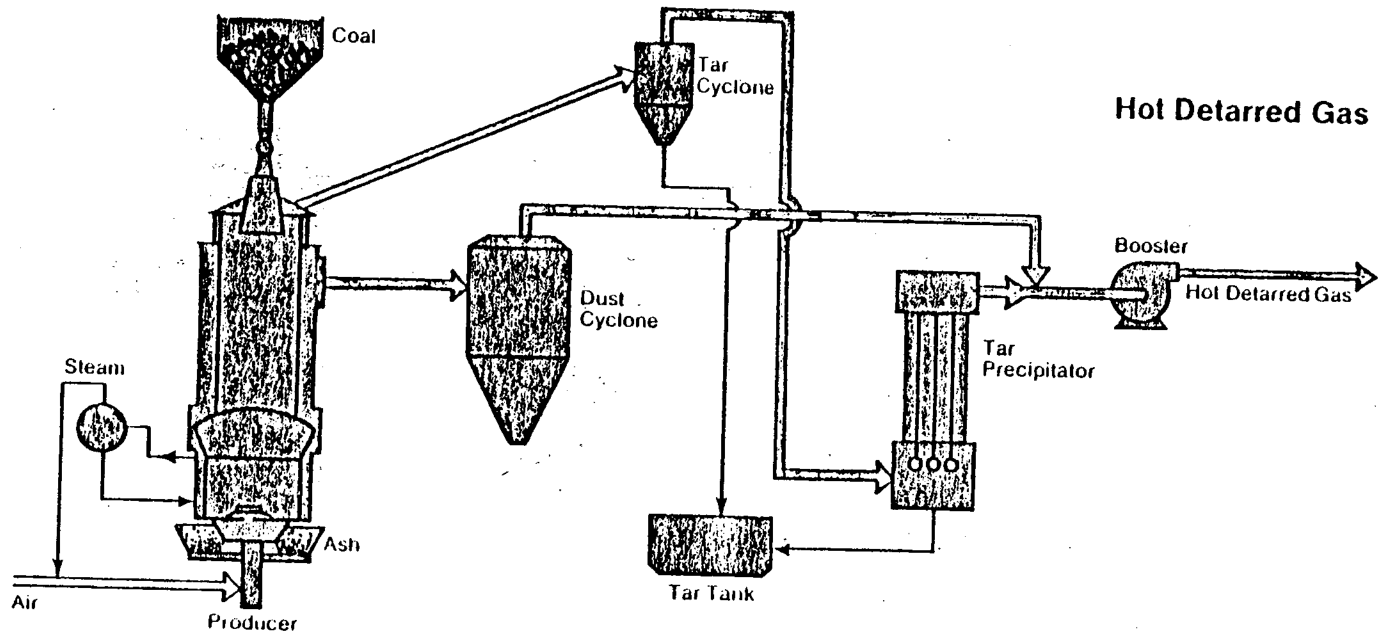

FIGURE 3.2–7 WI PROCESS FOR HOT DETARRED GAS

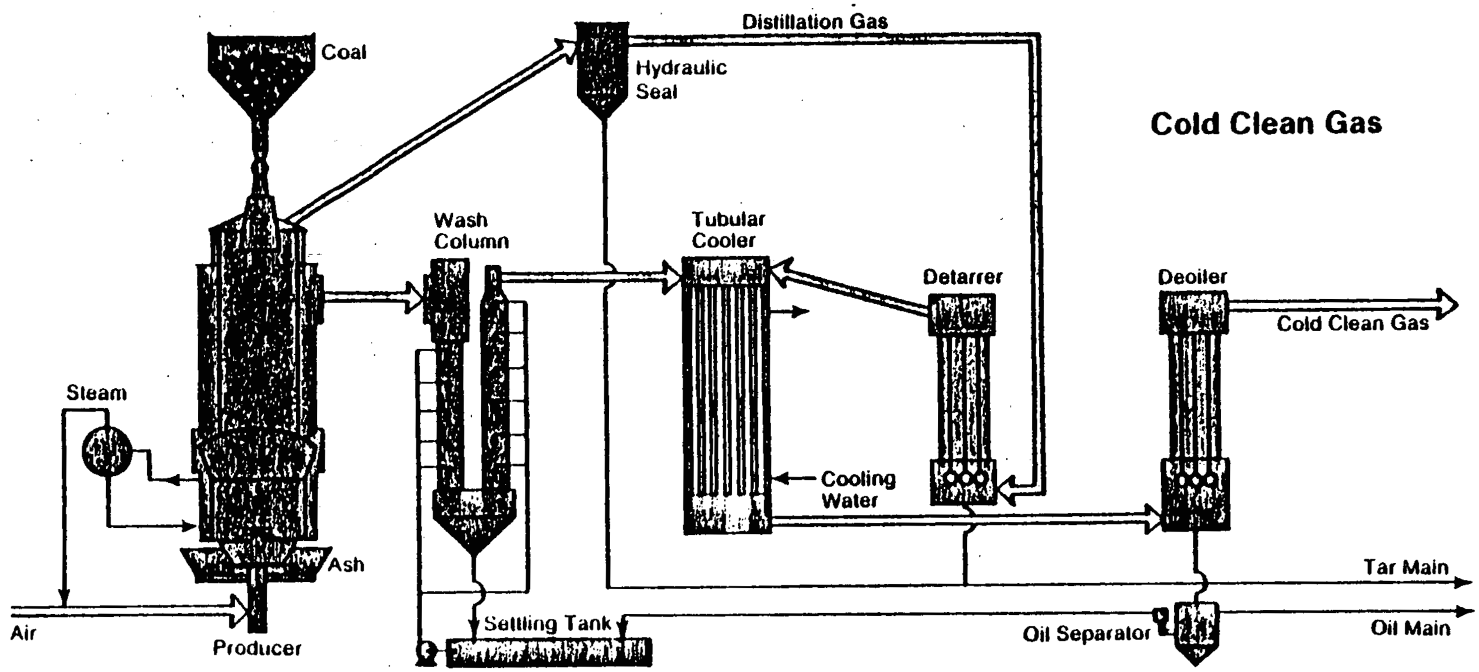

Figure 3.2-8 WI Process for Cold Clean Gas

Table 3.2-11

Typical Gas Conditions for
Hot Raw Gas Arrangement* (WI)

	Top	Bottom	Combined
H_2%	19.50	12.25	16.0
CO%	30.00	29.50	29.75
CH_4%	4.80	0.85	2.89
C_2H_4%	0.40	0.25	0.33
CO_2%	2.45	4.20	3.30
O_2%	0.35	0.55	0.45
N_2%	42.50	52.40	47.28
*H_2S ppmv	-	-	3200
Tar #/SCF	0.00398	-	0.0012
Oil #/SCF	0.0012	-	0.00036
Dust #/SCF	-	Traces	Traces
Temp. ^oF	240	1200	912
Relative Flow	0.30	0.70	1.0

* Based on a bituminous coal containing 2 wt % sulfur.

Table 3.2-12

By-product Tar Characteristics* (WI)

Specific Gravity	1.070 @ 15° C
Ash	0.25%
Insoluble	0.87%
Flash (AFNOR)	145° C
Pitch softening point	55° C

Distillation data

°C	% of Total	Characteristic of Fraction
0/170	5	-
170/270	18	70% phenols
270/300	14	15% paraffins
300/360	22	-
Residue	41	55°C softening point
Carbon	79.5	
Hydrogen	9.2	
Gross heat value		8600 Kcal./gm.
Moisture	0.6	

*Tar characteristics are affected by plant operation and coal. The data presented are at best typical.

Table 3.2-13

By-product Oil Characteristics (WI)

Specific gravity 0.980 @ 15°C

Distillation data

°C	% of Total	Cumulative (% of Total)
0/188	5	5
188/195	5	10
195/206	20	30
206/224	20	50
224/271	20	70
271/335	10	80
335 & over	20	100

Phenol content	15 grams/litre
Ammonia content	7 grams/litre
Carbon	76.5%
Hydrogen	11.5%
Heat value	8900 Kcal/gm.
Moisture	3.1%

Operating Conditions

In WI gasifiers, approximately 33 SCF (2.5 lbs) of air and 0.32 lbs of steam per lb of coal are used for continuous air-blown operation.[24] (Note: At this time ATC does not offer an oxygen-blown WI gasification system.) The steam-air mixture fed to the gasifier has therefore a steam-to-air ratio of 0.1275, and this corresponds to a blast saturation temperature of about 134°F. In practice, the blast saturation temperature is measured at the entrance to the gasifier base and is used to regulate the steam-air ratio and to control the quality of ash.

The pressure in the gasifier is essentially atmospheric. Gas leaves the gasifier at a pressure of approximately 14 inch w.g. The pressure drop through the gasifier bed is of the order of 2 to 10 inch w.g. depending on the gas flow rate.

The WI gasifier can be turned down to about 25% of its design capacity, and it can be boosted to full production in 15 to 20 minutes. The unit can utilize natural draft to remain in a warm standby condition and then be returned to full capacity in about one hour. If necessary, it can be operated above its rated capacity for short periods.

An estimate of utility requirements for three gasifier sizes with cold clean gas production given below:[21]

	INSIDE DIAMETER		
	10' - 0"	8' - 6"	6' - 6"
Electrical*	135 KW	90 KW	25 KW
Instrument Air	15-20 SCFM	15-20 SCFM	15-20 SCFM
Cooling Water	500 gpm	335 gpm	265 gpm
Process Water (Boiler Feed)	4 gpm	3 gpm	2 gpm
25 psig steam	450 lb/hr	none	none

* Gas booster and coal handling up to gasifier feed hoppers are excluded.

3.2.2.3 FW-Stoic Two-Stage Gasifier

Coal Feed

The FW-Stoic two-stage gasifier has operated on bituminous coal and has been described as suitable for operation on western subbituminous coal and lignite in addition to anthracite coal.[18] Although no details are available on the caking properties of feed coal, the allowable value of FSI is likely to be limited to about 3. The coal is normally graded in the size range of 1/2 to 1-1/2 inches or 1-1/2 to 3 inches, and if necessary fines are removed by a final screening prior to its transport to the top of the gasifier. When the gasifier is operating at capacity, its coal holdup is 8 hours. The nominal coal feed rates for the four available sizes of FW-Stoic gasifier are given below:

Gasifier Diameter, Ft	10^6 Btu/hr, Maximum	10^9 Btu/day, Maximum	Approximate Coal Rate* TPD
6.50	22.5	0.54	31.2
8.50	40	0.96	52.8
10.00	60	1.44	72.0
12.50	90	2.16	108.0

*Based on a coal having a HHV of about 12,000 Btu/lb with the gasifier producing hot detarred gas.

Product Gas

Three types of low-Btu gas can be produced with air-blown operation in the FW-Stoic gasification plant. In the first option, large droplets of tar-oil in the top gas (250°F) are removed in a cyclone without cooling. The bottom gas (1200°F) is dedusted in a separate cyclone, after which it is combined with the top gas. The resulting mixture is the hot raw gas having the highest Btu content for product gas (186-207 Btu/SCF). In the second optional mode which produces the hot detarred gas (175-195 Btu/SCF), additional tar-oil is removed by the use of an electrostatic precipitator in place of the tar cyclone (see Figure 3.2-9). The third mode of operation produces the cold clean gas having the lowest Btu content (160-175 Btu/SCF) among the three. In this mode, the bottom and the top gas streams are water cooled to remove condensibles. Most of the condensibles are recovered as liquid

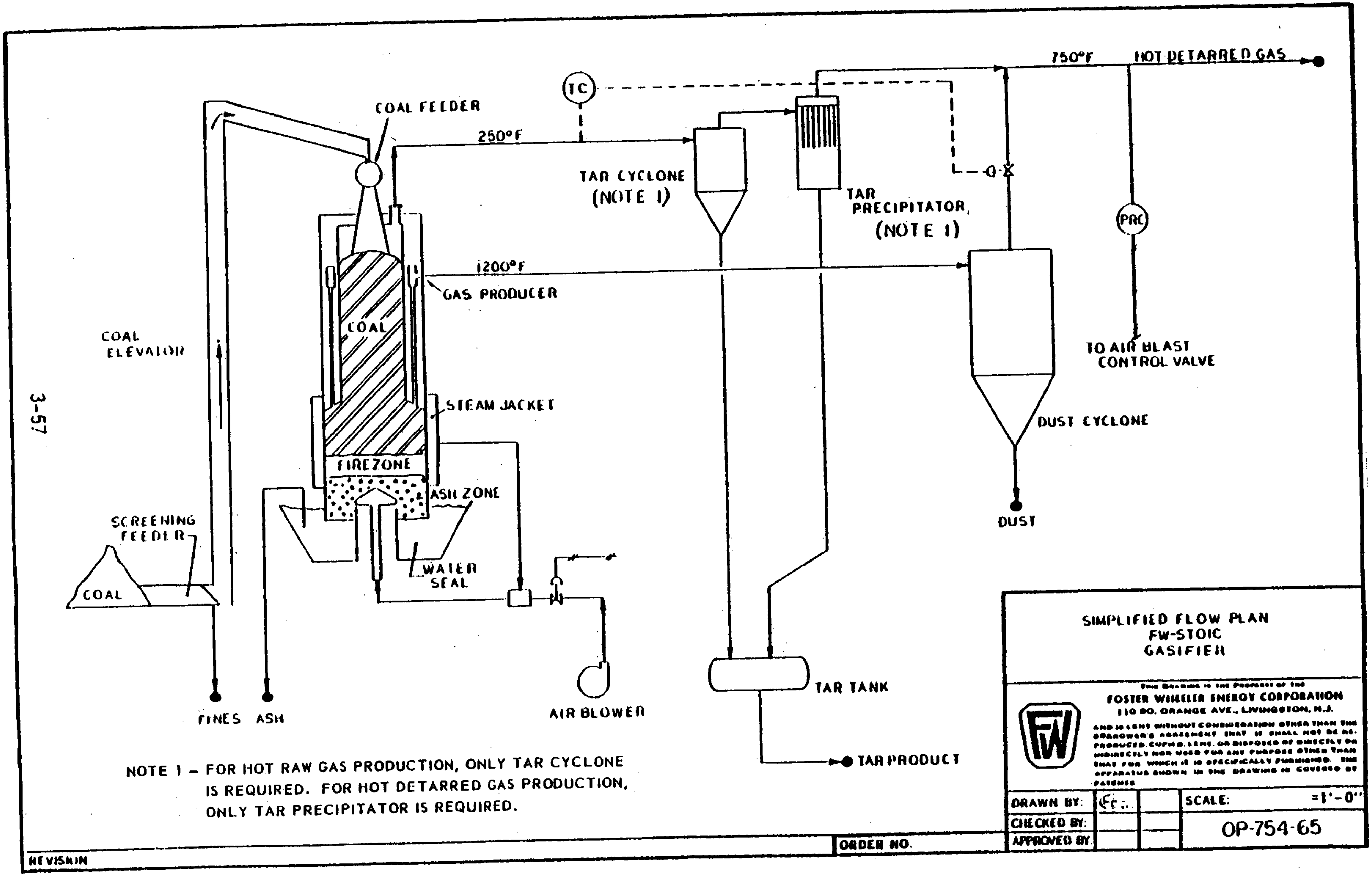

FIGURE 3.2-9 FW-STOIC PROCESS FOR HOT DETARRED GAS

fuel and the balance are incinerated. A summary of HHV, temperature of various product gases, and the overall thermal efficiency for each process is shown below:

Gas Type	Temperature of Product Gas, °F	Approximate Btu/SCF of Product Gas	Thermal Conversion Efficiency
Hot Raw Gas	750	186-207	85-93%
Hot Detarred Gas	750	175-195	77-87% *
Cold Clean Gas	100	160-175	69-76%

* Excluding tar-oil production.

Table 3.2-14 shows the typical range of gas compositions for a hot detarred gas and the properties of a typical tar-oil. The by-product tar-oil recovered by the cyclone or the precipitator is described to be similar to No. 6 fuel oil.

Operating Conditions

Each individual gasifier has a turndown ratio of about 5 to 1, i.e., the actual production rate can be reduced to 20% of its design capacity. Turndown ratio can be substantially increased in the case of manifolded gasifiers.

The normal air and steam requirements are not known. However, a 10-ft gasifier operating at capacity and making hot detarred gas is described to consume about 300 gal/hr of water.(18) The ratio of steam to air is apparently varied from coal to coal to control the quality of the ash. When a gasifier is put on standby, the necessary air for maintaining the large mass of gasifier refractory and carbonaceous contents at a minimum temperature is furnished by natural draft.

3.3. FIXED BED GASIFIER OPERATIONS

Operation of a single- or two-stage gasifier is in general simple and automatic. Typically, an operating staff of two is sufficient to handle a gasification plant with two or three gasifiers, whether they be single-or two-stage units, large or small. As described in Section 3.2, both gasifier types use similar coal-transport devices, and coal feed systems. Ash is typically withdrawn through the use of a revolving grate, with the exception of the Riley-Morgan gasifier. In both types of gasifier, coal is always filled to the top of the gasifier regardless of the load change in the product gas demand. However, the output of gas is regulated by a pressure controller in the gas distribution main, which increases the supply of air to the base of gasifier as the pressure falls, and vice versa.

Table 3.2-14

Analysis of Hot Detarred Gas and Typical Tar-Oil (FW-Stoic)

Analysis of Detarred Gas

Component	%
H_2	14.0-16.0
CH_4	2.6-3.0
CO	29.0-30.0
CO_2	3.0-4.0
N_2	47.6-51.4

Analysis of Tar-Oil

Physical Properties

Specific Gravity	1.0855
Viscosity, Centistokes, 122°F	555.4
Viscosity, Centistokes, 210°F	21.35
Pour Point, °F	80
Flash Point, C.O.C., °F	315
Higher Heating Value, Btu/gal	148,265

Chemical Composition

Component	%
Carbon	85.92
Hydrogen	7.92
Oxygen	4.18
Nitrogen	1.05
Sulfur	0.22
Ash	0.11
Moisture	0.60
Total	100.00

In some single-stage and two-stage gasifiers, the steam-to-air ratio is controlled by the blast saturation temperature (BST) of the steam-air mixture. Additional control is required in two-stage gasifiers to regulate the relative flow of top gas and bottom gas so that the top gas temperature is maintained at a relatively low temperature of $250^{o}F$.

The maintenance schedules for single- and two-stage gasifiers are comparable. Normally, both types of plant have scheduled annual shutdown to meet boiler code requirements. Items such as grate, feeder, and refractory are inspected at the same time. For single-stage gasifiers, agitator wear bars are also checked or replaced.

3.3.1 Single Stage Gasifiers

All single-stage, fixed bed gasifiers operate at essentially atmospheric pressure. Gas exit pressure varies slightly from one gasifier to another, i.e., 5 to 6 inches of water for M-W, 40 inches of water for R-M, and 2 to 4 inches of water for Wilputte.

During the period of normal operation, the following variables are either recorded or controlled:

- The blast saturation temperature (BST)
- Air/oxygen pressure at the gasifier inlet.
- Gas pressure at the gasifier outlet.
- Depth of ash and combustion zone.

Blast saturation temperature is controlled to regulate the amount of air/oxygen and steam going into the gasifier. In the McDowell Wellman the BST is held at the desired level by controlling the water supply valve. In the Wilputte gasifier, the BST controlling valve is on the steam line and regulates the steam supply. Riley-Morgan also controls the steam flow rate to attain a desired BST.

As the demand for product gas rate at the outlet of a single-stage gasifier increases, the pressure control valve allows more air and steam to flow to the gasifier and increase the gasification rate.

Depths of ash and combustion zone in all the single-stage gasifiers are determined by poking. In order to keep the depth of ash layer constant, the rate of ash withdrawal is adjusted by changing the grate speed for the Wilputte and M-W gasifiers. In the R-M gasifier, the ash removal is intermittent -- ash is released after one complete revolution of the gasifier shell through a stationary ash plow.

Major pieces of equipment in single-stage gasifiers which require regular maintenance are:

- Grate - grates made of cast iron are exposed to severe erosion. They last for one to two years of continuous operation after which they need replacement. Grate made of steel plate may last indefinitely.

- Gasifier - refractory lining in the gasifier lasts five to ten years. It may require patching after one to two years.

- Agitator - Agitators in single-stage fixed bed gasifiers are exposed to high temperature and dusty atmosphere. This causes erosion of the agitator wear bars on each arm and damage to the bearings and stuffing box of the agitator.

- Coal feeders - drum feeders or valves need adjustment at least once a year.

The startup procedure for single-stage fixed bed gasifier is as follows:

- Fill the gasifier with ash close to agitator bar

- Add about two feet of wood chips

- Fill most of the way to top with coke

- Soak with kerosene and ignite carefully

- Bring coal in slowly.

The entire operation requires about 24 hours. Gas is vented to a flare during startup.

Shutdown procedure consists of the following steps:

- Shut off the gas outlet

- Turn off the air supply

- Vent all the gas to flare

- Turn off the moving parts, e.g., grates, agitators, etc.

- Turn on the banking draft to desired banked fire setting

The above operation and maintenance items apply generally to all single-stage gasifiers. A detailed description of control and maintenance requirements is presented below for each of the three single-stage gasifiers evaluated.

3.3.1.1 McDowell-Wellman Gasifier [(1)(2)(3)]

The following variables are controlled and recorded:

- Blast saturation temperature

- Gas pressure

The following varibles are recorded:

- Agitator water pressure

- Gas temperature

High and low levels in the coal feed bin. The normal operation of one McDowell-Wellman gasifiers requires 1/3 man per shift. Due to continuous operation, little activity by the operator is required after a steady-state gas quality is reached. Operator's typical activities during normal operation include:

- Poking - once a shift

- Fire test - once a shift

- Oil and grease check - once a shift

- Flushing water jacket - twice a day.

A summary of typical operating conditions and maintenance schedules practiced for single-stage gasification plants is presented in Table 3.3-1.

McDowell-Wellmen gasifiers have in some cases been run 24 hours per day, 365 days per year for over four years without shutdown. The manufacturer does not have any specific recommendations for the maintenance of agitator, agitator bearing, grates, and grate holders. The following procedence is recommended by the manufacturers for general overhaul of the equipment:

> The entire gas equipment should be overhauled and thoroughly checked every 12 months. Fuel valves should be re-scraped to original maximum 0.005 inch clearance limit. The fuel bin interior should be repainted wherever rusty or bare. Elevator buckets and chain checked, also elevator casing. The 10-inch vent and 4-inch vent and offtake pipe checked for deposit. All 1/4-inch guage lines blown out with steam, gas piping around pump taken apart, and cleaned. Producer grates, etc. inspected and built up according to specifications. Water jacket checked and sediment cleaned

Table 3.3-1

Summary of Operating Conditions and Maintenance Schedule for Single-Stage Gas Production Plants

Company	National Lime	Holston Defense	SCAW Metal
Gasifiers			
Location	Ohio, USA	Tennessee, USA	South Africa
Initial Year of Operation	1945	1945	1963
Diameter, ft	10	10-1/3	10
Capacity, TPD/Gasifier	75	60	48
Number	2	12	1
Type	McDowell-Wellman (Air-Blown)	Wilputte (Air-Blown)	Wellman-Incandescent (Air/O_2 - Blown)
Operations			
Coal			
Size	1-1/4 to 2"	Up to 4"	1-1/4 to 3"
Fines	Up to 30%	Up to 10-15%	
FSI	Up to 9	Up to 6	<4; ideally <2
Ash Softening	Min 2200°F	2300°F	2552°F
Major Op. Variables	. Air saturation temp. . Poking/ash and fire depth	. Air saturation temp. . Poking/ash and fire depth	. poking/ash and fire depth . air pressure under grate
Manpower (per shift)	1 operator	2 head operators 2 foremen 1 basement man 2 laborers - day shift	1 foreman 3 operators
Maintenance			
Scheduled Shutdown	None	4 times/year	once/year
Maintenance Items	. Clean gas main every 2 mos. . Check agitator and agitator bearing . Check coal feed valve	. Clean gas main every 3 months	. Clean gas cooler . Adjust coal feeder . Steam clean tar precipitater every 3 mos.

out. All gas valves taken apart and cleaned. All other water and steam valves checked. Interior of all tanks carefully checked for corrosion, etc. All mechanical parts and bushings checked for wear, etc.

The following startup, shutdown, emergency shutdown and turndown/banking procedures are recommended by the M-W gasifier vendor:

Startup

1. Fill the water jacket with water.

2. Cover the grate with ash up to 16 inches in depth.

3. Place the boxes in the fire box, fill them with charcoal or coke and cover the top with burlap.

4. Pour kerosene oil down each of the boxes.

5. Fill the gasifier, the coal feed bin and the top bin with coke or anthracite coal.

6. Light the fire in the boxes and shut the ashpit door.

7. Start the air blower and throttle the vent valve.

8. After a few hours, open the gas valve to discharge raw hot gas into the fueling supply line and at the same time, close vent valve. The air blast is then put under the pressure controller and the gasifier starts producing the gas required in the factory.

9. Proceed as per regular operation.

Shutdown

1. Shut-off the hot gas supply valve and, at the same time, open the vent valve.

2. Shutdown the air blower.

3. Open the vent valve wide open.

4. Shutdown the pressure controller.

5. Stop the grates.

6. Shut off oil to the main bearing.

7. Close the air blast valve tight.

8. Open the banking draft disc to the desired banked fire setting.

Emergency Shutdown

The following procedure is used if an emergency shut down is required:

1. If power fails or the air blower stops IMMEDIATELY try to start it. If you cannot start it at once shut tight the gas to factory valve as fast as possible to prevent gas from other producers backing into the ashpit to cause an explosion and to prevent poison gas from coming back through the air blower out into the room.

2. Open the vent valve wide open.

3. Now proceed as with a regular shutdown.

4. If desired, start up can be made in the usual way as soon as power is available again or the cause of the shutdown has been overcome.

To Put In Operation a Banked Gas Producer

1. Be sure that the water jacket is full of clean water up to the overflow outlet. Shut off completely the water supply to the water jacket.

2. Shut the banking air disc tight.

3. Start the air blower with the air outlet damper shut tight; make sure the air blast damper is shut tight and the vent valve wide open.

4. Open the air damper at the blower outlet wide open.

5. Count the turns and open the angle valve enough to give the regular amount of load.

6. Start the grates at the usual speed.

7. Start the oil feed to the grates.

8. In about half-an-hour take a fire test.

9. Poke any holes that the fire test shows need poking.

10. Gradually increase the saturation to the regular temperature.

11. When up to desired saturation temperature, open the water valves to the saturation control instrument and have the instrument control the saturation.

12. Throttle the vent valve enough so the pilot gas flame can be lighted.

13. When the color of the gas flame shows the gas is good, the producer can be thrown onto the factory supply line.

A review of operation and maintenance schedule for M-W gasifiers disclosed the following advantage, disadvantages, and potential for improvement:

Advantages

Coal Feed System:

There are no moving parts in the coal feeding system for this gasifier, thus minimizing the maintenance costs common to gasifiers where mechanical devices are used on abrasive materials like coal. Moreover, since coal is fed continuously, the bed height remains constant and thus contributes towards producing gas of uniform quality.

Gasifier:

Since the inner wall of the gasifier is not brick-lined, this construction minimizes the initial cost of linings and reduces the maintenance costs. The gasifier is water jacketed and steam required in the gasifier is raised in the jacket.

Grate:

The design of the grate is such that ash is removed continuously and the rate of ash removed can be adjusted by changing the grate speed. This does not disturb the bed and gives gas of uniform quality. Moreover, elimination of water seals makes it possible to operate at higher pressures.

Disadvantages

Gas Leakage:

Gas may escape into the feeding compartments when dumping coal to lower bins.

Potential for Improvement

- Gas leakage can be minimized by using an air locking device in the feed system and the ash removal hopper.

- Like any other single-stage, fixed bed gasifier, the M-W gasifier also needs poking the object of which is to determine the depths of the combustion zone and the ash layer. The poking operation can be eliminated by using thermocouples.

- Again, as with other single-stage, fixed bed gasifiers, if the rate of ash removal can be automatically controlled by relating to the rate of coal feed, improved uniformity of product gas heating value and flow rate can be achieved at the design rate and at turndown conditions.

3.3.1.2 Wilputte Gasifier[4][5][6]

The Wilputte gasifier is provided with a blast saturation temperature controller for regulating the air-steam ratio and a gas pressure controller for regulating the amount of air/steam mixture in response to a change in the demand of product gas. In addition, the following instruments are also provided to either record or control various process variables:

- Temperature recorders for

  - Blast temperature
  - Gas temperature
  - Steam temperature

- Pressure indicators for

  - Blast pressure
  - Gas pressure at the gasifier outlet
  - Steam pressure

- Flow indicators for

  - Air flow rate
  - Gas flow rate
  - Steam flow rate

- Flow recorder to measure the gas product.

The gasification plant at Holston Defense Corporation, Kingsport, Tenn. was built by Semet Solvay Engineering Corporation (now Wilputte Corporation) in the 1940's. The plant has 12 gasifiers with a gas clean up system to produce dust-, tar-, and oil-free gas from low sulfur coal. The operating personnel on this plant are:

- 1 Head operator per shift for each 6 gasifiers
- 1 Foreman per shift for each 6 gasifiers
- 1 Basement man per shift for 12 gasifiers
- 2 laborers for day shift for coal handling

Startup Procedure

- Fill the gasifier with dry ashes to a point one inch below agitator bar.
- Spread over the ash a layer of kindlings 18 inches above agitator bar to a depth of 6 inches with dry wood.
- Pour 8 gallons of kerosene over the kindling and spread oily rags over the bed.
- Turn on the cooling water and then light the fire.
- After the kindling has gotten started turn on the air and increase the air pressure gradually as the fire begins to burn brightly.
- Charge the fire bed with coal as rapidly as the fire burns through until the fuel bed reaches the agitator.
- While the fire bed is being built, open all the poke holes, clean out openings and the vent pipe. Approximately 1 to 4 hours will be required to build up the bed. The following additional steps will be required afterwards:
- Put water in circulation
- Close vent line
- Start exhauster and open it gradually
- Add air gradually until the gasifier is on line

Shutdown Procedure

- Close down exhauster
- Cut back air to the gasifier

- Open up vent line

- Cut steam off completely

A review of the operation and maintenance schedule for the Wilputte gasifier disclosed the following advantages, disadvantages and potential for improvement:

Advantages

- For anthracite coal and coke the gasifier is self-sufficient in steam.

Disadvantages

- Brick-lining is liable to high maintenance cost.

- An external source of steam is required for gasification of bituminous coal.

Potential For Improvement

- The gasifier used for anthracite and coke (i.e., one equipped with water jacket) could be adapted for the gasification of bituminous coal.

- Ash withdrawal rate should be automatically controlled.

3.3.1.3 Riley-Morgan Gasifier (7)(8)(9)(10)(11)

Instrumentation on the Riley-Morgan gasifier is provided in accordance with the sophistication required by the individual customer. Though the Riley-Morgan gasifier has been used extensively as the Morgan producer, the manufacturer does not have any specific recommendation in the maintenance requirements of the present gasifier.

The following startup procedure can be used for the R-M gasifier:

- Fill gasifier with ash to 18 inches above the blast hood.

- Add 1 ft of charcoal.

- Ignite with MAPP gas igniter.

- Bring coal in slowly.

The entire operation requires 2 shifts and the gas is vented and flared during the startup.

A brief review of operation and maintenance schedule for the R-M gasifier disclosed the following:

Advantages

- The use of drum feeder and lock hopper as the coal feeding system does prevent gas leakage.

Disadvantages

- Steam for gasification is not produced integral with the gasifier.
- Brick-lining is liable to high maintenance cost.
- The pan, barrel and charge all rotate and may require maintenance.

Potential for Improvement

- Elimination of poking.
- Ash withdrawal rate should be automatically controlled and be related to the coal feed rate.

3.3.2 Two-Stage Gasifier

South African industry has had many years of operating experience with WD, WI, and Stoic two-stage gasifiers. Available information(16)(18)(21)(26)(27) indicates that operations and control of these gasifiers are generally similar to each other. These aspects are, therefore, discussed jointly in the following general description. Operator activity, manpower requirements, and maintenance are discussed separately in subsequent sub-sections.

Operations and Control

To startup a two-stage gasifier from cold, the following typical sequence is used at a South African gas plant(27):

- Fill the gasifier with 12 to 18 inches of ash to the bottom of retort.
- Add 3 ft of wood chips.
- Fill the rest of way to the top with coke.
- Soak with kerosene and ignite carefully.
- Bring the coal on slowly to maintain brick temperature.

The entire operation requires approximately 24 hours. The gas generated during start-up is vented.

The basic controls for maintaining steady-state operation are as follows:

<u>Coal Feed (Level Control)</u> The coal to the gasifier is controlled to maintain a constant level in the retort section regardless of load change in product gas demand. In the case of a drum-type rotary feeder, the level is measured by a paddle which rests on the top of coal. As gasification causes the coal bed to descend, the downward movement of the paddle actuates the drum feeder drive motor. The drum, which is full of coal, rotates 180° and discharges the coal into the retort. The drum then completes a 360° turn and is refilled. While the drum is revolving, a cam raises the paddle clear of the coal, and at the end of the cycle the paddle is once again lowered to rest on the coal.[26]

<u>Gasification Rate (Pressure Control)</u> The output of two-stage gasifiers is regulated by a pressure controller in the product gas distribution main. As product gas demand increases and line pressure falls, the variation in pressure resets a control valve in the air blower discharge. More air (and steam) flow to the bottom of the gasifier thereby increasing gas production rate. Since the response to pressure change is nearly instantaneous, the overall system response to load change is also relatively fast. In actual operations, it has not been necessary to use an intermediate gas holder.[18]

<u>Steam/Air Ratio (Temperature Control)</u> The steam-to-air ratio is typically controlled by the blast saturation temperature (BST) of the steam/air mixture. The BST is measured just before the mixture enters the gasifier and, assuming perfect saturation is achieved, it is related to the amount of steam carried by the air in the following ratio:

BST, °F	lb steam/lb dry air
122	0.086
131	0.115
140	0.153
149	0.205

The BST is usually set in the 130 to 140°F region, and from a theoretical consideration, 135°F is an optimum value which maximizes the heating value of product gas (see Figure 3.3-1).[26] It is also closely related to the condition of ash in the producer. A low BST produces a high bed temperature with the associated melting of the ash to form

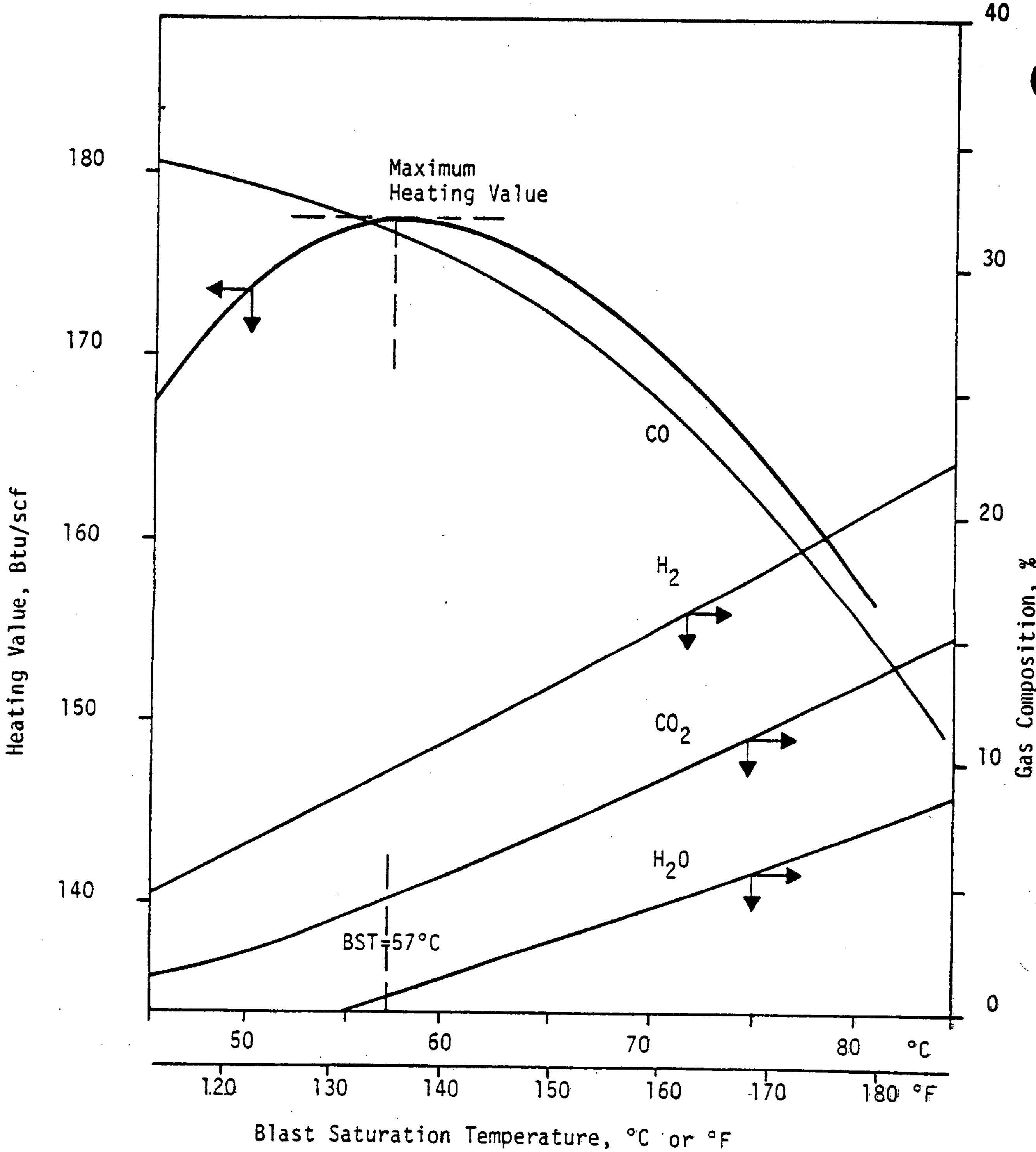

Figure 3.3-1 Gas Composition and Heating Value at Varying Blast Saturation Temperatures.

large clinkers. On the other hand, a high BST cools the bed and produces finely divided ash which, once it becomes wet, turns into a mud. In practice, the BST (and hence the steam-to-air ratio) is slightly varied with a change in the ash fusion point of feed coal in order to produce a gritty ash condition as required to facilitate ease of ash removal.

<u>Top Gas Temperature (Temperature/Flow Control)</u> The temperature of the top gas leaving the gasifier is controlled at about 240 to 260 ^oF by controlling the amount of gas passing up through the retort. This is done by opening or closing a butterfly valve located in the bottom gas line, since the gas generated in the gasification zone will preferentially flow out through the bottom gas offtake. The butterfly valve is reset by a temperature controller in the top gas off-take to provide smooth operation. Top gas temperature control is important because it will influence the quality of by-product tar and oil which may represent 10 to 15% of the total thermal output.

<u>Ash/Fire Bed (Speed Control)</u> The speed of grate, which rotates slowly with intermittent action, is regulated to maintain a proper ash withdrawal rate. Normally, approximately 12 to 18 inches of ash bed depth is required for protecting the grate from heat.

The ash and fire bed depths are usually determined by hand poking with rods. This is done by inserting a rod or poker down through a poke hole (a set of 8 or 16 poke holes are located on the lower circumference of the retort just above the water jacket) until the grate level is reached. The rod remains inserted for 2 minutes and, on withdrawal, the ash bed depth as well as the thickness and the condition of the fire zone are determined. Bed depths are usually checked once per hour.

The poke hole is normally provided with a steam curtain (25-45 psig) which minimizes gas leakage during poking. The steam curtain is provided by admitting steam through a ring of holes in the poke hole body. The steam valve is linked mechanically to the poke hole cover so that steam is used only when the poke hole is opened. Without the steam curtain, the loss of gas during poking could reach 2%.[26]

In addition to its normal function of measuring depths, poking is also used in place of a permanent mechanical stirrer (which a two-stage gasifier is not equipped with) to break up the agglomerating tendency of beds.

The important operating parameters described above are summarized below:

Parameter	Normal Value	Normal Range	Alarm Levels[a]
Top gas temperature, °F	250	240-260	210-280
Blast saturation temperature, °F	134	131-140	127-144
Ash level, inches	15	12-18	11-25
Fire thickness, inches	8	6-10	4-16

(a) The alarm levels are an indication of where help must be obtained if the normal corrective action has not brought the reading back into normal working range.

Turndown/Banking

As described in Section 3.2.2., an individual two-stage gasifier can be turned down to about 20-30% of its design capacity without significantly affecting the gas quality. To turn down a gasifier, the air and steam introduced to the bottom of the gasifier are reduced. The lower limit is reached when the butterfly valve in the bottom gas line will have to be nearly closed in order to maintain the top gas temperature. A turned-down gasifier can be brought back to full capacity in 15 to 20 minutes.

Gasifiers can be placed on a banked or warm-standby basis for several days. In this case the necessary air for maintaining the refractory and the carbonaceous contents in the gasification zone at a minimum temperature is furnished by natural draft. During this period, the gasifier is vented. Normally, a banked gasifier can be brought onstream within one hour.

Maintenance/Problem Areas

Generally, there are no significant maintenance problems with either the gasifier or cleanup systems, including tar and oil precipitators and gas coolers. A gas plant in South Africa may or may not have a scheduled annual shutdown for maintenance -- equipment life varies greatly from plant to plant. Refractory life may be as short as 5 years or as long as 18 years.[27] Grate life also varies widely, depending on the extent of erosion caused by the abrasive quality of the coal ash. On the average, grate components may require replacement ever four years.

Minor nuisances may be encountered in operating a two-stage gasifier. For example, with sliding valves or star type feeders, hot gas may permeate into the bunker above to cause premature distillation of the coal. Gas leakage during poking may still occur in spite of the use of the steam curtain. Grate erosion may be excessive. Finally, it should be noted that low-Btu gas is flamable and since it contains carbon monoxide it is toxic. Therefore, buildings should be well ventilated and equipment and piping should be purged with steam or inert gas prior to performing maintenance.

3.3.2.1 Woodall-Duckham Two-Stage Gasifier [16]

Operations and Control

The general description presented in Section 3.3.2. applies to the Woodall-Duckham two-stage gasifiers. It should be noted, however, that the alternate WD coal feeding system consisting of a lock hopper, feed buffer hopper, and flooded feed coal distributor may be used. The ash may be removed either wet or dry.

Operators

For a plant with two operating gasifiers, dust, tar and oil removal equipments as well as a desulfurization unit, two operators are normally sufficient to operate the plant. One operator would be based in the control room, the other would be responsible for outside duties. These would include tranferring the coal from the stockpile to the gasifier, checking the operation of the coal feeding mechanism, and checking the ash depth and fire zone in the gasifier by hand-poking with rods. The operator would also check the ash discharge mechanism, take a reading of the field instruments, and monitor the gas purification equipment.

Maintenance

The gasifier would normally be shut down annually for maintenance. This shutdown is primarily for boiler inspection, which is required by the Boiler Inspection Code. The gasifier refractory and the grate are inspected at this time. In actual operations, it has been found that the refractory usually lasts over 10 years without major rebuilding. The grate life has been found to be dependent on erosion caused by trace elements in the ash; it can vary between 3 years to over 10 years. The grate is constructed of segments and, therefore, only individual segments need be replaced as they become worn.

3.3.2.2. Wellman-Incandescent Two-Stage Gasifier

Operations and Control

The general description presented in Section 3.3.2. applies to the Wellman-Incandescent two-stage gasifiers. Table 3.3-3 is a summary of the operating experience with WI two-stage units in three South African plants.[27]

Operators

For a very small gasification plant (one 4.5 ft-diameter unit), two operators, one senior and one training, may be needed in the initial period after erection. After that period, one man is considered sufficient to handle all operating requirements.[21]

For a much larger gas plant involving multiple units of gasifiers more than one operator (but not necessarily proportional to the number of gasifiers) is needed. As can be seen in Table 3.3-3, one forman or supervisor, two to three operators, plus three to nine laborers are required to run a South African gas plant with two to five large-diameter gasifiers.

Maintenance

Table 3.3-2 also gives the frequency of scheduled shutdown, maintenance items, and equipment life experienced at the three WI gas plants in South Africa. At Highveld Steel Co., there is a scheduled shutdown of once a year for gasifier jacket and steam drum inspection to meet boiler code requirements. The precipitators are cleaned at the same time. Total down time is four weeks, including three days to empty the gasifier, one week to cool down, and one week to complete maintenance for boiler inspection.

SCAW Metals Co. also schedules a plant shutdown for maintenance once a year. The following maintenance schedule is typical:

- Replace grate once a year
- Replace grate holder every three years
- Clean gas cooler once a year
- Adjust coal feeder once a year
- Patch refractory once a year; rebrick every ten or fifteen years
- The tar precipitator is steam cleaned every three months

Table 3.3-2

Summary of Operating Experience with WI Two-Stage Gasifiers in South Africa

Company	Union Steel	Highveld Steel	SCAW Metals
Gasifiers			
Year	1965	1968	1970, 1975
Diameter	10'	10'	10'-9"
Number & Type	4 operational 2 spare 4 cold clean	4 operational 4 cold clean	3 operational 1 under const. 1 cold clean 2 hot detarred
Output, 10^9 Btu/day	4.8	5.0	4.1
Operations			
Coal	Size 1"-3" FSI, 1-1/2 to 2-1/2 AFT, >2460°F	Bituminous	Size, 1-1/2 to 3" FSI, <4 AFT, >2550°F
Major Op. Variables	• BST, 130°F • Top gas 230°F • Bottom gas 1020-1200°F • Ash and fire bed depths	• BST • Top gas temp. • Bottom gas temp. • Undergrate press. • Grate Speed • Air flow (Note: gas sample collected once/day)	• BST • Top gas temp. • Bottom gas temp. • Undergrate air pressure • Ash & fire bed depths
Poking	• Clinker poking - once/shift • Fire depth checking - once/hr	• Clinker poking - once/shift • Fire depth checking - once/hr	• Half of the holes poked every 2 hrs.
Manpower (per shift)	1 daytime supervisor 2 operators 4 laborers	1 daytime supervisor 2 operators 2 laborers	1 foreman 3 operators 9 laborers
Maintenance			
Scheduled Shutdown	None	once/yr	once/yr
Average Downtime/year	10 days	4 weeks	unknown
Maintenance item and equip. life	Refractory, 5-18 yrs. grate comp. 1-1/2 to 2 yrs.	Inspect gasifier jacket, steam drum; clean precipitators	Clean gas cooler, adjust coal feeder Refractory, 10-15 yrs. (patched once/yr) grate 2-3 yrs. grate holder 3 yrs.

It should be mentioned that SCAW has replaced their original cast iron grates with cast steel, and now expect the grate life to be two or three years.

3.3.2.3. FW-Stoic Two-Stage Gasifier [18]

Operations and Control

The general description presented in Section 3.3.2 applies to the FW-Stoic two-stage gasifiers, with the exception of poking procedure. Automated poking is under development but no detail is available. Figure 3.2-9 also shows the instrumentation schematic for producing hot raw or hot detarred gas. It can be seen that the butterfly valve that controls the top gas temperature is located downstream of the dust cyclone, and the control valve in the air blower discharge side is reset by the pneumatic signal from the product gas main.

Operators

No number has been quoted but an operating staff of two for a plant with two gasifiers should be sufficient.

Maintenance

To insure reliability of plant operation, Foster Wheeler has recommended the use of spare air blowers.

3.4 COMMERCIAL EXPERIENCE

3.4.1 Single-Stage Gasifiers

3.4.1.1 McDowell-Wellman Gasifier [1][2][3]

Gas produced by McDowell-Wellman gasifiers has been used in the following industrial plants:

- o Chemicals and Allied Products
  - Synthesis fertilizer manufacturer
  - Synthesis gas for various petrochemical feedstocks
- o Primary Metals Products
  - Steel mills for normalizing, annealing
  - Zinc smelting
  - Magnesium and aluminum manufacture
- o Stone, Clay and Glasses
  - Fuel gas

A 25-year listing of commercial installations in North America utilizing the McDowell-Wellman gasifiers is given in Table 3.4-1. The table does not include all the McDowell-Wellman installations. There are multiple M-W gasifier units installed in Cuba, Eastern Europe, and Taiwan for which current data are not available.

3.4.1.2 Wilputte Gasifier[4][5][6]

Wilputte Corporation has experience in the engineering and construction of over 250 fuel gas manufacturing installations.[5] The facilities have been installed throughout the United States, Europe, the Far East and Australia. Some of the industries served by Wilputte gasifiers are given below:

- Chemical Industries
  - heat for different types of furnaces
  - heat for distillation of different products
  - heat for reaction of different products
  - heat for drying products and sludges
- Metal Industries
  - heat for annealing
  - a reducing atmosphere for certain heat treating processes
- Cement and glass industries

A partial listing of Wilputte gasifier users is presented in Table 3.4-2.

3.4.1.3 Riley-Morgan Gasifier[7][8][9][10][11]

Basically the Riley-Morgan gasifier is successor to Morgan Gas producer which has served steel and other heavy industries. Some 9000 Morgan gas producers were sold through the 1940's. Existing units currently include six at ISCOR melting plant, Pretorea, South Africa installed in 1933, one at their forge plant installed in 1941 and two at Tolana Glassworks, Dundee, South Africa installed in 1949.

A commercial size demonstration unit has been constructed at the Riley Research Center in Worcester, Massachusetts. It has been operated since 1975 to test the new Riley-Morgan Producer.

3.4.2 Two-Stage Gasifier

The two-stage gasification process has been used for over 30 years to produce various coal gases for industrial and utility sectors in Europe, South Africa, Australia, and Japan. Although the steel industry is a major user of two-stage gasifiers, other industries such as glass

Table 3.4-1

Commercial Experience for McDowell-Wellman Gasifier

Company/ Location	No. of Units	Gasifier Diameter, ft	Coal Type	Scope of System	Application	Status
Gypsum Lime Ltd. Beechville, Ont.	1	10 with agitator	Bituminous	Low-Btu	Lime Kiln	Inoperative since 1965
Stelco Limited Beechville, Ont.	1	10 with agitator	Bituminous	Low-Btu	Heat Treating Furnace	Inoperative since 1963
Mississippi Lime, St. Genevieve, MO	1	10 with agitator	Bituminous	Low-Btu	Lime Kiln	Inoperative since 1964. In place
Union Carbide, Nopco Chemical Div. Linden, NJ	1	3.5	Coke	Med-Btu	Chemical Feed Stock	Inoperative In place
NL Industries National Lead Div. South Amboy, NJ	1	2	Coke	Med-Btu	Chemical Feed Stock	Inoperative Since 1966 In place
Allied Chemical, Ltd. Corunna, Ont.	1	3	Bituminous	Low-Btu	Fuel Gas	Inoperative
New Jersey Zinc Ashtabula, Ohio	1	6.5 with agitator	Coke	Med-Btu	Chemical Feedstock-Production of Titanium Dioxide (TiO_2)	Operating
U.S. Bureau of Mines Morgantown, West Virginia	1	3.5	Bituminous/ Lignite	Low/Med-Btu	Experimental with 300 psi pressure	Operating

Table 3.4-1 (Continued)

Commercial Expereince for McDowell-Wellman Gasifier

Company/ Location	No. of Units	Gasifier Diameter, ft	Coal Type	Scope of System	Application	Status
U.S. Bureau of Mines Twin Cities, Minnesota	1	10	Bituminous/ Litnite	Low-Btu	Iron Ore Pellet Kilns (Induration of Iron Ore)	Operating
Olin - Mathieson Ashtabula, Ohio	1	5	Petroleum Coke	Med-Btu	Feedstock in Producing Phosgene	Operating
Riley-Stoker Worcester, Mass	1	2	Bituminous anthracite coke, lignite	Low-Btu	Performing with various coals	Operating
Glen-Gary Corp. Reading, PA	12	10 with agitator	Anthracite	Low-Btu	Brick Kiln Firing	Operating
National Lime & Stone Co. Carey, Ohio	2	10 with agitator	Bituminous	Low-Btu	Lime Kiln	Operating
Pikeville Energy Center Pikeville, Ky.	2	6.5 with agitator	Bituminous	Low-Btu	Commercial Fuel Gas	1979 Operation
Can Do, Inc. Hazelton, PA	2	6.5	Anthracite	Low-Btu	Industrial Fuel GAs	1979 Operation
Tiwan Fertilizer, Co Formosa	7	10 with agitator	Korean Anthracite	Med-Btu	150 TPD NH_3 Prod.	Operating
Nickel Processing Corp.	14	10	Bituminous	Low-Btu	Industrial Fuel Gas	Operating

Table 3.4-2

Partial Listing of Typical
Commercial Experience for Wilputte Gasifier [(a)]

	Capacity					
Company/ Location	No. of Units	Gasifier Diameter, ft	Heat Rate 10^9 Btu/Day	Coal Type	Application	Date & Comments
Perth Amboy, N.H. Municipality	1	6.6	-	-	-	1918
Pennsylvania Gas and Water	1	-	-	Converted Water Gas Machine	High Btu (1,000 Btu/cf) Oil Gas Machines	
Paccal (Austrialia)	2	-	-	-	High Btu (1,000 Btu/cf) Oil Gas Machines	
Semet Solvay Ironton, OH	2	9.3	0.8 Total	Coke	Underfiring B.P. Coke Ovens	1930
Staten Island Shipbuilding Staten Island, N.Y.	1 1	6 9	-	-	-	1912
Tennessee Eastman Kingsport, TN	2	9.2	-	Bituminous	Chemical Operations	1933 36 tons/day of coal
Virginia Carolina Chemicals Charleston, S.C.	1	9.2	-	Coke	Furnaces	1933 1,600 lbs./ hr. of coke
Eastern Rolling Mills Baltimore, MD	1 2	5.5 9.2	- 0.2 Each	Anthracite #1 Buckwheat Anthracite	Heating Rolls Normalizing Furnace	1917 1925
Jefferey Mfg. Co. Columbus, OH	1	10.5	0.4	Bituminous	Heating Treating Gas Engines	1929

Table 3.4-2 (Continued)

Partial Listing of Typical Commercial Experience for Wilputte Gasifier (a)

Company/ Location	No. of Units	Capacity: Gasifier Diameter, ft	Capacity: Heat Rate 10^9 Btu/Day	Coal Type	Application	Date & Comments
Allis Chalmers of Canada	4	1-4.5 2-5.0 1-5.5	-	Anthracite	-	1913 to 1917
A.O. Smith Milwaukee, WI	1	9	-	-	-	1912
Citizens Light Heat & Power Cangy, Minn.	1	9	-	Buckwheat Anthracite	Utility Station	1917
Dupont Carney's Pt., N.J.	3	9.2	0.3 each	#1-Buckwheat Anthracite	Chemical Operations	1927 to 1930
Ford Motor Company of Canada Walkersville, Ontario	3	9.2	-	Bituminous	Heat Treating	1926 1,500 lbs./ hr. coal each
General Electric Erie, PA	1	5.5	-	-	-	1917
Holston Defense Corporation Kingsport, TN	12	9.1	-	Bituminous	Furnaces	1945 4 operating
International Harvester	3	3.5 4.0 5.0	-	-	Test use	1910 to 1911
Johns Hopkin Univ. Baltimore, MD	1	3.5	-	-	Test use	1915

Table 3.4-2 (Continued)

Partial Listing of Typical Commercial Experience for Wilputte Gasifier [(a)]

Company/ Location	Capacity			Coal Type	Application	Date & Comments
	No. of Units	Gasifier Diameter, ft	Heat Rate 10^9 Btu/Day			
Kellog Company Battlecreek, MI	2 (plus 7 other 9'0" size)	9.5	0.2-0.3 each	#1, #2, #3 Anthracite Buckwheat	Roasting Food Products	1927 to 1930
Long Island Lighting Co.	1	-	-	-	High Btu (1,000 Btu/cf) Oil gas machines	

(a) Data for plants sold from 1934 to 1944 are not fully available.

and ceramics are also represented, and there are a range of miscellaneous users including paper mills, coke-oven underfiring, and metallurgical operation.[20][28]

Each type of gas produced in the two-stage process by air-blown operation, i.e., hot raw, hot-detarred, cold clean, and cyclic gases, has its advantages for specific applications. The hot raw gas, being highest in heating value but least clean, is typically applied to firing open-hearth steel furnaces, heat treatment furnaces, cement kilns, tunnel kilns for the heavy clay industry, and glass melting tanks. If distribution mains are relatively short, firing in these applications can be carried on continuously and there is no need to burn out the mains.

Hot detarred gas is moderately clean and still retains the sensible heat (approximately 5% of the fuel heating value). It is applied, typically, for glass works retorts and any other process requiring a partially cleaned gas.

Cold clean gas is used with small diameter burners and where fine control is essential. Kilns for ceramic ware, coke ovens, and heat-treatment furnaces are examples of uses for this type of gas. It can also be considered for use as a fuel in gas turbines to generate electricity.

Oxygen-blown gas or cyclic gas (WD/GI) has a much higher heating value and is very low in nitrogen content. This gas is traditionally used in public utility and synthesis gas plants.[16]

Descriptions of commercial experience with two-stage gasifiers (as provided by Woodall-Duckham Ltd., Applied Technology Corp., and Foster Wheeler Energy Corporation) are given in the following sections. To the extent available, information detailing plant location/company, initial year of operation, capacity (or gasifier diameter), number of units, coal and/or gas type, and application is included.

3.4.2.1 Woodall-Duckham Two-Stage Gasifier

The WD/GI two-stage gasifier has been in commercial use as a cyclic medium-Btu gas generator since the 1920's and as a continuous air-blown fuel gas generator since 1942. It is estimated that over 100 units have been built in Europe alone.[16]

A. Industrial Fuel Gas Plants

The tabulation of plants given in Table 3.4-3 is a partial listing of industrial fuel gas plants built since 1946. These units all employ a continuous air-steam blast as a gasification agent. At each plant, different numbers of standard size gasifiers are used to obtain the required output. As indicated in the table, a variety of coal types, including mixtures, is used. Gas purification is said to be included in some plants but no further detail was disclosed.

Table 3.4-3

Commercial Experience for Woodall-Duckham Gasifier
(Industrial Fuel Gas Plants)

Company/Location	No. of Units	Gasifier Diameter, ft	Type	Status
Weldless Steel Tube Co. Wedensfield, England	2	10	Bituminous	Non-Operational
Ziar Aluminum Works Czechoslovakia	7	10	Bituminous	Non-Operational
Chomutov Tube Works Czechoslovakia	14	10	Lignite	Operational
Istanbul Gas Utility Turkey	1	8.5	Lignite	Operational
Australian Consolidated Industries, Ltd., Sydney, Australia	4	10	Bituminous	Non-Operational
Melbourne Gas Works Melbourne, Australia	2	10	Bituminous Brown	Non-Operational
Elgin Fireclay Ltd. Springs, South Africa	1	8.5	Bituminous	Operational
Vaal Potteries Ltd. Meyerton, South Africa	1	8.5	Bituminous	Operational
Union Steel Corp. Johannesburg, South Africa	2	10	Bituminous	Operational
Stewarts & Lloyds Steelworks, South Africa	3	10	Bituminous	Operational
Masonite, Escault South Africa	3	10	Bituminous	Operational
SAAPI, Mandini, South Africa	2	10	Bituminous	Operational
Rand Water Board, Vereeniging, South Africa	1	8.5	Bituminous	Operational

Table 3.4-3 (Continued)

Commercial Experience for Woodall-Duckham Gasifier
(Industrial Fuel Gas Plants)

Company/Location	No. of Units	Gasifier Diameter, ft	Type	Status
Driefontein, Carltonville, South Africa	2	10	Bituminous	Operational
Vereeniging Refractories South Africa	2	10	Bituminous	Operational
General Refractory Hitchins, Ky.	1	10	Bituminous	Starting Anticipated 1979

B. Public Utility Gas Plants

Public utility gas plants employ the same type of two-stage gasifiers, including coal and ash handling systems, but operate in a cyclic mode (alternate blasting of steam and air separately) so as to produce a gas with a very low nitrogen content.[14] The heating value of the product gas is from 330 to 500 Btu/SCF, depending on the extent of carburation with distillate or residual oil, or by enrichment with LPG. Information pertaining to a few of the more than 30 utility gas plants built since 1946 in presented on Table 3.4-4. None of these plants are currently in operation.

C. Synthesis Gas and Water Gas Plants

Synthesis gas, suitable for manufacture of ammonia or methanol, requires a low level of methane content. Such gas is produced in WD/GI two-stage gasifiers by cyclic operation or by continuous blasting with oxygen or an oxygen/air mixture. If coke is used as the feed, the first stage (distillation retort) of the gasifier is omitted. A partial listing of Synthesis gas plants built since 1946 is given on Table 3.4-5. None of these plants are currently in operation.

3.4.2.2 Wellman-Incandescent Two-Stage Gasifier

Commercial application of the Wellman-Incandescent two-stage gasifier is largely confined to South Africa. Table 3.4-6 is a list of WI gas plants installed in South Africa since 1964.[29] These plants all employ continuous air-steam blasting to produce fuel gases for various industrial applications. At Highveld Steel Company, each of the four 10 ft-diameter units delivers 300,000 SCF/hr of cold clean gas (1.26 x 10^9 Btu/day) for use primarily in the hot rolling mill. The gas generated is mixed with off gas from Highveld's electric arc furnaces and then burned.[27] At SCAW Metals Ltd., hot detarred gas is used for miscellaneous large furnace applications and cold clean gas for heat treating applications.[27] SCAW has both gas and electric heat treating furnaces, but finds producer gas more economical for most of their applications.[27] Union Steel Corp. of South Africa (USCO) has six two-stage units of which four are kept in operation with two as spares. There are four gas clean-up trains, one system for each operating producer. The cold clean gas generated is used for drying ovens, annealing furnaces, and miscellaneous heat treating furnaces.[27]

In the United States, two 10-ft WI two-stage gasifiers are being installed at the York, PA, Plant of the Caterpillar Tractor Co.; Gilbert Associates is serving as A/E on this project. The gas plant (2.5 x 10^9 Btu/day) is scheduled to be on-stream by Oct., 1978, producing desulfurized cold clean gas for heat treating applications.

Table 3.4-4

Commercial Experience for Woodall-Duckham Gasifier
(Public Utility Gas Plants)

Company/Location	No. of Units	Gasifier Diameter, ft
St. Poelten, Austria	2	6
Rome, Italy	5	8.5
Trieste, Italy	2	10
Como, Italy	1	6
Genoa, Italy	4	12
Vierzon, France	2	8.5
Kensal Green, England	1	10
Ulm, West Germany	2	8.5
Zagabria, Yugoslavia	1	6
Prague, Czechoslovakia	6	8.5
Warsaw, Poland	3	12
Posen, Poland	3	10
Thom, Poland	2	6
Tokyo, Japan	5	12

Table 3.4-5

Commercial Experience for Woodall-Duckham Gasifier
(Synthesis and Water Gas Plants)

Company/Location	No. of Units	Gasifier Diameter, ft.	Coal Type	Scope of System
OSW Fertilizer Plant Linz, Austria	4	8.5	Unknown	Med-Btu Gas
Vetrocoke, Porto Marghera, Italy	2	6	Bituminous	Med-Btu Cyclic Gas[(a)]
Montecatini, Crotone, Italy	2	8.5	Unknown	Med-Btu gas
Montecatini, St. Giuseppe di Cairo, Italy	2	10	Unknown	Med-Btu gas
I.M.A.D., Naples, Italy	2	6	Bituminous	Med-Btu Cyclic Gas
State Works, Semtin, Czechoslovakia	4	6	Coke[(b)]	Med-Btu Cyclic Gas
D. Swarovski Co., Wattens, Austria	2	6	Coke[(b)]	Med-Btu Cyclic Gas
Edison S.P.A., Milan, Italy	1	10	Coke[(b)]	Med-Btu Cyclic Gas
Marconi S.P.A., Aquila, Italy	1	6	Coke[(b)]	Med-Btu Cyclic Gas
Public Utility, Paris, France	3	14	Coke[(b)]	Med-Btu Cyclic Gas
Public Utility, Fuerth, West Germany	1	6	Coke[(b)]	Med-Btu Cyclic Gas

(a) Cyclic gas by alternate blasting of superheated steam and air separately.

(b) When coke is used as feed, the top retort zone is not required and the gasifier in reality becomes a single-stage system.

Table 3.4-6

Commercial Experience for Wellman-Incandescent Gasifier

Plant Owner[a]	No. of Operating Gasifiers	Gasifier Diameter, (Feet)	Heat Rate, 10^9 Btu/Day	Coal Type	Scope of System[b]	Application	Status[c]
SCAW Metals, Ltd.	1	10.00	0.7	Bituminous	Single Stage	Rolling Mill and Miscellaneous	1963
Stewarts & Lloyds	1	8.50	1.0	Bituminous	Two-Stage Hot Raw	Miscellaneous Furnaces	1964
Cullinan Refractories	2	6.50	0.6	Bituminous	Two-Stage Hot Raw	Tunnel Kilns	1964
Cullinan Refractories	1	8.50	1.0	Bituminous	Two-Stage Hot Raw	Basic Refractory Kilns	1965
Union Steel Corp.	4	10.00	4.8	Bituminous	Two-Stage (Three Hot Raw) (One Cold Clean)	Steel Making Furnaces and Miscellaneous	1965
Southern Cross Steel	1	10.00	1.2	Bituminous	Two-Stage Cold Clean	Stainless Steel Reheating and Heat Treatment Furnaces	1966
Consolidated Glass	2	10.00	2.7	Bituminous	Two-Stage Hot Raw	Glass Making Furnace	1967
Union Steel Corp.	1	10.00	0.7	Anthracite	Single Stage	Steel Making Furnaces and Miscellaneous	1968
SCAW Metals, Ltd.	2	10.75	2.6	Bituminous	Two-Stage (One Cold Clean) (One Hot Detarred)	Rolling Mill and Miscellaneous	1968
Highveld Steel	4	10.00	5.4	Bituminous	Two-Stage Cold Clean	Rolling Mill Furnaces	1968

Table 3.4-6 (Continued)

Commercial Experience for Wellman-Incandescent Gasifier

Plant Owner[a]	No. of Operating Gasifiers	Gasifier Diameter, (Feet)	Heat Rate, 10^9 Btu/Day	Coal Type	Scope of System[b]	Application	Status[c]
Lurgi, Groolfontein	1	6.50	0.6	Bituminous	Two-Stage Hot Raw	Rotary Zinc Kiln	1970
SCAW Metals, Ltd.	1	10.75	1.5	Bituminous	Two-Stage Hot Detarred	Rolling Mill and Miscellaneous	1970
Cullinan Refractories	1	8.50	1.0	Bituminous	Two-Stage Hot Raw	Refractory Brick Kilns	1973
SAICCOR	1	10.00	1.2	Bituminous	Two-Stage Cold Clean	Pulp and Paper Drying	1973
Johannesburg Consolidated Inv. Co.	1	6.50	0.66	Bituminous	Two-Stage Hot Raw	Antimony Concentrate	1975
SCAW Metals, Ltd.	1	10.75	1.5	Bituminous	Two-Stage Hot Detarred	Steelworks, Reheat Annealing Furnaces, etc.	1975
Southern Cross Steel	1	10.00	1.2	Bituminous	Two-Stage Cold Clean	Stainless Steel Reheat Furnaces, etc.	1976
Highveld Steel	2	10.00	2.3	Bituminous	Two-Stage Cold Clean	Steel Mill Reheat Furnaces	1976
Caterpillar Tractor Co., York, PA	1	10.00	2.5	Bituminous	Two-Stage Cold Clean	Heat Treating	1978

Table 3.4-6 (Continued)

Commercial Experience for Wellman-Incandescent Gasifier

Plant Owner[(a)]	No. of Operating Gasifiers	Gasifier Diameter, (Feet)	Heat Rate, 10^9 Btu/Day	Coal Type	Scope of System[(b)]	Application	Status[(c)]
Land O'Lakes, Minnesota	1	10.00	1.3	Bituminous	Two-Stage Hot Raw	Boilers and Whey Drying	1979

(a) All plants are located in South Africa, except Caterpillar Tractor Co. and Land O'Lakes.

(b) All products are low-Btu gas.

(c) Year completed.

3.4.2.3 FW-Stoic Two-Stage Gasifier[18]

There are two Stoic gasifiers currently in operation in South Africa, as shown in Table 3.4-7. A 10-ft diameter gasifier located at Driefontein was started up in 1973, using a bituminous coal to produce hot detarred gas for service in a brick kiln. The other, a 8.5 ft gasifier located at Lydenberg, was started up in 1976, also using a bituminous coal as feed. This plant, however, produces cold clean gas for metal drying operations.

In the United States, Foster Wheeler Energy Corporation is currently furnishing a 10-ft diameter FW-Stoic gasifier to provide a low-Btu fuel gas for firing two existing 25,000 lb steam/hr boilers designed with dual oil natural gas firing capability. The boilers are located on the Duluth campus of the University of Minnesota. This FW-Stoic unit will gasify a western subbituminous coal to produce hot detarred gas. Under a contract with ERDA, the plant is scheduled to startup in April, 1978.

3.5 REFERENCES

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Table 3.4-7

Commercial Experience for FW-Stoic Gasifier

Company/ Location	Capacity: No. of Units	Capacity: Size, Diameter, Ft	Capacity: Heat Rate 10^9 Btu/day	Coal Type	Scope of System	Application	Status
Driefontein, South Africa	1	10	1.44	Bituminous	Low Btu gas - Hot Detarred	Brick Kiln	1973
Lydenberg, South Africa	1	8.5	0.96	Bituminous	Low-Btu gas - Cold Clean	Metal Drying	1976
University of Minnesota Duluth, Minn.	1	10	1.44	Subbituminous Lignite	Low-Btu gas Hot Detarred	Boiler Fuel	1978

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4.0 ECONOMIC ANALYSIS OF GASIFICATION

This section provides the basic economic information on commercially available fixed bed gasification systems. With this information, industrial organizations can explore the feasibility of producing low-Btu gaseous fuel for retrofit and/or new industrial plant applications.

Much previously developed cost data obtained from contacts with gasifier vendors for Gilbert's industrial projects were reviewed. Direct capital cost data were available for all single-stage gasifiers and two of the two-stage gasifiers. The five direct capital costs were averaged to determine an average capital cost, and this average cost was assumed to be applicable to all fixed-bed gasifiers evaluated.

Operating and fuel costs were generated using the average capital cost for producing low-Btu gases of the following three levels of gas quality (cleanliness):

Gas 1: Hot raw gas

Gas 2: Dust-, tar-, and oil-free gas

Gas 3: Dust-, tar-, oil-free and desulfurized gas

For producing Gases 1 and 2, a typical low-sulfur bituminous coal of Stockton, WV (see Tables 4.1-1 and A-3 in Appendix A for characteristics) was used for the economic evaluation. A typical high-sulfur bituminous coal of Belmont, Ohio (see Tables 4.1-1 and A-3 in Appendix A for characteristics) was used for production of Gas 3.

Depending on end-use application, coal gas produced from fixed-bed gasifiers can be cleaned to one of the three degrees of cleanliness described below:

- Hot Raw Gas is suitable in cases where the gas is utilized in very close proximity to the gasifier and tar condensation with associated particulate deposition is not a problem. Additionally, to permit the direct use of hot raw gas requires low sulfur coal in order to minimize environmental problems.

- Dust-, Tar-, and Oil-Free Gas is suitable if a low sulfur coal is fed to the gasifier and if the gas must be boosted in pressure to permit distribution to point of consumption.

- Dust-, Tar-, Oil-Free and Desulfurized Gas is an environmentally acceptable fuel gas if high sulfur coal is fed to the gasifier.

The fuel costs were calculated for each of the three degrees of cleanliness using 8%, 10%, 12% Discounted Cash Flow (DCF) returns on 100% equity capital. Figure 4.0-1 shows the sensitivity of differential coal cost between low sulfur coal for producing Gases 1 and 2 against high-sulfur coal for producing Gas 3. In order to produce a low-Btu gas at $3.0/MM Btu the cost difference between low-sulfur coal to yield Gas 2 and high-sulfur coal for Gas 3 is $12.0/ton at 12% DCF return rate. Likewise, the cost difference between low-sulfur coal to produce Gas 1 and high-sulfur coal to produce Gas 3 is $23.0/ton. Therefore, the desulfurization cost is equivalent to $12.0/ton, the cost of sulfur, dust, tar and oil removal $23.0/ton and the cost of dust, tar and oil removal $11.0/ton. Similar procedures can be applied with varying fuel costs and DCF rates as shown below:

DCF Return Rate	Fuel Cost, $/MM Btu	Differential Coal Cost (Low Sulfur Coal-High Sulfur Coal), $/Ton	
		Hot Raw Gas	Dust-, Tar-, Oil-Free Gas
8%	2.5	18.3	10.0
	3.5	23.8	11.0
10%	2.5	19.5	11.3
	3.5	24.5	12.5
12%	2.5	20.5	12.0
	3.5	25.5	13.0

Figure 4.0-2 shows the sensitivity of differential fuel cost for producing Gases 3 and 1 or Gases 3 and 2 for varying delivered coal cost. At 12% DCF return for a $30/ton of coal, the cost of sulfur removal in terms of fuel cost is $0.60/MM Btu, and the cost of sulfur, dust, tar, and oil removal is $1.20/MM Btu. Therefore, the cost of dust, tar, and oil removal is $0.60/MM Btu.

Similar procedures can be applied with varying coal costs and DCF rates. In general, the differential fuel cost calculated at a given DCF rate increases with increasing coal cost, as summarized below:

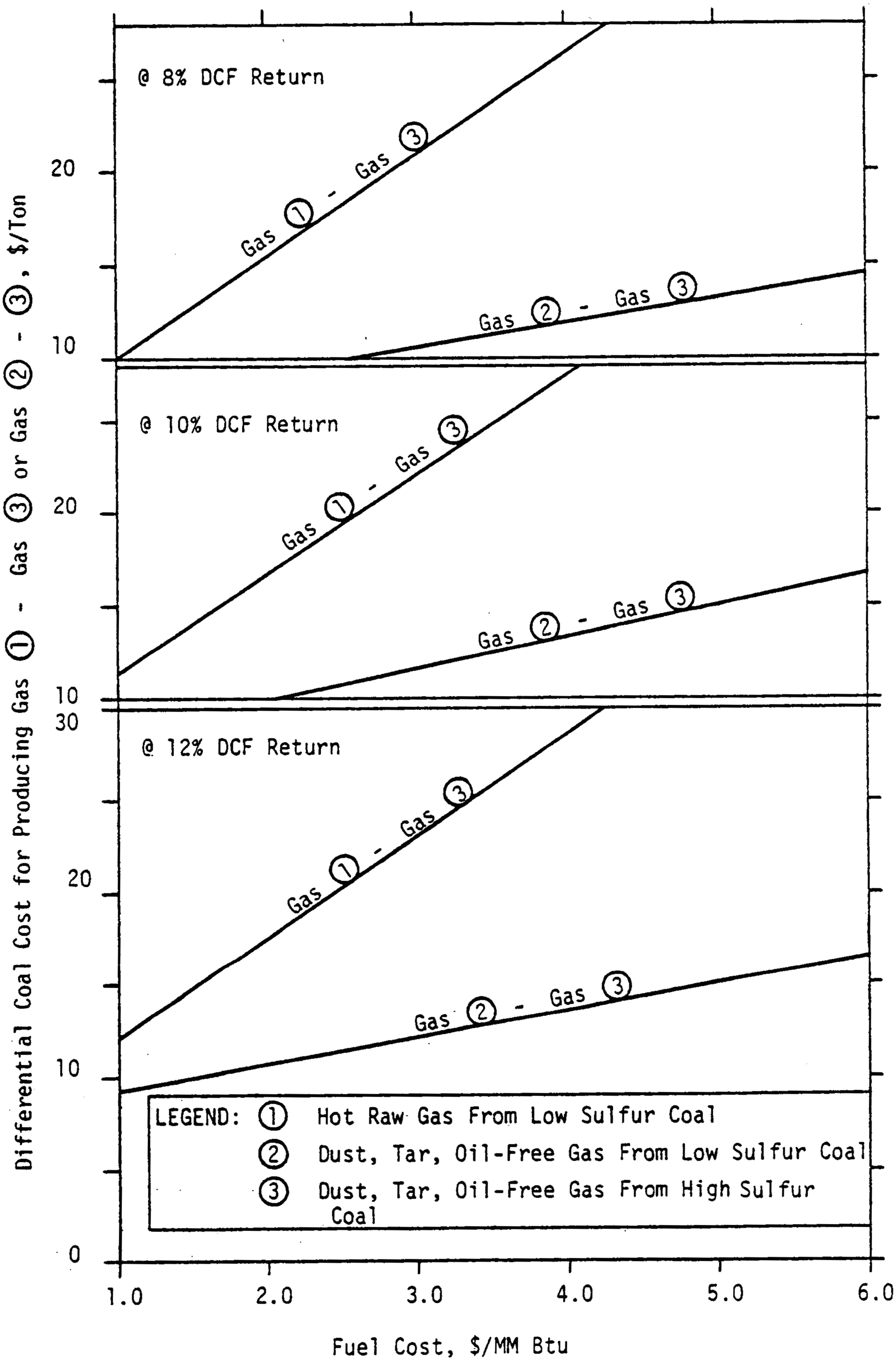

Figure 4.0-1 Sensitivity of Differential Coal Cost Between Low Sulfur and High Sulfur Coal vs Fuel Cost

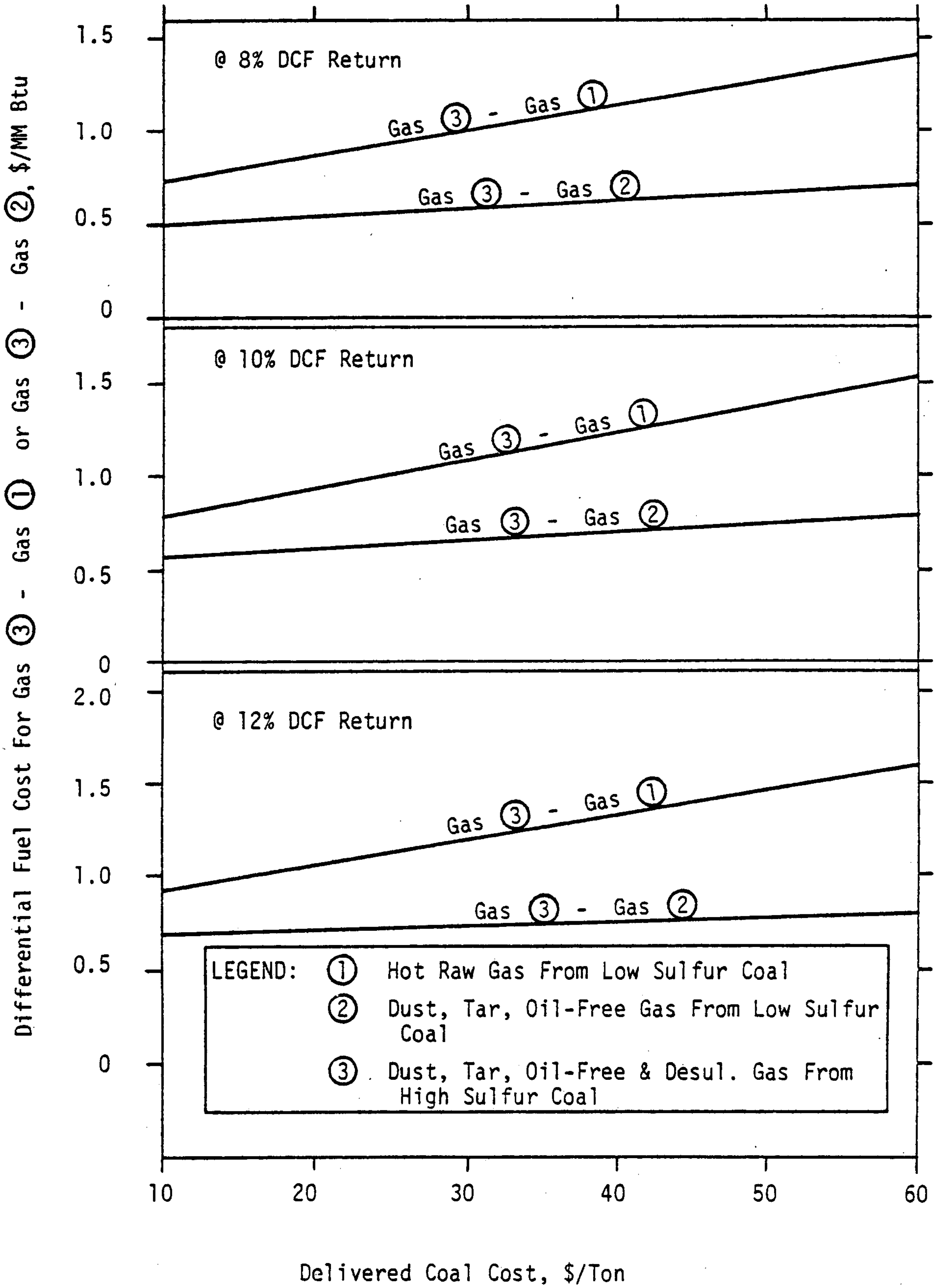

Figure 4.0-2 Sensitivity of Differential Fuel Cost vs Delivered Coal Cost.

DCF Return Rate	Delivered Coal Cost, $/Ton	Diff. Fuel Cost, $/MM Btu	
		Gas 3-Gas 2	Gas 3-Gas 1
8%	20	0.56	0.86
	40	0.64	1.14
10%	20	0.60	0.98
	40	0.70	1.25
12%	20	0.68	1.20
	40	0.75	1.33

4.1 BASIS OF ECONOMIC ANALYSIS

Figures 4.1-1 and 4.1-2 show the generalized process configuration utilizing, respectively, single- and two-stage gasifiers to produce a low-Btu gas. Each process contains three main sections:

- Coal handling and gasification section--for producing hot raw gas,
- Tar/oil recovery section--for producing dust-, tar-, and oil-free gas, and
- Desulfurization section--for producing dust-, tar-, oil-free and desulfurized gas.

The process design conditions used in the economic analysis are summarized in Table 4.1-1. Characteristics of low- and high-sulfur coals used are also presented in this table together with the performance data necessary to determine thermal efficiencies, coal throughputs required, and by-products produced for the three degrees of gas cleanliness considered.

Discounted Cash Flow (DCF) equations using 8%, 10%, and 12% return rates were derived and the results are presented in Table 4.1-2 along with the significant financial parameters used.[1][2] A DCF return rate of 12% was used by Synthetic Gas-Coal Task Force of ERDA[2] to estimate the cost of manufacturing SNG from coal on a private investor financing basis. However, fixed bed gasification involved proven technologies and is therefore much less risky than production of SNG from coal. Thus, fuel costs were also calculated at lower than 12% DCF return rates, i.e., at 8% and 10%.

4.2 CAPITAL COST

Table 4.2-1 summarizes the capital costs in mid-1977 dollars for producing 2.5 x 10^9 Btu/day of hot raw gas; dust-, tar-, and oil-free gas; and dust-, tar-, oil-free and desulfurized gas. The costs cover major equipment included in Figures 4.1-1 for single-stage and 4.1-2

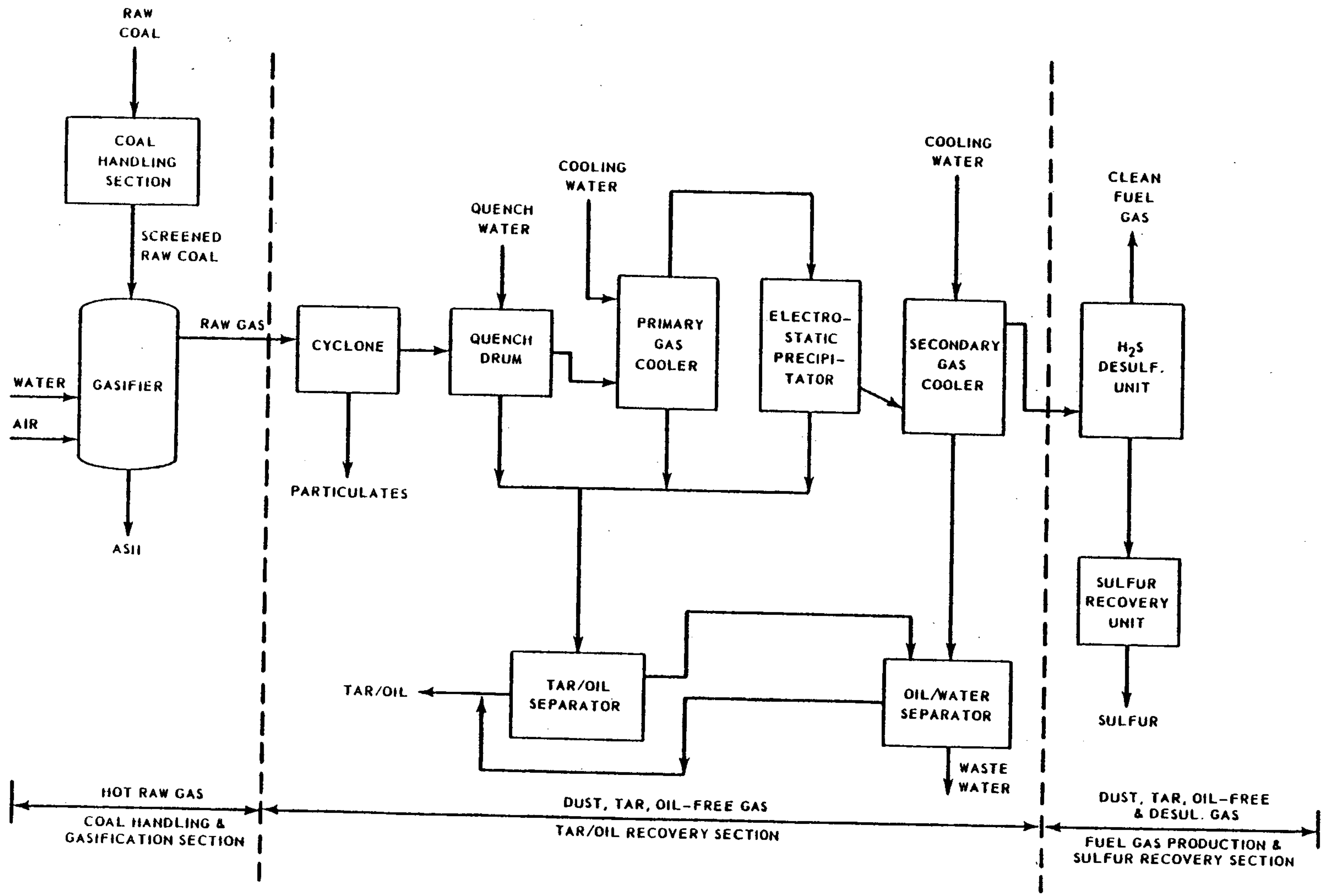

FIGURE 4.1-1 SINGLE-STAGE GASIFICATION PROCESS FLOWSHEET

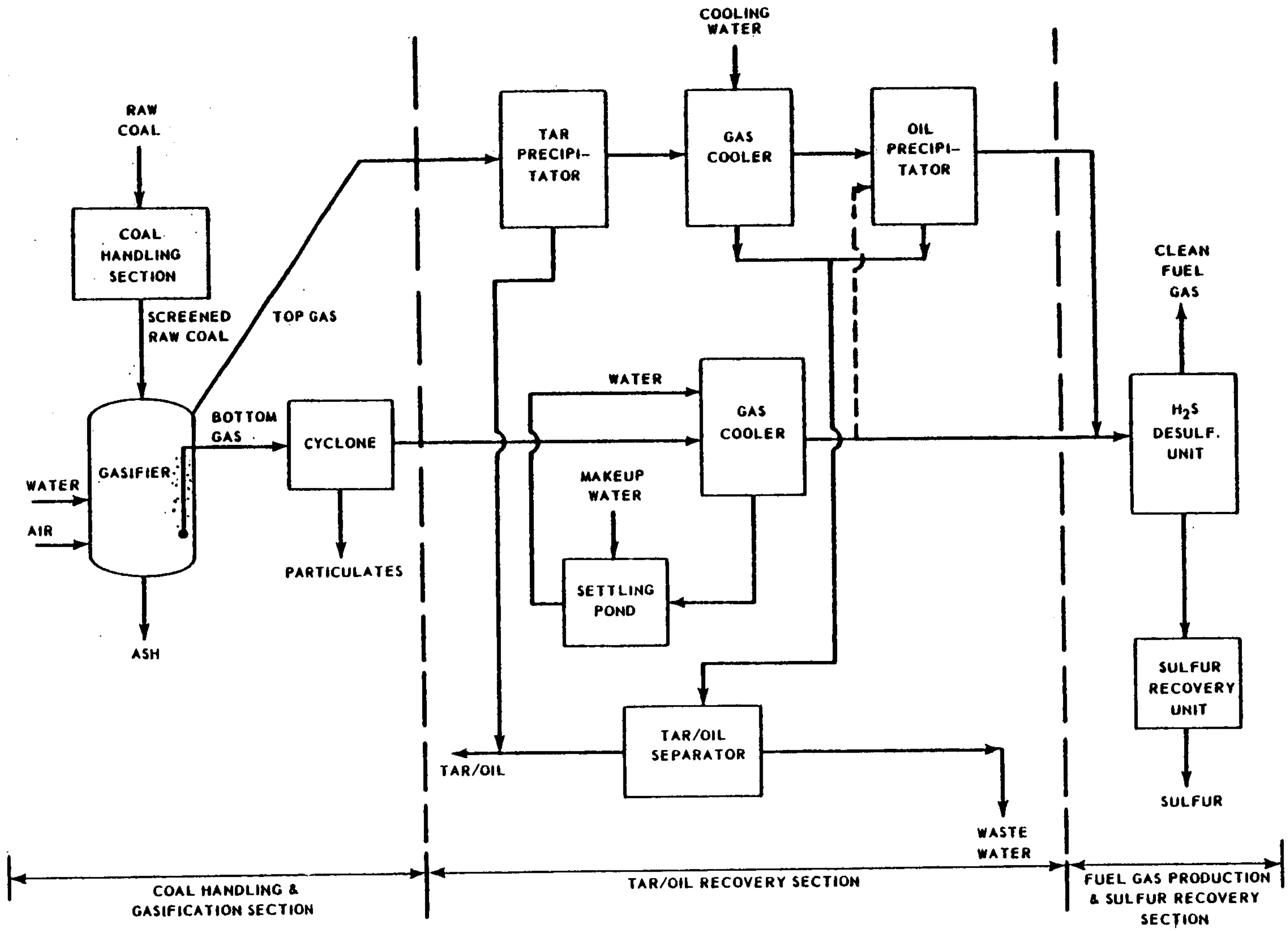

FIGURE 4.1-2 TWO-STAGE GASIFICATION PROCESS FLOWSHEET

<u>Table 4.1-1</u>

<u>Process Design Conditions for Fixed Bed Gasifier Plant</u>

<u>Process Design Conditions</u>

Plant Capacity, MMBtu/day		2,500	
Coal Type	Stockton, W. Va.		Belmont, Ohio
	Low Sulfur		High Sulfur
Sulfur, Wt. %	0.60		3.33
HHV, Btu/Lb	13,084		12,473
Sulfur Emissions, Direct Combustion, lb SO_2/MMBtu	0.92		5.29

Degree of Cleanliness	Hot Raw Gas	Dust-Tar-& Oil-Free Gas	Dust, Tar, Oil-Free, and Desulf. Gas
Thermal Efficiency, %	91.8	76.0	74.0
Coal Throughput, TPD	104.8	125.7	135.4
By-Product			
Tar, GPD	-(a)	1,998.6	2,152.9
Sulfur, GPD	-	-	3.45
Sulfur Emission, Fuel Gas Combustion, lb SO_2/MMBtu (b)	1.0	1.10	1.2
Desulfurization process	-	-	Stretford

(a) Two-stage fixed bed gasifier produces some tar in its hot raw gas production whereas a single-stage gasifier does not. Thermal efficiency of two-stage fixed bed gasifier is around 90% in hot raw gas production, compared with 93% from a single-stage gasifier. Since an average efficiency of 91.8% is used for all gasifiers considered, the tar produced in the two-stage gasifier is credited to the improvement of efficiency.

(b) Sulfur emissions are based on SO_2 formed as a result of combusting the fuel gas; in the case of Dust-, Tar-, Oil-Free gas a portion of the coal sulfur remains with the tar.

Table 4.1-2

Calculation of Fuel Cost by Discount-Cash Flow Analysis For Fixed Bed Gasifier System

Financial Parameters

Plant Life, Years	25
Capacity Factor, %	90
Depreciation	16 years "sum-of-the-years'" digits
By-Product Credit	
Tar, ¢/Gallon	10
Sulfur, $/Ton	25
Federal Income Tax Rate, %	48
DCF Return, %	12, 10, 8
Equity Capital, %	100
Interest During Construction (IDC)	Payable within 12 months

Calculation of Fuel Cost

$$\text{Fuel Cost (\$/MMBtu)} = \frac{aN + bI + cS + dW}{G}$$

a = is a dimensionless parameter describing escalation of operating cost during the project life. In the present calculation, a = 1.0 assuming there is no escalation from start-up through project completion date.

b = 0.2095 at 12% DCF return, 0.1719 at 10% DCF return, 0.1377 at 8% DCF return.

c = 0.1275 at 12% DCF return, 0.1102 at 10% DCF return, 0.0937 at 8% DCF return.

d = 0.2308 at 12% DCF return, 0.1922 at 10% DCF return, 0.1538 at 8% DCF return.

N = Total Net Operating Cost including Coal Feed Cost in the first year, MM$/Year.

I = Total Plant Investment, MM$

S = Start-up Cost, MM$; 20% of Total Annual Gross Operating Cost including Coal Feed Cost.

W = Working Capital, MM$; 60 Days Coal Inventory plus 1% of Total Plant Investment.

G = Annual Fuel Production, Trillion Btu/Year.

The values of I, S, W and N above must be adjusted to reflect the actual costs for the start-up completion date.

Table 4.2-1

Capital Cost for Fixed Bed Gasifier of 2.5×10^9 Btu/day Capacity

(Based on Mid-1977 Pricing)

Gasifier Supplier		A	B	C	D	E	Average
Gasification	MM$						
Coal & Ash Handling							
Gasifiers							
Cyclones		0.950	2.175	1.663	2.438	3.082	2.061
Site Building & Installation							
Gas Manifold							
Subtotal	MM$	0.950	2.175	1.663	2.438	3.082	2.061
Facilities	MM$						
Elect. Power Distribution		0.093	0.093	0.093	0.093	0.118	
Cooling Water Piping		0.002	0.002	0.002	0.002	0.003	
Instrument Air & Dryer		0.005	0.005	0.005	0.005	0.006	0.149
Steam System for Startup/Shutdown		0.020	0.020	0.020	0.020	0.025	
Air Cooler		0.021	0.021	0.021	0.021	0.027	
Subtotal	MM$	0.141	0.141	0.141	0.141	0.179	0.149
Total Direct Capital Cost for Hot Raw Gas		1.091	2.316	1.804	2.579	3.261	2.210
Gas Cleanup							
Tar, Oil Removal & Water Treatment		0.747	0.747	1.707	0.650	0.822	0.935
Total Direct Capital Cost for Dust, Tar & Oil-Free Gas	MM$	1.838	3.063	3.511	3.229	4.083	3.145
Desulfurization[(a)]	MM$	1.375	1.357	1.246	1.375	1.828	1.440
Total Direct Capital Cost for Dust, Tar & Oil-Free and Desulf. Gas	MM$	3.213	4.438	4.757	4.604	5.911	4.585

(a) Desulfurization costs are based on Stretford process.

for two-stage gasifier systems. The costs associated with gasification facilities, site and building were also included. However, such indirect cost elements as engineering, project contingency, construction management, and escalation were not included in the cost estimates.

The capital costs are based on quotations received from vendors for two different sized plants: 2.5×10^9 Btu/day and 6×10^9 Btu/day. A capacity exponent of 0.7 on the plant capacity ratio was used to adjust the capital cost for the 6×10^9 Btu/day plant to 2.5×10^9 Btu/day, the capacity used for the present study.

The capital costs ranged from $1.09 MM to 3.26 MM for the hot raw gas (Gas 1); $1.84 MM to $4.08 MM for cold, dust-, tar-, oil-free gas (Gas 2); and $3.21 MM to 5.91 MM for cold dust-, tar-, oil-free and desulfurized gas (Gas 3). The average capital costs for the three cases of the gas cleanliness were $2.21 MM, $3.15 MM, and $4.59 MM, respectively, for production of Gases 1, 2 and 3.

4.3 OPERATING AND FUEL COSTS

Table 4.3-1 presents the annual operating cost excluding coal cost and separately, the product fuel gas costs calculated at 8%, 10%, and 12% DCF rate on 100% equity for varying delivered coal costs for each of the three degrees of gas cleanliness evaluated. The gas costs based on less than 100% equity will be lower because the interest on the debt portion of the capital is expendable for tax purposes. For example, based on 50% debt, 50% equity with 8.5% bond interest and 10% return on equity, the gas cost will decrease by approximately $0.15/MM Btu for the hot raw gas and $0.30/MM Btu for the desulfurized gas. With the investment tax credit such as 20% applied to the capital for the desulfurization unit and 10% for the rest of the plant, a further reduction of $0.06/MM Btu can be realized.

Sensitivity of fuel cost to variation in delivered coal cost for the three product gases is depicted on Figures 4.3-1, 2 and 3 for DCF rates of 12, 10 and 8% respectively.

4.4 TYPICAL PROJECT SCHEDULE

A typical project schedule for engineering and construction of commercially available fixed bed gasification plant is presented in Figure 4.4-1. The average project schedule is 24 months from the time of contract initiation to the completion of the performance tests. The schedule does not include the retrofit work. It is anticipated that if retrofit work is needed, it will be accomplished in parallel with the gasification plant construction and the overall schedule will not be affected.

4.5 REFERENCES

1. EPRI, "Evaluation of Coal Conversion Processes to Provide Clean Fuels," Part II, NTIS PB-234203 (February, 1974).

2. Federal Power Commission, "National Gas Survey, Vol. 2, Supply Task Force Reports" (1973).

Table 4.3-1

Fuel Cost For Fixed-Bed Gasifier System

	Hot Raw Gas	Dust, Tar & Oil-Free Gas	Dust, Tar, Oil-Free and Desulf. Gas
Plant Investment Cost, MM$[a]	2.210	3.145	4.585
Operating Cost, MM$/Yr			
Utilities & Materials (3% of Plant Investment)	0.066	0.094	0.138
General Overhead (1.67% of Plant Investment)	0.037	0.053	0.077
Labor Cost, MM$/Yr.			
Process[b]	0.248	0.248	0.248
Maintenance (1.5% of Plant Investment)	0.033	0.047	0.069
Supervision (15% of Sum of Process & Maintenance Labor)	0.045	0.049	0.054
Taxes & Insurance (2.7% of Plant Investment), MM$/Yr.	0.060	0.085	0.124
GROSS OPERATING COST, MM$/Yr.	0.489	0.576	0.710
By-Product Credit, MM$/Yr.			
Tar	-	0.066	0.071
Sulfur	-	-	0.028
		0.066	0.099
NET OPERATING COST (Excluding Coal Cost), MM$/Yr.	0.489	0.510	0.611

	Hot Raw Gas			Dust, Tar & Oil-Free Gas			Dust, Tar, Oil-Free and Desulf. Gas		
Delivered Coal Cost, $/Ton	30	40	50	30	40	50	20	30	40
Fuel Cost, $/MMBtu (at 12% DCF Return)	2.52	2.96	3.41	3.06	3.49	4.13	3.14	3.72	4.29
(at 10% DCF Return)	2.40	2.84	3.28	2.90	3.32	3.96	2.91	3.48	4.06
(at 8% DCF Return)	2.29	2.73	3.17	2.75	3.17	3.80	2.70	3.27	3.84

(a) Average of all fixed-bed gasifiers considered (Table 5.2-1).

(b) Process labor cost = (4 Men/Shift) (8304 manhours/year) ($5.2/manhour) (1.433) where 1.433 is an escalation factor to mid-1977 from mid-1973.

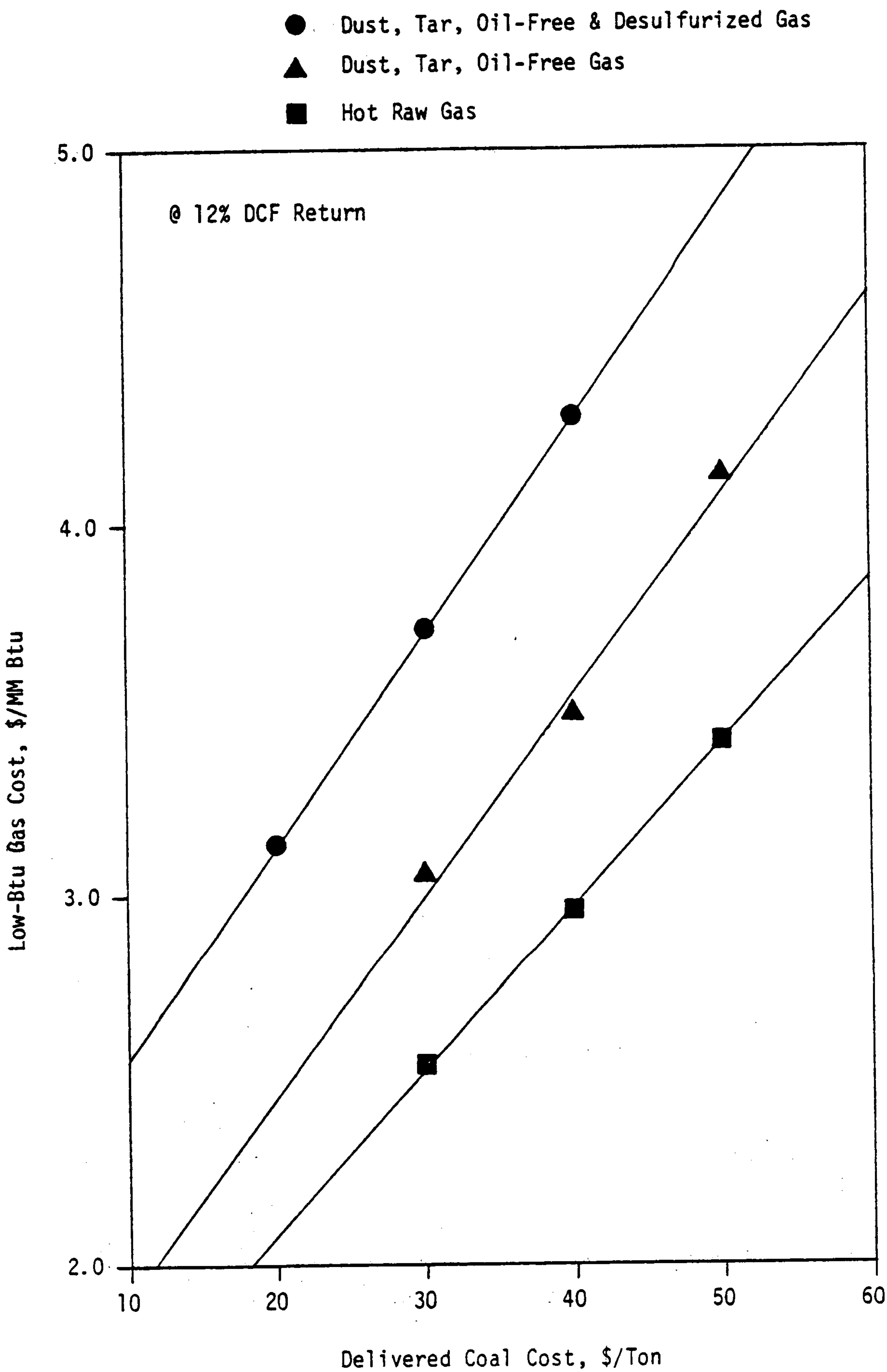

Figure 4.3-1 Low-Btu Gas Cost vs. Delivered Coal Cost for 12% DCF Return

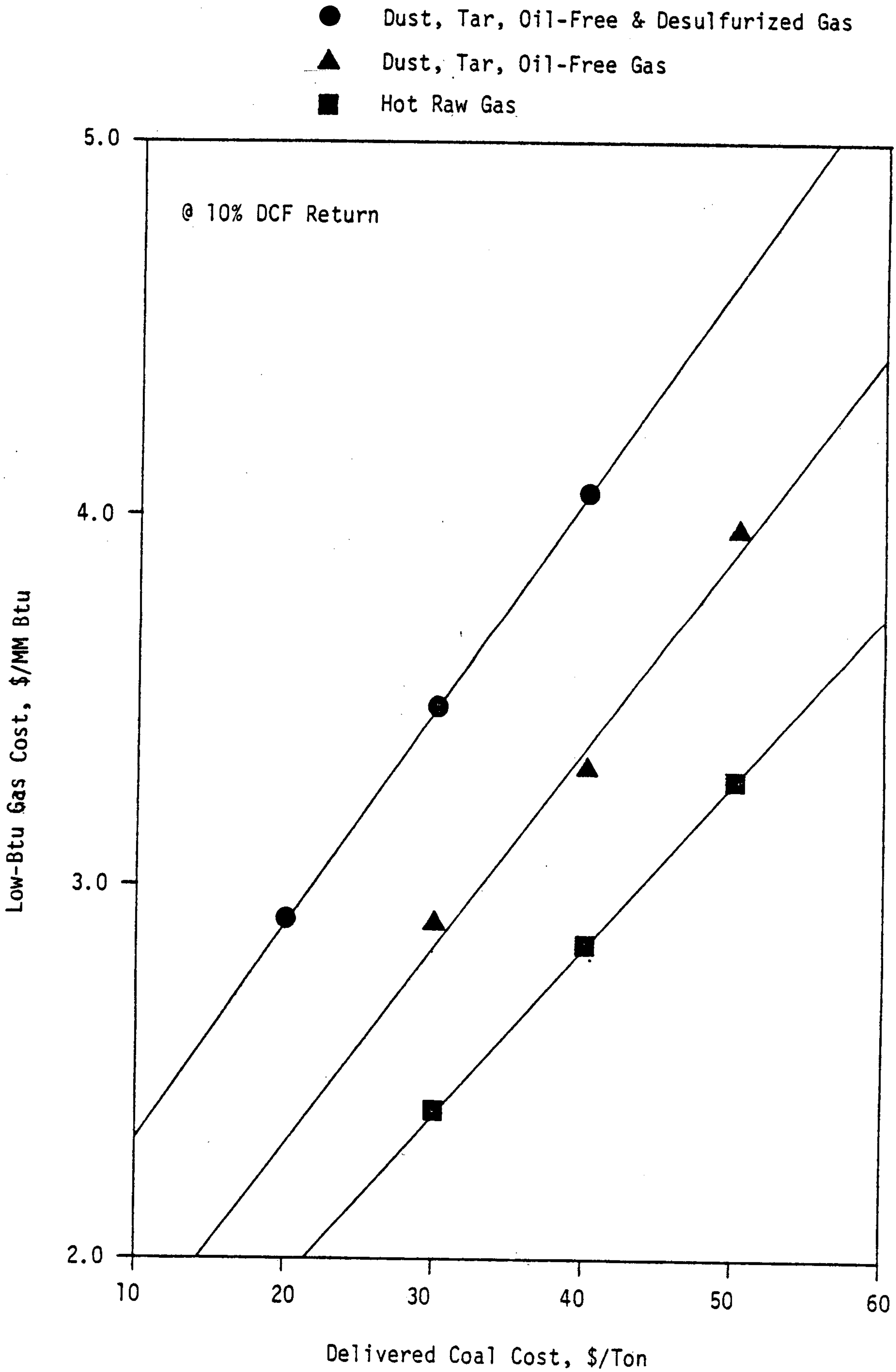

Figure 4.3-2 Low-Btu Gas Cost vs. Delivered Coal Cost for 10% DCG Return

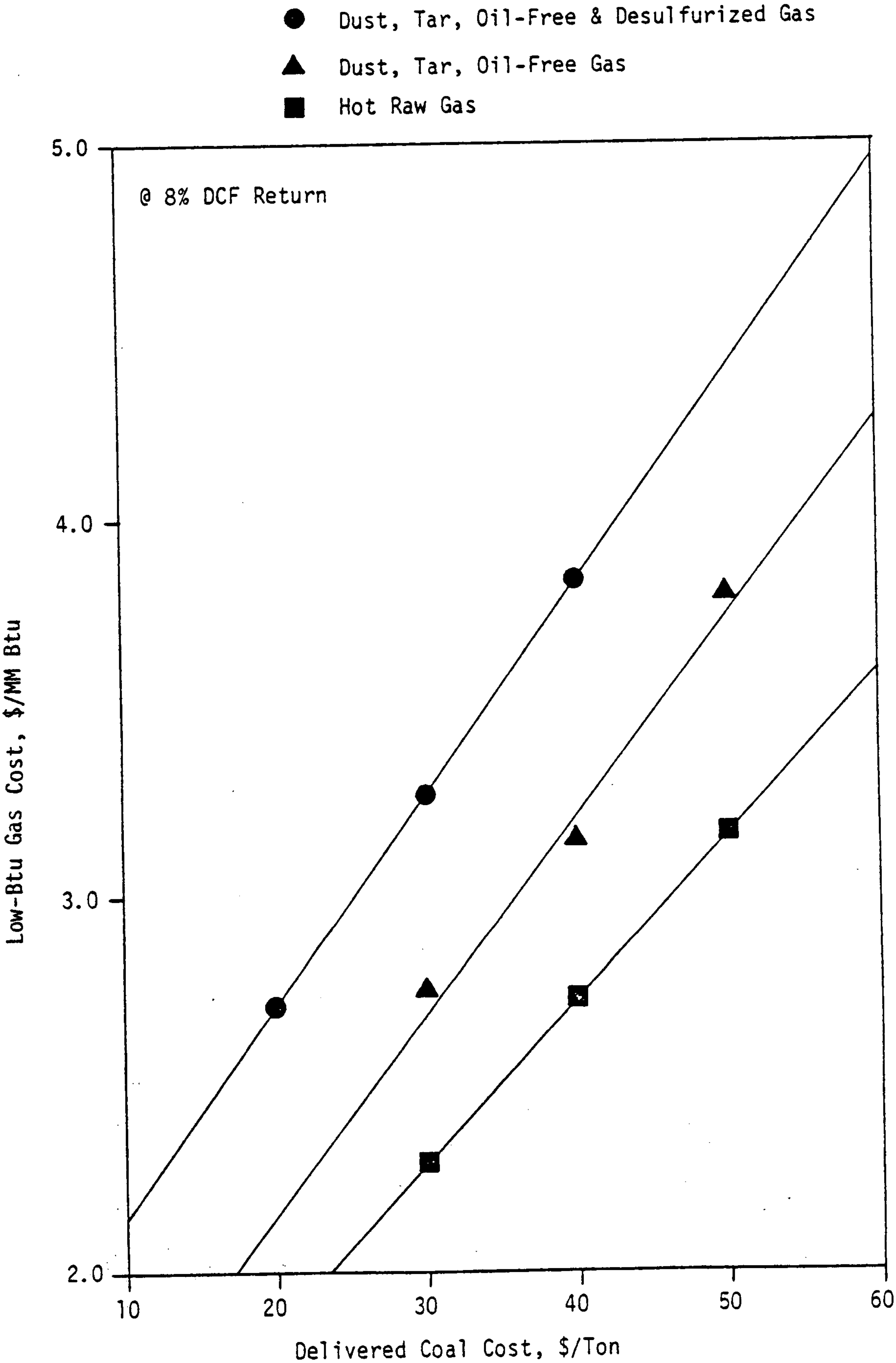

Figure 4.3-3 Low-Btu Gas Cost vs. Delivered Coal Cost

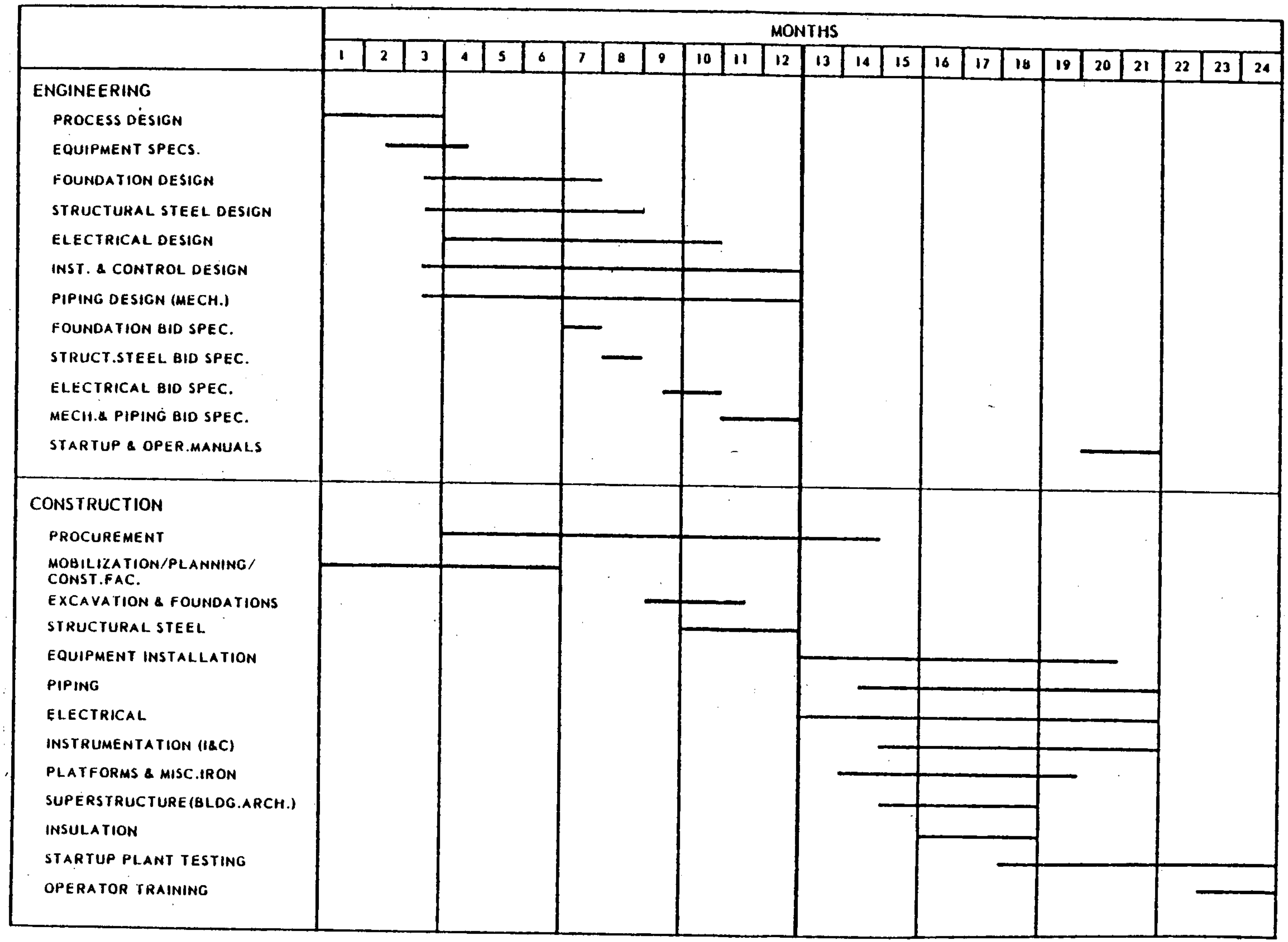

FIGURE 4.4-1 TYPICAL PROJECT SCHEDULE

5.0 SUMMARY OF RESULTS

5.1 TECHNICAL ANALYSIS

The technical analyses of six fixed bed gasifiers were performed by consideration of their physical configurations, performance capabilities, operating conditions and maintenance schedule, and commercial experience.

5.1.1 Physical System

Table 5.1-1 summarizes the physical configurations of the single-stage and two-stage gasifiers. Included in the table are descriptions of physical components such as the coal feed system, gasifier, ash withdrawal system, oxygen/air feed system, steam feeding system, and physical dimensions. Advantages, disadvantages, maintenance areas, and potential for improvements are also summarized in the table. The table indicates that the characteristics and configurations of the three two-stage gasifiers evaluated are very similar. Only the coal feeding system and a part of ash withdrawal systems vary slightly.

5.1.2 Performance Capability

Table 5.1-2 presents the gasifier performance data. Typical coal feed sizes and acceptability of fines are presented as well as the capability of gasifying caking coals. The two-stage gasifiers can not handle highly agglomerating coals with a FSI higher than 3, whereas all three single-stage gasifiers can gasify high FSI (greater than 5) coals by use of the stirrer installed in the gasifier. Both single and two-stage gasifier types require coals with an ash fusion temperature of at least 2100-2200°F.

Coal throughputs vary considerably, depending on the type of coals being gasified. However, for a given coal type, the throughputs are nearly independent of the type of gasifier evaluated. The type of oxidizing medium used -- air or oxygen -- does influence the coal throughputs. When bituminous coals are gasified, the coal throughputs ranged from about 60 to 89 $lb/hr\text{-}ft^2$ for air-blown, single-stage gasifiers and 62 to 76 $lb/hr\text{-}ft^2$ for air-blown, two-stage gasifiers. For the single-stage gasifiers, using oxygen instead of air results in an increased coal throughput by 33-60%, 11-43%, and 72% for anthracite, coke, and bituminous coal feeds, respectively. Coal throughput data are not available for oxygen-blown, two-stage gasifiers.

Analysis of the product gas indicates that, for a given gasifier type, the characteristics (composition and heating value) of product gas vary only slightly with the type of coal feed. The data presented in Table 5.1-2 are the typical characteristics of low- and medium-Btu gas which can be produced from the six fixed bed gasifiers.

Table 5.1-1

Summary of Physical System for Commercially Available Fixed Bed Gasifiers

	SINGLE-STAGE GASIFIERS				TWO-STAGE GASIFIERS	
	McDowell-Wellman	Riley-Morgan	Wilputte	Woodall-Duckham	Wellman-Incandescent	FW-Stoic
Physical Components						
Coal Feeding System	. Continuous automatic gravity coal feeding . Two-compartment feed bin	. Continuous automatic drum feeder and lock hopper	. Chapman drum feeder . Fuel magazine	. Lock hoppers . Coal distributor	. Automatic drum feeders	. Automatic drum feeders
Gasifier	. Coal fed from top . Ash discharged from bottom . Stirrer available to handle caking coals . Completely water-jacketed . 1" thick inner-wall steel plate	. Coal fed from top, ash discharged from bottom . Leveller arms to ensure uniform coal distribution across gasifier . Water-cooled rotating cylindrical shaped gasifier shell . Water-cooled stationary agitators . Uses refractory lining	. Coal from top and ash from bottom . Chapman agitators . Coal distributor . Water filled ash pan forms seal . For anthracite and coke, shell is jacketed . For bituminous, shell is brick-lined	. Coal from top, ash to bottom . Two levels of gas withdrawal, top gas from upper offtake and clear gas from lower outlet . No stirrer . Retort section divided into four compartments; refractory-lined	. Coal from top, ash to bottom . Two gas offtakes - top and bottom . No agitator . Four compartments in retort section; refractory-lined . Water-jacketed gasification section	. Coal from top, ash to bottom . Two gas offtakes . No agitator . Refractory-lined retort . Water-jacketed gasification section
Ash Withdraw System	. Rotating grates . Continuous discharge . Elevated ash pit	. Intermittent removal by means of ash plow . Ash plow is stationary, release ash after one complete revolution by gasifier shell . No grate	. Rotating grate, stationary ash plow and rotating ash pan	. Rotating grate . Dry or wet ash removal	. Rotating grate . Water-sealed ash pan . Wet ash removal	. Rotating grate . Damp ash removal through water-sealed ash pan
Air/Oxygen Feeding System	. Direct-driven fan blast . Saturated with steam from jacket	. F.D. fan blast . Blast hood to ensure uniform distribution . Air and steam both metered	. F.D. blast is mixed with steam from the jacket or external source	. Air saturated with steam introduced from under the grate	. Air saturated with steam introduced from under the grate	. Air/steam mixture fed from under the grate
Steam Feeding System	. Waste heat in water jacket generates steam	. Metered steam from external source	. For coke and anthracite, 15 psig steam is raised in water jacket & used to saturate air . For bituminous coal, steam is taken from waste heat boiler or outside source	. Gasification steam generated in the gasifier jacket	. Gasification steam generated in the gasifier jacket	. Gasification steam generated in the water jacket
Inside Diameter	. Brick-lined - 1'-6"; 1'-10"; 2'; 3'; 4'; 5' . Jacketed - 6'-6"; 8'; 10'	. 10'-6"; 18'	. 9'-2"; 10'-4"	. 10'; 12'	. 4'-6"; 5'-6"; 6'-6"; 8'-6"; 10' 10'-9" and 12'	. 6'-6"; 8'-6"; 10' and 12'-6"
Advantages						
Coal Feeding System	. No moving parts - minimum abrasive effects . Simple design & operation	. No gas leakage from the feed system	. No gas leakage from the feed system	. Minimum free-falling of coal . Gradual heating of coal	. Minimum free-falling of coal . Gradual heating of coal	. Minimum free-falling of coal
Gasifier	. Inner wall is not brick-lined; low maintenance cost . Stirrer permits use of coals . No limit on FSI	. Rotating cylinder surrounded by stationary dust hood for clean de-ashing	. For anthracite and coke, the gasifier is self-sufficient in steam	. No dust carryover (top gas) . Negligible cracking of tar/oil . Separate control of distallation and gasification	. Separate control of distillation and gasification . No dust carryover (top gas) . High quality byproduct tar	. No dust carryover (top gas) . Separate control of distillation and gasification . Automated poking operation
Air/O_2 Feeding System	. Air/O_2 saturation temperature controlled by controlling jacket-water supply	. Air/O_2 and steam streams metered	. Air saturation temperature controlled in air saturator	. Cyclic mode with air and superheated steam . Air saturation temp. control	. Air saturation temp. control	. Air saturation temp. control
Disadvantages	. Gas leakage from the feed system . Feed system not suitable for operation at pressure . Needs poking for ash level indication in combustion zone	. Steam is not produced . Needs poking	. It does not produce its own steam for bituminous coal gasifier . Needs poking	. Limited to weak-caking coal (FSI < 3)	. Limited to weak-caking coal (FSI < 3)	. Limited to weak-caking coal (FSI < 3)
Maintenance Areas	. Wear bars on agitator blade . Disc valves in coal feeding system	. The pan, barrel and charge all rotate; this may need more maintenance	. Bituminous coal gasifier is brick-lined and is liable to increased maintenance requirement	. Possible gas leakage from coal feeder or poke holes	. Possible gas leakage from coal feed or poke holes	. Possible gas leakage during coal feeding
Potential for Improvements	. Addition of air lock in the feed system will remove gas leakage . Elimination of poking . Automatic control of ash withdrawal rate	. Elimination of poking . Automatic control of ash withdrawal rate	. Adaption of anthracite gasifier for bituminous coals . Automation or elimination of poking . Ash withdrawal rate should be related to the coal feed rate	. Addition of stirrer for handling higher swelling coal . Increased slope at the retort wall to handle high swelling coal . Automated poking	. Addition of stirrer for handling higher swelling coal . Increased slope at the retort wall to handle coals with high FSI . Automated poking	. Addition of stirrer to handle strong caking coals . Increased slope at the retort wall for handling coals with high FSI

Table 5.1-2

Summary of Performance Capabilities For Commercially Available Fixed Bed Gasifiers

	SINGLE-STAGE FIXED-BED GASIFIERS			TWO-STAGE FIXED-BED GASIFIERS		
	Mc-Dowell-Wellman	Riley-Morgan	Wilputte	Woodall-Duckham	Wellman-Incandescent	FW-Stoic
Coal Feed						
Size	. 3/16" to 9/16" for anthracite	. 3/8" to 5/8" for anthracite	. 1-7/8" to 4" or 3" to 4"	. Must be fairly uniform; 3/8 to 1", 1/2 to 1-1/2", or 3/4" to 2"	Must be fairly uniformly sized; 2" to 3", 1-1/2" to 2-1/2", or 3/4" to 1-1/2"	. Must be fairly uniform; . 3/4" to 1-1/2" or 1-1/2" to 3"
	. 1-1/4" to 2" for bituminous coal	. 1-1/4" to 2" for bituminous		. Can accept a limited quantity of fines.	15% max. of fines	. Can accept a limited quantity of fines.
	. 1/4" to 5/8" for coke-charcoal	. 3/4" to 1-1/2" for coke				
Free Swelling Index	. Can use up to 9 with stirrer	. Can handle up to 6	. Can handle up to 6	. <1-1/2 ideally, but could use coals with FSI up to 2-1/2 or 3	1-3	. Approximately up to 3
Ash Fusion Temp.	. Minimum 2200° F	. Bituminous 2400-2600° F	. 2300° F	. >2200° F ideally, but can use as low as 2050° F	>2200° F	. Minimum 2200° F
		. Anthracite 2700° F				
Type	. All type coals	. All type coals	. All type coals	. All except anthracite	Bituminous, brown coal	. Subbituminous, lignite, bituminous

Proximate Analysis, wt. %	Mc-Dowell-Wellman Anthracite	Mc-Dowell-Wellman Coke	Mc-Dowell-Wellman Bituminous	Riley-Morgan Anthracite	Riley-Morgan Coke	Riley-Morgan Bituminous	Wilputte Typical Bituminous	Woodall-Duckham Typical Bituminous Coal	Wellman-Incandescent Typical Bituminous Coal	FW-Stoic Typical Bituminous Coal
Moisture	4.2	5.0	1.4	3.95	9.2	3.43	3.28	3.02	4.65	9.20
Volatile Matter	4.4	-	30.1	4.45	1.0	30.93	35.31	31.96	34.24	36.70
Fixed Carbon	80.7	83.1	58.5	81.70	81.2	53.81	55.87	56.64	52.33	43.80
Ash	10.7	11.9	10.0	9.90	8.6	11.83	5.54	8.38	8.78	10.30
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sulfur, wt. %	0.6	0.6	2.5-3.9	0.7	-	2.5	0.47	3.89	3.87	3.2
HHV, Btu/lb.	12,700	16,000	13,400	12,700	16,000	13,400	13,200	13,000	12,470	12,000

Feed Rate (TPD)

Diameter, ft.	MDW Anthracite O_2	MDW Anthracite Air	MDW Coke O_2	MDW Coke Air	MDW Bituminous O_2	MDW Bituminous Air	RM Anthracite O_2	RM Anthracite Air	RM Coke O_2	RM Coke Air	RM Bituminous O_2	RM Bituminous Air	Wilputte Air	Woodall-Duckham Air	Wellman-Incandescent Air	FW-Stoic Air
3.5		2.5		2.9		-		-		-		-	-	-	-	-
4.5		-		-		-		-		-		-	-	-	13.92	-
6.5		10.7*		12.4*		34.8*		-		-		-	-	-	29.40	31.2
8.5		-		-		-		-		-		-	-	-	51.90	52.8
10.0	31.1	25.8	30.0	30.0*		84		-		-		-	-	-	71.40	72.0
10.5		-		-		-	71	42	85	50	156	90	60*	72-84	82.56*	-
12.0		-		-		-		-		-		-	-	-	103.20	-
12.5		-		-		-		-		-		-	-	-	-	108.0
Throughput, lb/hr-ft^2	33	27	32	32		89	68	40	82	49	150	87	60	53-71	63-76	73-78

*With agitator

*For 10'-4" I.D. gasifier

*For 10'-9" I.D. gasifier

Table 5.1-2 (Continued)

	SINGLE-STAGE FIXED-BED GASIFIERS				TWO-STAGE FIXED-BED GASIFIERS	
	McDowell-Wellman	Riley-Morgan	Wilputte	Woodall-Duckham	Wellman-Incandescent	FW-Stoic
Product Gas, Typical						
Temperature, °F						
. Top	-	-	-	250	240	250
. Bottom	800-1,200	1,080-1,100	1,200	1,200	1,170	1,200
. Hot Raw	-	-	-	600-700	690	750
. Cold Clean	120	120	120	120	-	100
Heating Value, Btu/SCF						
Low-Btu						
. Hot Raw	160-210	185-201	207	207	200	186-207
. Hot Detarred	155-200	165-179	185	-	185	175-195
. Cold Clean Before Desulfurization	146-170	138-163	170	176	170	160-175
Medium-Btu						
. Cyclic Gas	-	-	-	335	-	-
. O_2 Blown	258-270	262-305	290	285	-	-
Flow Rate						
. SCF/lb Coal	50-56	58-63	57.3	50-53	50-51	-

Typical Composition, mole %	McDowell-Wellman Med-Btu	McDowell-Wellman Low-Btu	Riley-Morgan Med-Btu	Riley-Morgan Low-Btu	Wilputte Low-Btu	Woodall-Duckham Med-Btu Cyclic	Woodall-Duckham Med-Btu Steam/O_2	Woodall-Duckham Low-Btu	Wellman-Incandescent Low-Btu	FW-Stoic Low-Btu
H_2	36.52	14.7	39.2	18.7	16.6	52.2	38.4	17.0	16.0	14.0-16.0
CO	47.05	28.1	41.3	24.9	22.7	28.5	37.5	28.3	29.8	29.0-30.0
CO_2	13.90	3.5	17.5	6.2	5.9	8.0	18.0	4.5	3.3	3.0- 4.0
CH_4	0.65	2.7	1.4	0.6	3.6	6.5	3.5	2.7	2.9	2.6- 3.0
N_2	2.05	50.0	0.6	49.3	50.9	4.2	2.2	47.2	47.3	47.6-51.4
H_2O	(dry)	(dry)	(dry)	(dry)	(dry)	-	-	-	-	-
H_2S + COS	(desulfurized)	1.0	(desulfurized)	0.3	0.3	-	-	-	-	-
Others	0.1	-	-	-	-	0.6	0.4	0.3	0.7	-
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	

	McDowell-Wellman	Riley-Morgan	Wilputte	Woodall-Duckham	Wellman-Incandescent	FW-Stoic
By-product, lb/lb Coal						
Tar	0.06	0.078	0.1	0.0750	0.0173	-
Oil		0.009	0.02		0.0281	-
NH_3	0.0014	-	-	-	-	-
Typical Operating Conditions						
Oxidant Rate						
. lb air/lb coal	3.5	2.98 - 3.44	3.31 - 3.67	2.3 (Air rate controlled by monitoring the product gas pressure in the downstream main)	2.5 (Air rate controlled by monitoring the product gas pressure in the downstream main)	Air rate controlled by monitoring the product gas pressure in the downstream main.
. lb O_2/lb coal	0.8	0.6 - 0.7	-	-	-	-
Steam Rate, lb/lb coal						
. Air Blown	0.4	0.56	0.53	0.25	0.32	Steam/air ratio is varied to control the quality of the ash.
. Oxygen Blown	-	1.4	-	-	-	-
Temperature Profile, °F						
. Devolatilization Zone	800-1000 for anthracite 1100-1200 for bituminous	1100-1500	1200-1500	-	-	-
. Gasification Zone	-	1500-2000	1500-1850	2000-2500	-	-
. Combustion Zone	2400	2100	2200-2300	-	-	-
Pressures, "w.g. at gas outlet	5-6	40	2-4	30-40 (for dry grates) 40-60 (at inlet)	10-14 (2"-4" w.g. pressure drop through coal bed)	-
Thermal Efficiency, %						
. Hot Raw Gas	93 for bituminous	88-90 for bituminous	90 for bituminous	88-92 for bituminous	90-93 for bituminous	85-93 for bituminous
. Hot Detarred Gas	-	-	-	-	85 for bituminous	77-87 for bituminous
. Cold Gas	85 for anthracite 71-75 for bituminous	78 for anthracite 70-71 for bituminous	80 for bituminous	74-76 for bituminous	75 for bituminous	69-76 for bituminous
Turndown Capability						
. % of maximum capacity	8	14	10	25	25	20

The gas compositions and heating values of cold, clean low-Btu gas produced from a given type of coal vary only slightly among all fixed bed gasifiers considered. When bituminous coals are gasified, the hydrogen, carbon monoxide, carbon dioxide, and methane concentrations were 13.3 - 18.7%, 22.7 - 28.3%, 3.5 - 6.2%, and 0.6 - 3.6%, respectively, and the heating values ranged from 138 to 176 Btu/scf for all gasifiers evaluated.

For the medium-Btu gas, the variations in gas composition and heating values were small for all fixed bed gasifiers evaluated if the steam/oxygen mode of operation were used. However, when the two-stage gasifier is operated in a cyclic mode of operation with air and superheated steam, the gas compositions varied appreciably and the heating value increased from 285 to 335 Btu/scf.

In the two-stage gasifiers, the air feed rate is controlled by the product gas pressure in the downstream main and ranges from 2 to 3 lb/lb coal. The single-stage gasifiers use approximately 3.0 to 3.5 lb air per lb coal for air-blown and 0.6 to 0.8 lb oxygen per lb coal for oxygen- blown cases. The steam rate is controlled to maintain a blast saturation temperature in the range of 131 - 140°F in the two-stage gasifiers and the requirement is about 0.25 to 0.3 lb steam/lb coal. The steam rate varies from 0.4 to 0.5 lb/lb coal for the single-stage gasifiers.

Thermal efficiencies of hot raw gas produced from all fixed-bed gasifiers range from 88-94%. Since both sensible heat and tar are included in the product gas thermal values of the hot raw gas, the hot raw gas efficiency does not vary appreciably among the gasifiers and types of coals fed to the gasifiers. The cold gas efficiency, on the other hand, depends on the type of coal used because the amount of tar produced varies with the volatile matter content of the coal feed. When anthracite coal, which contains little volatile matter, is gasified, very little tar is formed, and the difference between the hot and cold gas efficiencies is usually accounted for by the difference in the sensible heat of the product gas. The high volatile bituminous coal, on the other hand, yields an appreciable amount of tar which is removed from the product gas upon cooling and reduces the thermal efficiency based on the cold gas product. Table 5.1-2 indicates that, when tar is not included in the cold gas efficiency calculation, anthracite coal provides cold gas efficiency of 78 to 85%, whereas high volatile bituminous coal yields a cold gas efficiency of only 70 to 75%.

The two-stage gasifier also operates on a "hot detarred" mode wherein the tar is removed but the sensible heat of the product gas is partially retained. The thermal efficiency of the "hot detarred" product gas is approximately 85% when high volatile bituminous coal is used.

Turndown capability is 14-20% of maximum throughput for the single-stage gasifiers and 25% of maximum throughput for the two-stage gasifiers. Product gas heating value is reduced slightly as the gasification plant is turned down.

5.1.3 Operation and Maintenance

The two-stage gasifiers are normally operated by controlling the blast saturation temperature at approximately 135°F to maximize the heating value of the product gas. Ash and fire-bed depths are determines by manual poking in both the single- and two-stage gasifiers.

Manpower requirements for operating gasifiers in the U.S. average about one operator per two gasifiers per shift.

The major maintenance items identified for both single- and two-stage gasifiers include cleaning the gas cooler, checking and adjusting the coal feeder to avoid gas leakage, and cleaning tar precipitated in the gas main. The single-stage gasifiers with stirrer experience erosion of agitator wear bars. In addition, the high temperature and dusty atmosphere of the gasifier may damage the agitator bearings. Checking and adjusting the agitator bearings and wear bars are therefore required to avoid mechanical problems.

5.1.4 Commercial Experience

There are several single-stage McDowell-Wellman (M-W) gasifiers in operation, ranging in sizes from 2 to 10 ft diameter both with and without a stirrer. National Lime and Stone Co., with two 10-ft diameter gasifiers with stirrers, using bituminous coal with FSI as high as 9, and Glen-Gery Corporation, with nine 10-ft diameter gasifiers using anthracite coal, are the two largest plants utilizing the M-W gasifiers in the U.S. Two smaller M-W gasifiers (5 and 6.5 ft) are being operated at Ashtabula, Ohio, using coke as feed. The Holston Defense Corporation installed twelve 9 ft-2 in Wilputte gasifiers at Kingsport, Tennessee, in 1945, and 4 are still operating. Two primary metal processing plants in South Africa use 10-ft diameter M-W gasifiers.

Most of two-stage gasifiers are installed in foreign countries in both industrial and utility applications. The most publicized plants are located in South Africa - more than thirty units are being operated to produce hot raw gas, cold clean gas, and hot detarred gas. Three 10-ft two-stage gasifiers are planned to start up in the U.S. in 1978.

5.2 ECONOMIC ANALYSIS

The direct capital costs for producing hot raw gas; dust-, tar-, and oil-free gas; and cold, dust-tar-oil-free and desulfurized gas are tabulated in Table 5.2-1. The capital costs include gasification system facilities (such as air blowers, feed bins, etc.), site, and

Table 5.2-1

Average Capital Cost for Fixed-Bed Gasifier of 2.5×10^9 Btu/day Capacity

(Based on Mid-1977 Pricing)

		Average
Gasification	MM$	
Coal & Ash Handling Gasifiers Cyclones Site Building & Installation Gas Manifold		2.061
Subtotal	MM$	2.061
Facilities	MM$	
Electrical Power Distribution Cooling Water Piping Instrument Air & Dryer Steam System for Startup/Shutdown Air Cooler		0.149
Subtotal	MM$	0.149
Total Direct Capital Cost for Hot Raw Gas		2.210
Gas Cleanup		
Tar, Oil Removal & Water Treatment		0.935
Total Direct Capital Cost for Dust, Tar & Oil-Free Gas	MM$	3.145
Desulfurization[a]	MM$	1.440
Total Direct Capital Cost for Dust, Tar & Oil-Free and Desulfurization Gas	MM$	4.585

[a] Desulfurization costs are based on Stretford process.

building. The estimate was based on a low-Btu gas plant of 2.5 x 10^9 Btu/day capacity from bituminous coal and was priced on mid-1977 dollars. The average capital costs for the three cases of the gas cleanliness were $2.20 MM, $3.15 MM and $4.58 MM, respectively, for hot raw gas, tar-free gas, and tar-free and desulfurized gas.

The low-Btu gas costs were calculated for each of the three degrees of gas quality by utilizing 8%, 10% and 12% discounted cash flow (DCF) analysis. Since fixed bed gasification is a proven technology which involves minimum risk factors, lower DCF rates of 8% and 10% were included in the analysis (usually 12% for developing technologies). A plant life of 25 years and a plant capacity factor of 90% were assumed. By-product credits were 10¢/gal for tar and $25/ton for sulfur. Representative low sulfur (Stockton, WV) and high sulfur (Belmont, OH) bituminous coals were used to estimate thermal efficiencies and coal throughputs. Coal cost was varied from $20 to $50 per ton delivered. The variation of fuel cost (calculated at the three DCF rates) vs. delivered coal costs is depicted in Figure 5.2-3 for the three product gas streams considered.

The differential coal costs between low sulfur coal for production of hot raw gas or tar-free gas and high sulfur coal for production of cold clean gas are shown in Figure 2.2-4. Figure 2.2-5 presents a similar chart for differential fuel costs for producing the three product streams from a given coal cost.

A typical project schedule is approximately 24 months for any of the fixed bed gasifiers considered.

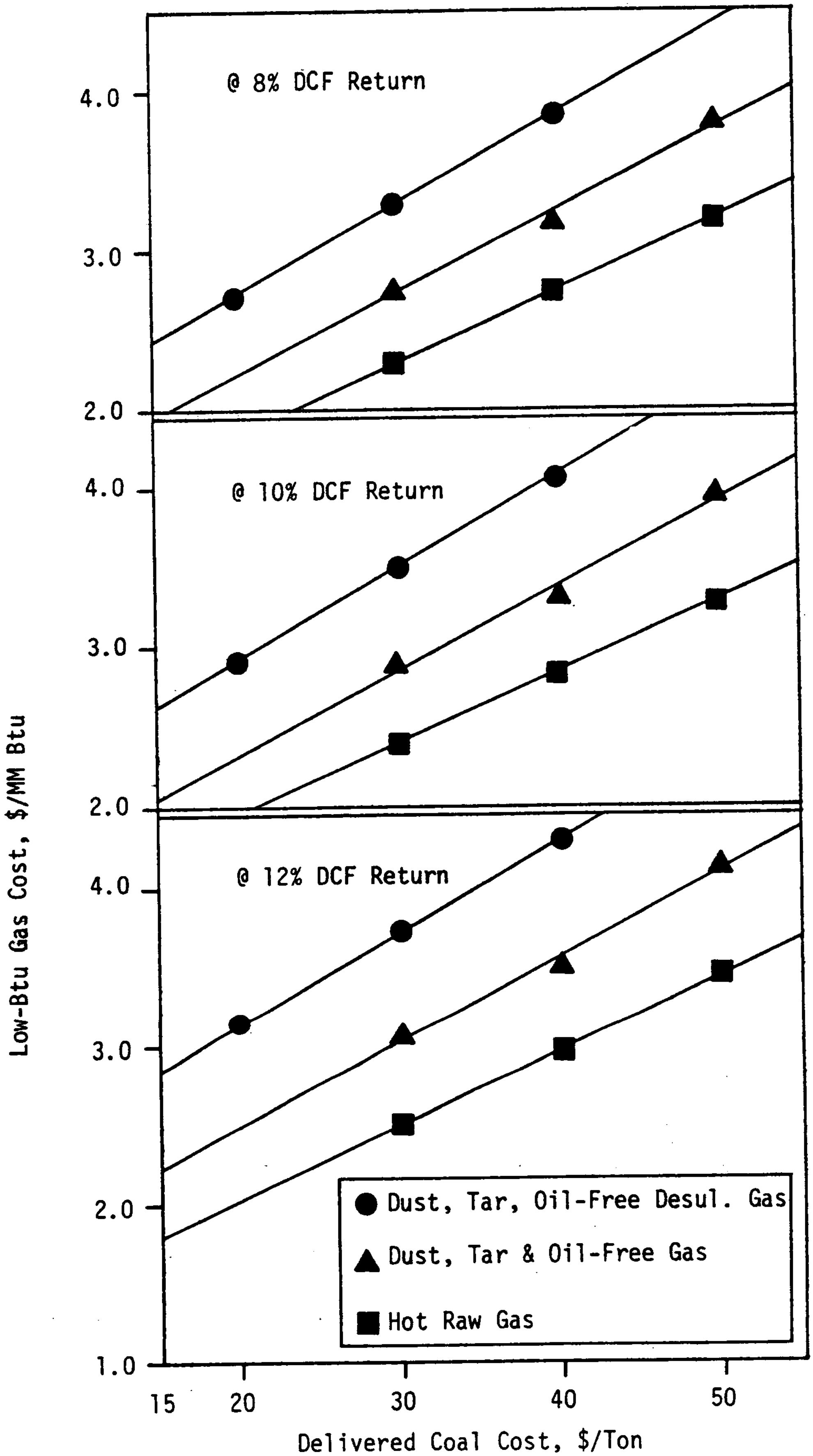

Figure 5.2-3 Low-Btu Gas Cost vs. Delivered Coal Cost

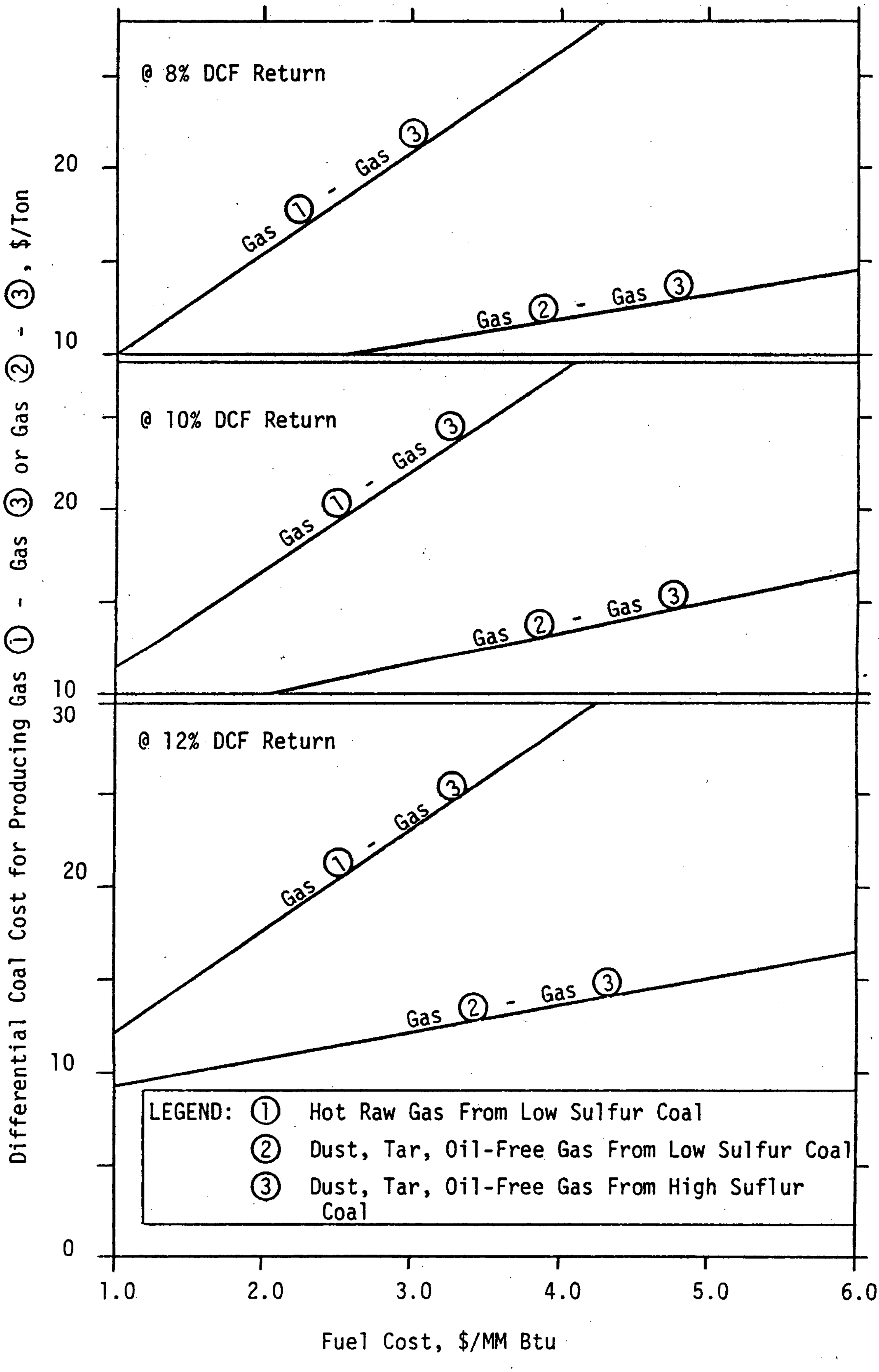

Figure 5.2-4 Sensitivity of Differential Coal Cost Between Low Sulfur and High Sulfur Coal vs Fuel Cost

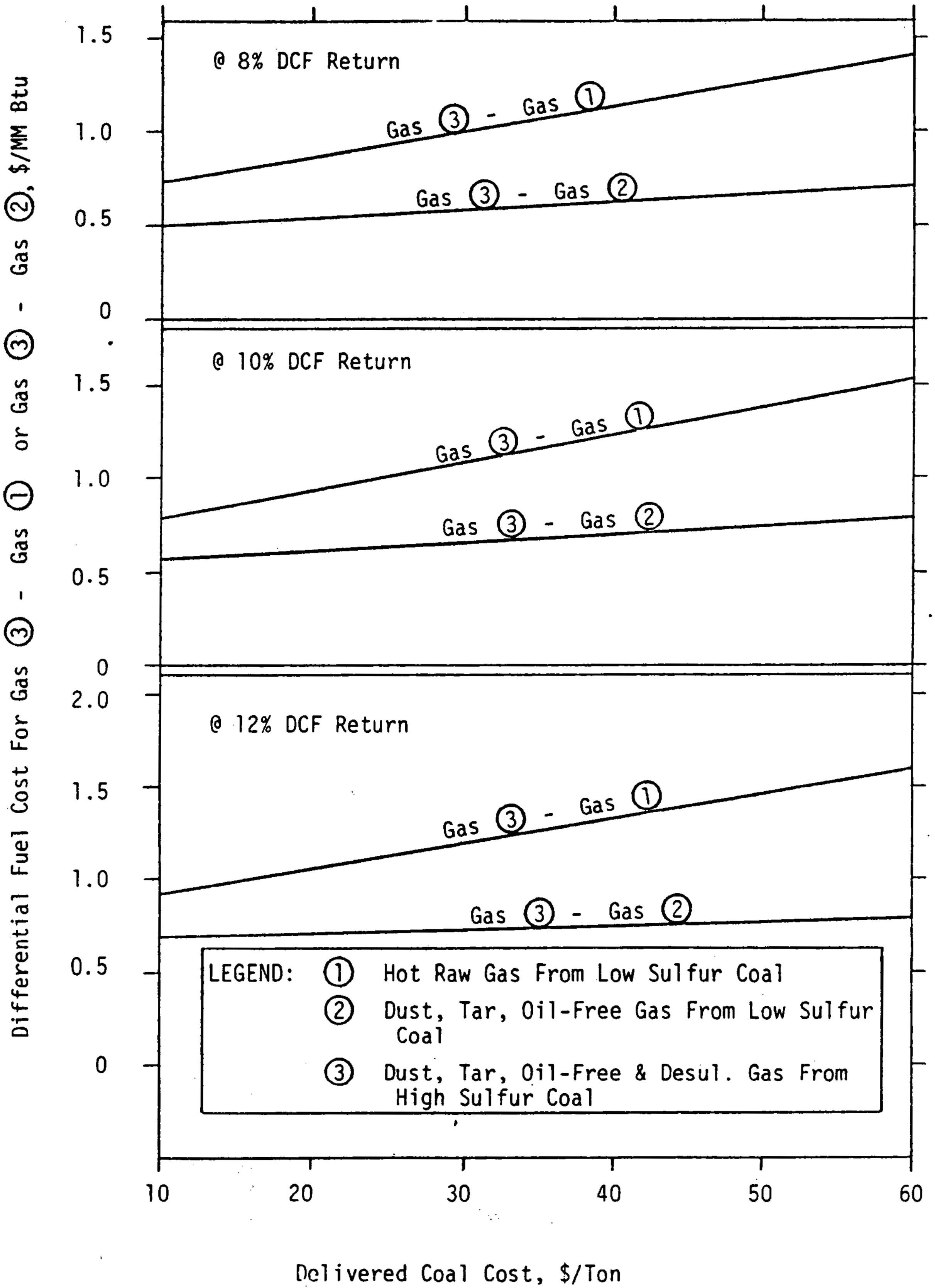

Figure 5.2-5 Sensitivity of Differential Fuel Cost vs Delivered Coal Cost.

APPENDIX A

Coal Availability and Characteristics

The vast coal resources of the United States are located in many areas of the country as shown in Figure A-1. The U.S. Geological Survey estimates the total identified coal resources as being 1,600 billion tons. Another 1,600 billion tons of unidentified resources are postulated. By comparison, in 1974 we consumed and exported a total of 0.6 billion tons. The reserves are summarized in Tables A-1 and A-2.(1)

Of the total resource, however, only some 434 billion tons are in deposits of the type considered amenable to mining, given today's economics and mining technology. About two-thirds of this demonstrated coal reserve base is in deposits of the type that would normally be mined by underground methods; the remainder is in deposits so close to the surface that lower cost surface recovery methods can be employed.

Large as our coal resources and reserves are, there is some geographic dislocation. Most of our coal is found west of the Mississippi River, far from concentrated industrial areas of the East and Far West. Moreover, much of the western coal is in arid or semi-arid areas. The scarcity of water could constrain coal production and consequent coal use in these areas.

A portion of the demonstrated reserve base that is available for use depends on whether the coal deposit can legally be mined; and, if it can, whether it is suited for underground or surface mining. For example, only 50 to 60 percent of the coal may be recovered in an underground mine with traditional room and pillar mining methods, whereas up to 90 percent of the coal may be recovered in a given surface mine. Long-wall mining, while holding promise for greater coal recovery in underground mining, is not widely practiced in this country. With respect to the total reserve base, average recovery would be about 50 percent with present mining methods because of the necessity for leaving support pillars in underground mines and the inaccessibility of much coal for one reason or another. Development of higher recovery mining methods is indicated as part of a national program for conservation and efficient energy utilization.

Two-thirds of the country's coal resources contain 1% or less sulfur by weight, and almost half contain 0.7% or less sulfur. Most of these coals, however, again are located in the West. Low-sulfur eastern coals are not as abundant, and much of what is readily minable is reserved for the metallurgical and export markets. The high sulfur coal of the East appears more and more applicable for energy conversion to liquids or low Btu gas for use in industry or electrical power generation as economics dictate.

The "effective" reserves of lower rank coal (subbituminous and lignite) are further reduced because of their lower heating values. For example, reserves of lignite on a weight basis represent 6.5 percent of the total demonstrated reserve

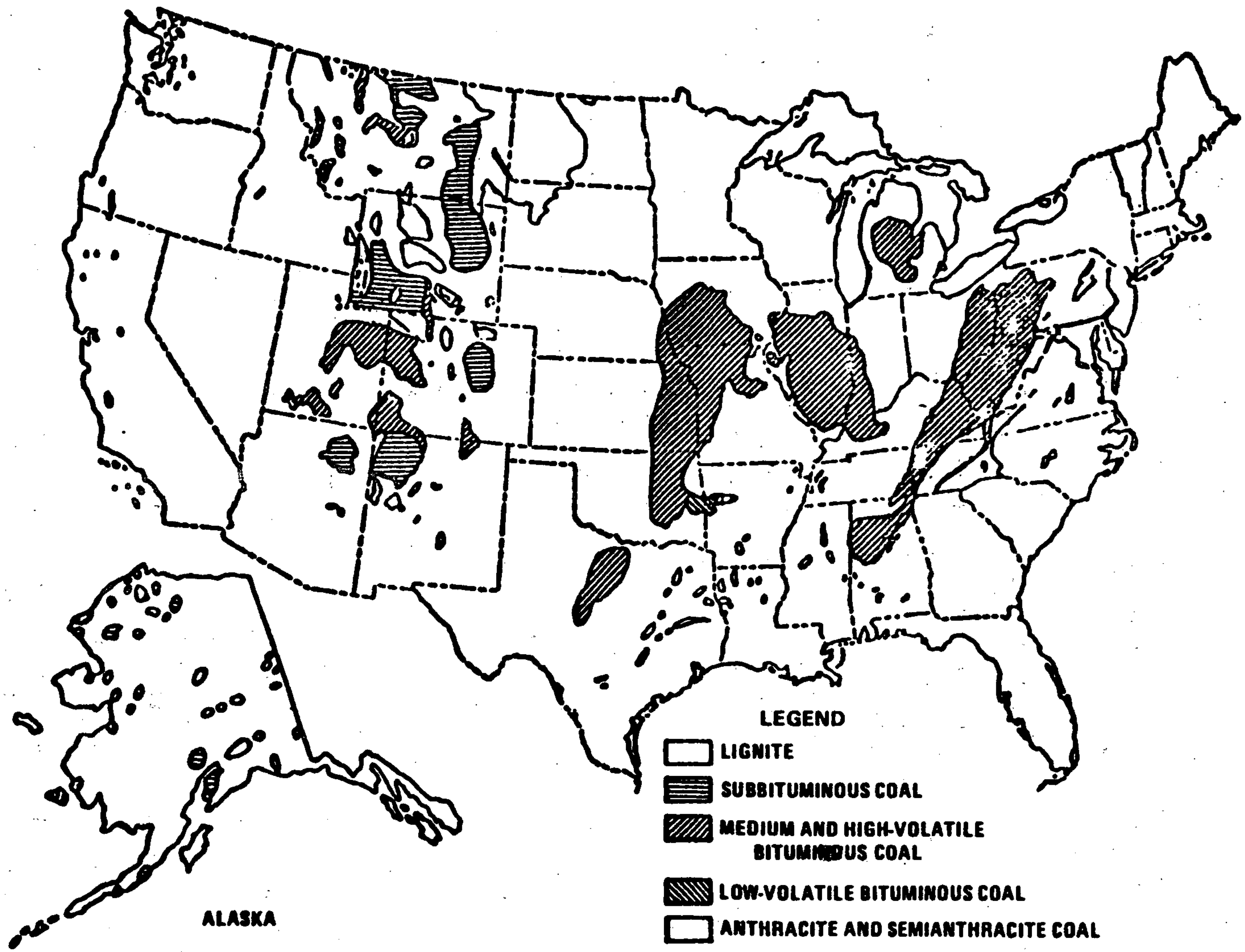

Figure A-1. Coal Fields of the United States

Table A-1

Summary of Demonstrated Coal Reserve Base of the United States (Billion Tons)

Rank of Coal	Underground Mining Reserve	Surface Mining Reserve	Total	Estimated Total Heat Value (Quadrillion Btu)
Bituminous	192	41	233	6,100
Subbituminous	98	67	165	2,800
Lignite	0	28	28	400
Anthracite	7	-	7	200
Total	297	137	434	9,500

(Note: This table does not include deposits not amenable to mining given today's economics and mining technology.)

Table A-2

Coal Reserves of the United States, By State
(Million of Tons)

	Resources determined by mapping and explosion					Est. addtl. resources in unmapped and unexplored areas	Est. total remaining resources in the ground 0 - 3,000 ft. overburden	Est. resources in deeper structural basins 3,000-6,000 ft. overburden	Est. total remaining resources in the ground 0 - 4,000 ft. overburden
	Bituminous coal	Sub-bituminous coal	Lignite	Anthracite and semi-anthracite	Total				
Alabama.........	13,518	0	20	0	13,538	20,000	33,538	6,000	39,538
Alaska..........	19,415	110,675	....	....	130,089	130,000	260,089	5,000	265,089
Arkansas........	1,640	0	350	430	2,420	4,000	6,420	0	6,420
Colorado........	62,389	18,248	0	78	80,715	146,000	226,715	145,000	371,715
Georgia.........	18	0	0	0	18	60	78	0	76
Illinois........	139,756	0	0	0	139,850	100,000	239,756	0	239,756
Indiana.........	34,779	0	0	0	34,779	22,000	56,779	0	56,779
Iowa............	6,519	0	0	0	6,519	14,000	20,519	0	20,519
Kansas..........	18,686	0	....	0	18,686	4,000	22,686	0	22,686
Kentucky........	65,952	0	0	0	65,952	52,000	117,952	0	117,952
Maryland........	1,172	0	0	0	1,172	400	1,572	0	1,572
Michigan........	205	0	0	0	205	500	705	0	705
Missouri........	23,359	0	0	0	23,359	0	23,359	0	23,359
Montana.........	2,299	131,877	87,525	0	221,701	157,000	378,701	0	378,701
New Mexico......	10,760	50,715	0	4	61,479	27,000	88,479	21,000	109,479
North Carolina..	110	0	0	0	110	20	130	5	158
North Dakota....	0	0	350,680	0	350,680	180,000	530,680	0	530,686
Ohio............	41,864	0	0	0	41,864	2,000	43,864	0	43,864
Oklahoma........	3,299	0	....	0	3,299	20,000	23,299	10,000	33,299
Oregon..........	48	284	0	0	332	100	432	0	432
Pennsylvania....	57,533	0	0	12,117	69,650	10,000	79,650	0	79,650
South Dakota....	0	0	2,031	0	2,031	1,000	3,031	0	3,031
Tennessee.......	2,652	0	0	0	2,652	2,000	4,652	0	4,652
Texas...........	6,048	0	6,876	0	12,928	14,000	26,926	0	26,926
Utah............	32,100	150	0	0	32,250	48,000	80,250	35,000	115,250
Virginia........	9,710	0	0	335	10,045	3,000	13,045	100	13,145
Washington......	1,867	4,194	117	5	6,183	30,000	36,183	15,000	51,183
West Virginia...	102,034	0	0	0	102,034	0	102,034	0	102,034
Wyoming.........	12,699	108,011	....	0	120,710	325,000	445,710	100,000	545,710
Other States....	618	0	46	0	4,721	1,000	5,721	0	5,721
Total	671,049	428,210	447,647	12,969	1,559,875	1,313,000	2,872,955	337,105	3,210,060

base, but on a Btu basis they represent only 4.2 percent of the total. Equivalent numbers for subbituminous are 38 and 29.5 percent.

Heating values also affect the amount of coals that can meet sulfur limits called for under the Clean Air Act. For example, a 12,000 Btu/lb coal cannot contain more than 0.7% sulfur by weight as consumed, and an 8,500 Btu/lb coal cannot contain more than about 0.5% sulfur. This factor further reduces the apparent low-sulfur reserves, particularly in the West, that can meet present sulfur standards. However, western coal that is high in sulfur appears to have potential for conversion by high Btu gasification to pipeline gas where extensive cleaning of all gas adulterants is required.

It should be noted that nearly all of the coal lands and reserves in the East are privately owned, whereas coal lands and reserves in the West are owned principally by the Federal government.

In general, there is no foreseeable set of circumstances that would cause the availability of our reserves to be a constraint on significantly accelerated production by 1985. There are, however, potential actions on the Federal and state levels that can cause serious disruption in the development and extraction of certain specific reserves. These potential disruptions can be avoided through careful consideration of regional and national needs by those agencies in a position to influence production.

The properties of coal and subsequently their behavior during gasification, vary from rank to rank and within a rank. Therefore, in the selection of a coal for gasification, it is desirable to understand what relationships exist between the characteristics of coal and its performance. Table A-3 presents typical values for several properties of coal as they exist in the different ranks.

The Hardgrove grindability index (HGI) is a relative measure of the ease of pulverizing coal. The crushing of the raw coal is important since particle size and distribution in the feed will affect the rate of gasification. An excess of fine particles is to be prevented since these particles can be carried out of the reactor with the exiting gas stream.

One two-stage gasifier manufacturer specifies a coal feed of 2-3 inch particles but will allow smaller particles of not more than 10% of the feed in the 5/16 to 2 inch range and not more than 15% of the feed in the less than 5/16 inch size.[2] Similarly, a single-stage gasifier manufacturer limits fines concentrations to 30% of the feed.[3] A homogeneous feed size is desirable to promote uniform gas distribution and maximum solid-gas contacting time. Uniform temperature profiles and stable reaction zones are more easily maintained with proper gas distribution.

The moisture content of coal varies widely among ranks. Generally, lower rank coals contain more inherent moisture than do high rank bituminous or anthracites. The presence of moisture has no effect on the final char product to be gasified in the lower regions of the gasifier. All the moisture is vaporized during drying and devolatilization of the feed near the top of the unit. Therefore,

TABLE A-3

Coal Characteristics Data

Region	State	County	Bed Name	Bed No.	As Received Analysis: % Moisture	Ash	Sulfur	Btu/Lb (AR)	Btu/Lb (MAF)	Lb SO_2 MM Btu	Proximate Analysis: % Moisture	Volatile Matter	Fixed Carbon	Ash	Ultimate Analysis: % Hydrogen	Carbon	Nitrogen	Oxygen	Sulfur	Chlorine	Ash	Ash Softening Temp. °F	HGI	FSI	Est. Reserves (MM Tons)
Low Sulfur Coal																									
N.A.	PA	Cambria	U.Kittan.	076	2.1	8.3	1.0	13,930	15,550	1.44	2.2	17.3	72.0	8.5	4.5	80.2	1.4	4.2	1.2	-	8.5	2,800	110.0	8.5	73.26
C.A.	W.Vir.	Kanawha	Stockton	103	2.6	7.9	0.7	13,480	15,083	1.04	3.0	34.9	54.3	7.8	5.2	75.4	1.4	9.6	0.6	-	7.8	2,910	56.7	5.5	223.74
S.A.	Ala.	Jefferson	Mary Lee	279	2.0	12.2	0.9	13,120	15,300	1.37	1.9	26.1	62.0	10.0	4.5	77.1	1.7	5.9	0.8	-	10.0	2,680	60.1	7.5	85.82
E.INT.	Ill.	Franklin	No. 6	484	8.2	9.2	1.0	11,890	14,410	1.68	8.3	33.7	48.5	9.5	5.3	67.0	1.5	15.6	1.1	-	9.5	2,320	57.4	4.5	384.51
W.INT.	Okl.	Haskell	U.Hartshorne	880	4.4	11.3	0.7	12,960	15,380	1.08	3.5	21.7	68.3	6.5	5.0	79.6	1.7	5.7	1.5	-	6.5	2,204	110.0	9.0	54.83
GULF	Tx.	Van Zandt	Uncorrelated	799	27.2	4.8	0.5	7,680	11,081	1.30	27.5	35.7	26.8	10.0	6.0	49.1	0.7	33.7	0.5	-	10.0	2,290	68.4	-	174.05
E.NGP (Lignite)	N.Dak.	Mercer	Uncorrelated	799	33.8	6.8	0.5	7,200	12,140	1.39	34.1	29.5	30.0	6.4	6.7	42.2	0.9	43.3	0.4	-	6.4	2,223	62.9	-	182.71
W.NGP (Sub-bituminous)	Wy.	Campbell	Roland (Wyodak-Anderson)	-	31.1	6.4	0.6	8,040	12,467	1.49	29.5	30.1	33.9	6.5	7.3	45.7	1.1	39.0	0.4	-	6.5	2,690	50.0	-	1,753.05
S.W. (Sub-bituminous)	N.Mex.	San Juan	Uncorrelated	799	10.2	8.9	0.7	11,350	14,040	1.23	11.1	35.7	45.4	7.8	5.8	63.1	1.3	21.2	0.8	-	7.8	2,080	47.0	0.5	678.78
High Sulfur Coal																									
N.A.	PA	Clearfield	M.Kittan.	-	3.5	10.3	2.0	13,290	15,353	3.01	3.3	30.1	57.5	9.1	5.2	75.3	1.3	6.9	2.2	-	9.1	2,080	103.8	8.0	16.08
N.A.	Ohio	Belmont	No. 8	036	3.6	10.1	3.7	12,600	14,670	5.87	4.0	38.3	47.0	10.7	5.2	69.4	1.5	9.8	3.3	0.1	10.7	2,080	56.0	4.5	2,532.53
C.A.	W.Vir.	Kanawha	Pitt.	-	2.8	6.2	1.8	13,580	14,894	2.65	4.2	39.9	49.2	6.7	5.5	73.2	1.4	11.2	2.0	-	6.7	2,300	-	5.0	17.16
W.NGP	Mont.	Carbon	Rosebud No. 3	811	9.0	9.2	2.0	11,030	13,349	3.63	9.8	35.2	46.7	8.3	5.2	60.8	0.9	22.8	2.0	-	8.3	2,060	50.4	-	-
S.A.	Ala.	Jefferson	Jeff.	298	2.2	7.2	2.7	13,810	15,250	3.91	2.2	33.9	57.5	6.4	4.7	79.8	1.3	5.1	2.7	-	6.4	2,300	65.0	5.5	3.84
GULF (Lignite)	Tx.	Milam	Uncorrelated	799	26.6	9.9	1.0	8,070	12,710	2.48	24.5	32.0	35.7	7.8	6.1	50.3	0.7	34.5	0.5	0.1	7.8	2,204	68.4	0.5	277.20
S.W.	Ariz.	Navajo	Uncorrelated	799	11.0	13.4	0.8	10,260	13,311	1.56	10.7	38.5	44.9	5.9	6.0	64.8	1.2	21.3	0.8	0.04	5.9	2,420	45.6	0.5	44.98
E.INT.	Ill.	Perry	No. 6	484	9.7	11.1	3.0	11,220	14,180	5.35	9.7	36.6	42.2	11.5	5.3	63.4	1.4	13.9	4.3	.2	11.5	2,430	60.1	-	974.96
E.INT.	Ky.	Hopkins	No. 9	-	5.6	10.3	3.9	12,170	14,372	6.41	6.1	37.2	48.3	8.4	5.4	68.0	2.1	12.2	3.9	0.01	8.4	2,140	62.9	5.0	1,312.03
W.INT.	Mo.	Henry	Tebo	509	6.8	11.5	3.6	11,960	14,670	6.02	9.2	36.7	43.8	10.3	5.5	65.3	1.0	14.7	3.2	-	10.3	2,020	68.1	-	282.12
W.INT.	Ia.	Monroe	Ford	-	13.8	14.0	2.8	10,240	13,813	5.47	11.1	36.7	36.4	15.8	5.8	56.7	1.3	16.4	4.0	0.04	15.8	2,070	56.7	-	76.45

the only effect moisture has is to increase the amount of heat required for vaporization. The increased moisture also lowers the overall heating value of the product gas. If the moisture content is high and the heat required for vaporization is abundant, an increase in residence time of the coal during drying is necessary. This will result in lower gasifier capacity and lower overall gasification efficiency.

The volatile matter content of coal is defined as the matter which can be released from coal by heating the coal to $1740^{\circ}F$ for 7 minutes. During heating (devolatilization), light weight gases, oils and tars evolve from the coal. The rate of heating has a direct effect on the devolatilization process and final char produced. During heating, many bituminous coals swell and become sticky. To classify coals that behave in this manner, the free swelling index number was developed. The FSI is a relative measure of a coals agglomerating tendency during devolatilization. Some manufacturers report that volatile bituminous coals with FSI's as high as 9 have been successfully gasified in fixed beds.(5) To gasify these coals, adequate agitation of the bed must be supplied to break up any fused material present. As noted earlier, the rate of heating will affect devolatilization and the agglomerating tendency of the coal. Slow heating allows the coal to devolatilize with less caking. Coal particle size can also influence caking. Small particles of caking coal easily agglomerate, whereas larger particles show little swelling and sticking but rather form blisters of fused material on their surfaces which prevent other particles from fusing to them.

The fixed carbon in coal supplies the fuel for gasification and combustion. Part of this carbon is gasified with steam to form oxides of carbon. The remaining carbon is burned with oxygen to supply all the heat necessary for the other endothermic reactions. High ranking coals contain more fixed carbon than lower ranks. Therefore, more oxygen and steam are required to gasify these coals and yield higher percentages of carbon monoxide and hydrogen in the fuel gas produced. With the increased fuel supply to these lower zones, temperatures run hotter and thus increase the rate of gasification throughout.

Sulfur appears in three forms in coal: As pyrites (FeS_2); as organics; or sulfates. The amount present will vary from 0.5% to as high as 8.0%, depending on coal type. Deep mine coals generally contain higher amounts of sulfur. During gasification, the organic sulfur and a portion of the pyritic sulfur in the coal is reduced to hydrogen sulfide and carbonyl sulfide by reaction with hydrogen and carbon monoxide. The resultant lowering the product gas heating value reduces slightly the gasifiers overall efficiency as the sulfur content increases.

Oxygen has been found to occur in lower ranked coals in the form of phenolic hydroxides.(6) As the carbon content or coal rank increases, the oxygen content decreases, but also the oxygen as hydroxyl decreases. As the oxygen content in coal decreases, the coal reactivity decreases. Highly reactive coals can be gasified at relatively lower temperatures than coals of low oxygen content. The low gasifier temperature requires less carbon combustion and increases thermal efficiency. At one time it was thought that all the oxygen evolved during devolatilization as water. Researchers have found that all the oxygen cannot be accounted for as water.[7] It has thus been suggested that the oxygen is also released in the form of carbon oxides and phenols present in the tars. During carbonization of the coal, the hydroxyl oxygen appears in the phenols. In theory then, the phenol production could be greatly increased by forcing phenol production. In practice, these yields are never attained, but work continues toward this end.

Ash is the inorganic material in coal which remains after total combustion. Generally, low ranking coals contain higher percentages of ash than do high ranking coals. The composition of the ash in a coal will determine the temperature at which melting occurs. At these high temperatures, the ash will melt and depending on conditions in the gasifier at the time, clinkers may form. For this reason, the ash-softening temperature was developed to determine a coal's potential for clinkering. In non-slagging gasification operations, the ash-softening temperature will set maximum temperature limits in the combustion zone. Since the ash is considered inert during gasification, its presence limits the capacity and efficiency of the gasifier by requiring more energy to be expended in the coal preparation section for drying and crushing. Additionally, the energy losses in the gasifier system also increase with increasing ash content because of the increased power required to feed the coal and because of the loss of some sensible heat with ash leaving the gasifier.

Western coals, in general, contain more and lower softening temperature ash then eastern coals. With these coals, lower temperatures must be used for gasification. Fortunately, the western coals are generally higher in oxygen content and thus are very reactive and can be adequately gasified at lower temperatures than can the eastern coals.

The reactivity of a coal to gasification varies with volatile content, rate of devolatilization, oxygen content and ash composition. High volatile coals exhibit high reactivity due to the rapid evolution of volatiles. It has also been observed that the char remaining after devolatilization is more reactive for high volatile coals than for low volatile coals.[8] High volatile content western coals fit into this classification. Rapid devolatilization also produces more reactive chars when gasified. The factors influencing reactivity are not well known, but particle structure is under study.[9] Porous coal particles have increased surface area available for gas contact and would be expected to result in more rapid gasification. A high reactivity coal is preferred in fixed bed gasifiers to minimize residence time and thus increase reactor capacity.

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APPENDIX B

Correlation of HHV and Gasification Rate Vs. Fixed Carbon Content of Coal Feed

In preparing this report, attempts were made to correlate HHV of product gas and gasification rate against fixed carbon content of coal feed. Both air-blown and oxygen-blown gasification systems were considered. Data obtained from vendors were supplemented with data available in the literature and experimental data supplied by the Morgantown Energy Research Center (MERC) based on low pressure operation of their 42 inch I.D. fixed bed gasifier.

Figure B-1 shows a graphical representation of a correlation developed for HHV of low-Btu gas vs. fixed carbon content of coal feed. The HHV decreases as fixed carbon content increases from bituminous to anthracite. Because other gasification variables (e.g., air-to-coal ratio, steam-to-coal ratio, pressure, etc.) also affect the HHV of the product gas, a band of lower and upper values of the HHV is indicated instead of a single regression line.

Figure B-2 shows the variation of gasification rate vs. fixed carbon content of coal in air-blown gasification systems. Vendor data on the gasification rates were obtained approximately at 2-10 inch w.g. pressure. Gasification rates decrease with an increase in fixed carbon content of the coal feed.

As fixed carbon content increases, the oxygen content and reactivity of the coal decreases and consequently the residence time in the gasifier increases resulting in a decrease in the gasification rate and product gas heating value.

Much less data were available from vendor and literature on the oxygen-blown, fixed bed gasifier than on the air-blown, fixed bed gasifier. Figures B-3 and B-4 present the HHV and gasification rates, respectively, for the oxygen-blown gasification process.

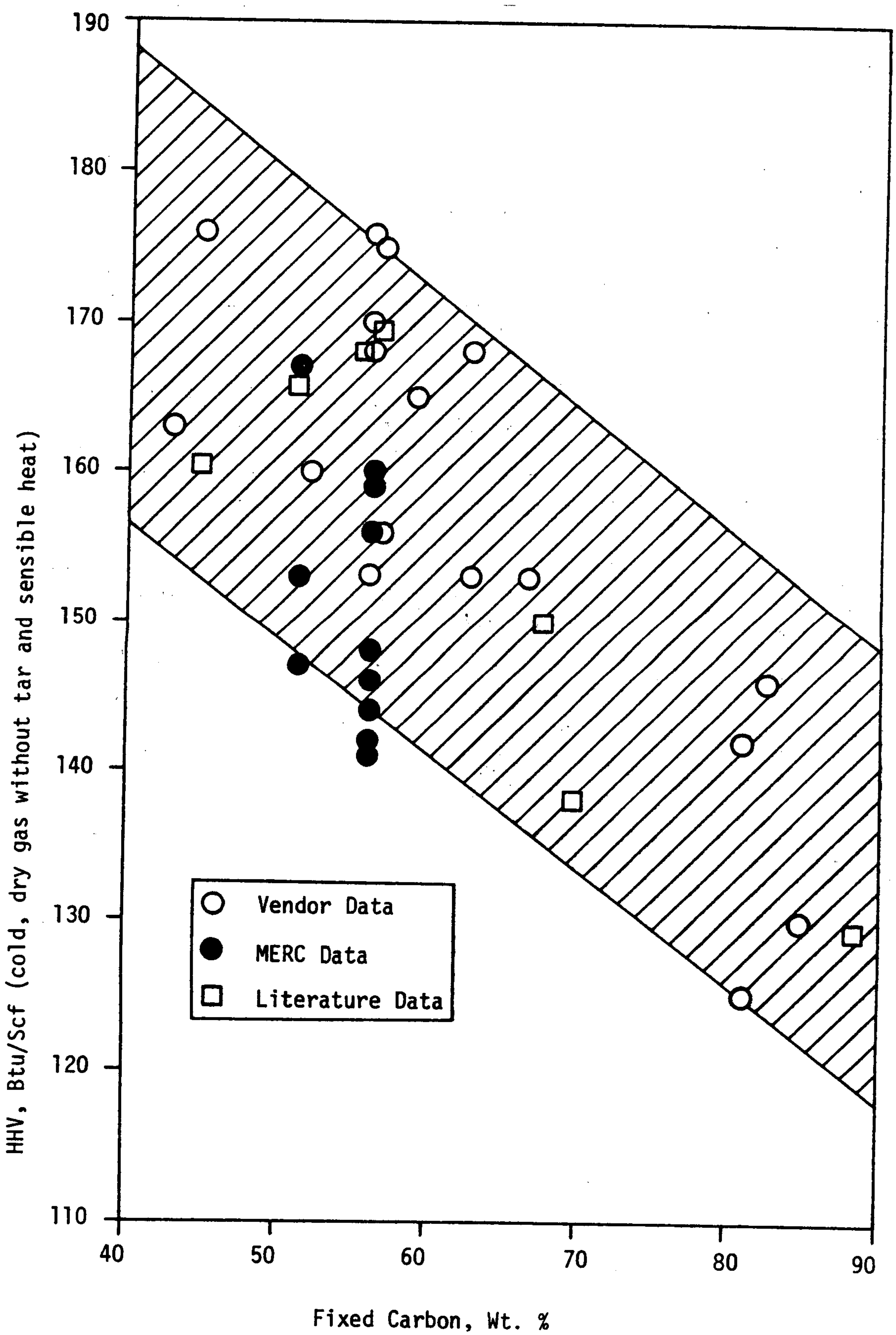

Figure B-1 HHV of Product Gas vs Fixed Carbon Content of Coal Feed for Air-Blown, Fixed Bed Gasifier Operating at Atmospheric Pressure

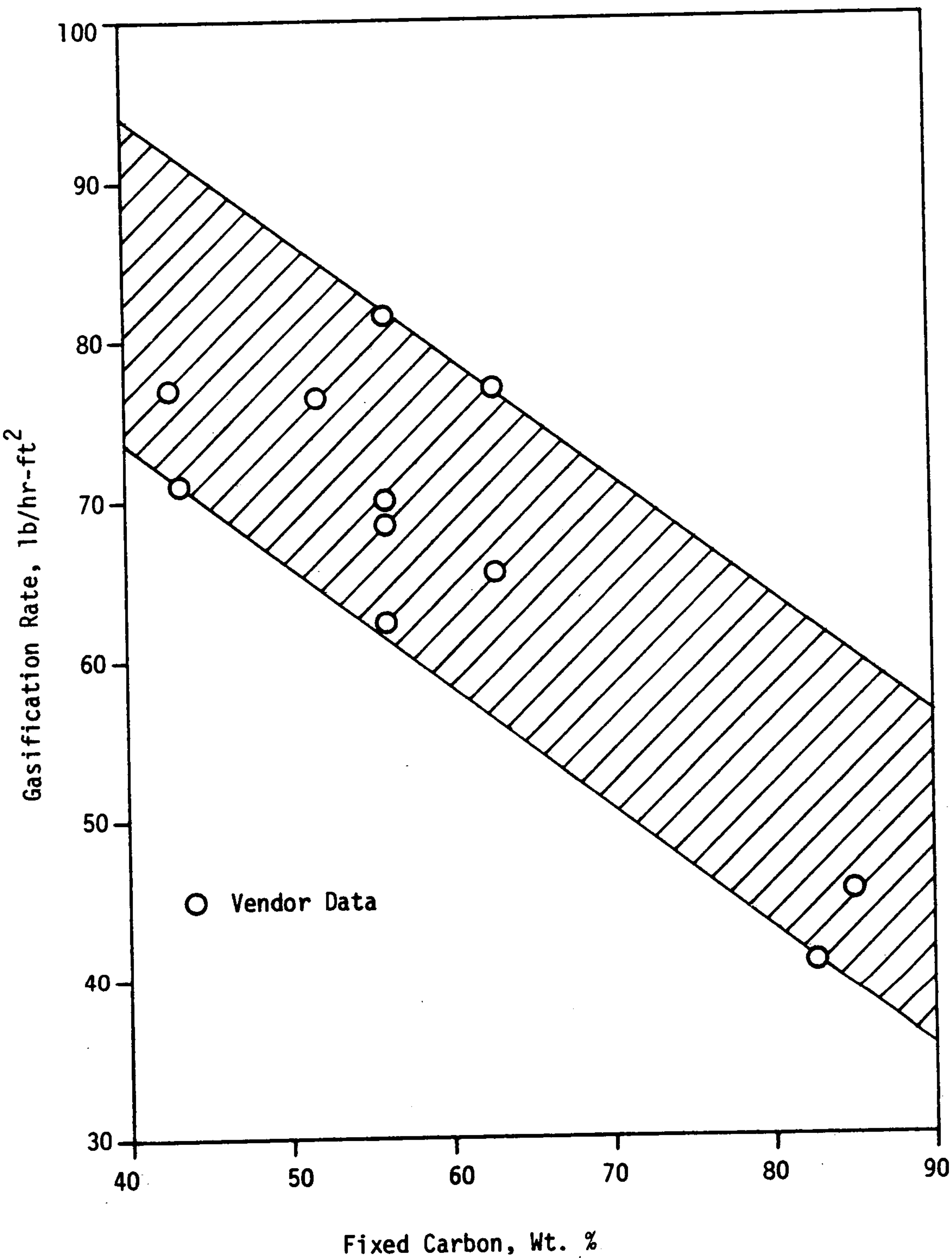

Figure B-2 Gasification Rate vs Fixed Carbon Content of Coal Feed for Air-Blown, Fixed Bed Gasifier Operating at Atmospheric Pressure

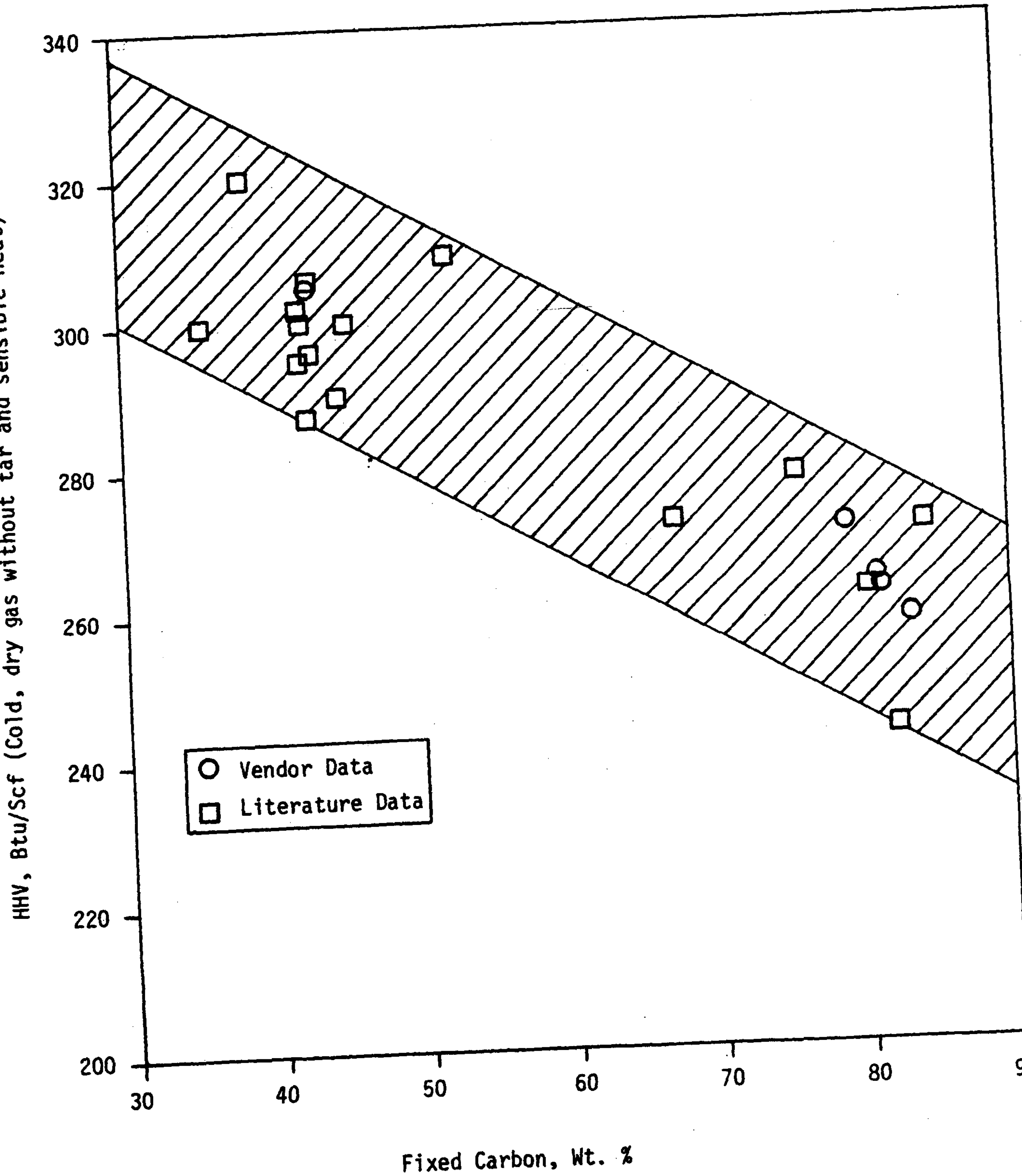

Figure B-3 HHV of Product Gas vs Fixed Carbon Content of Coal Feed for Oxygen-Blown, Fixed Bed Gasifier Operating at Atmospheric Pressure

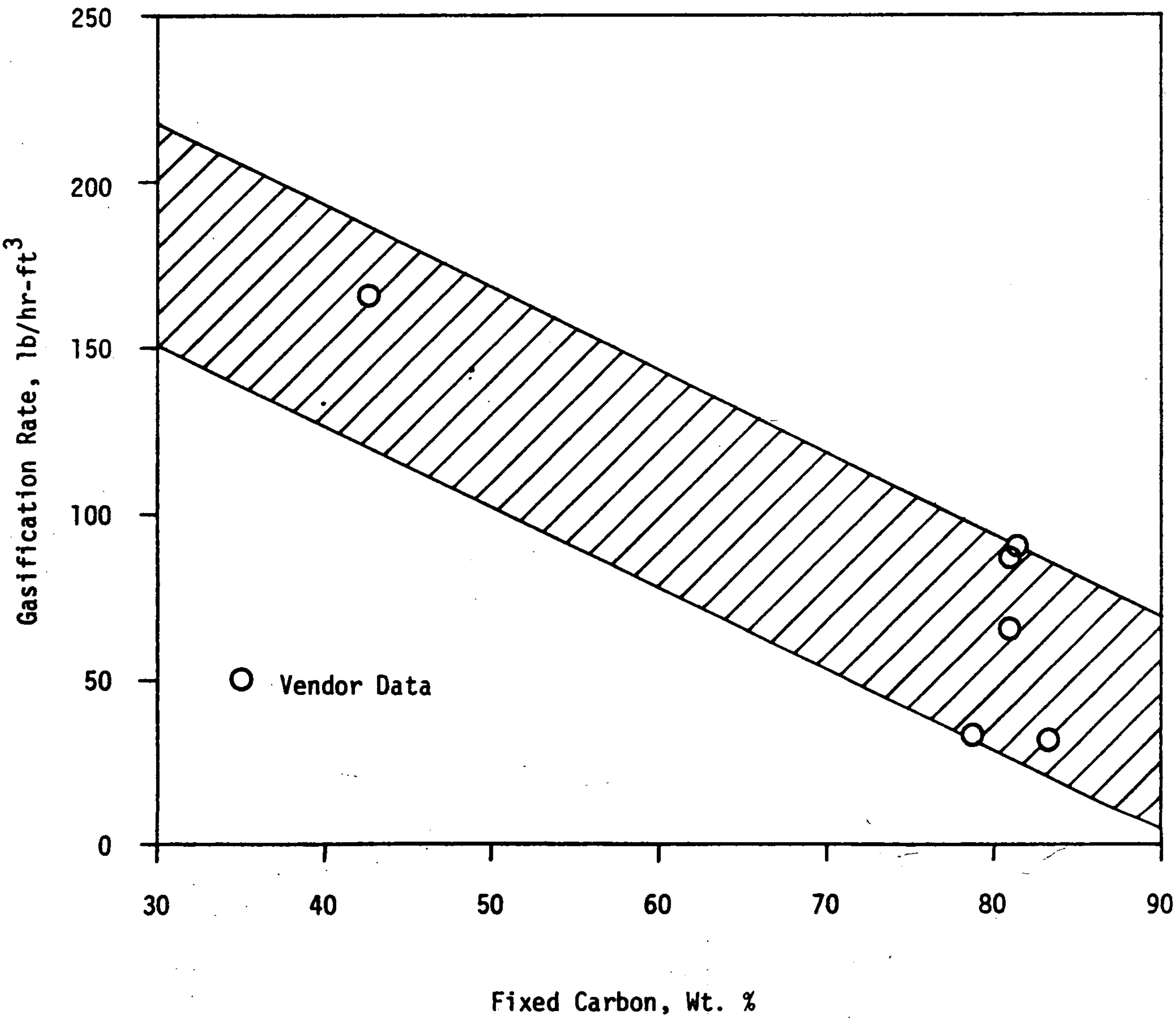

Figure B-4 Gasification Rate vs Fixed Carbon Content of Coal Feed for Oxygen-Blown, Fixed Bed Gasifier Operating at Atmospheric Pressure

APPENDIX C

Combustion Characteristics of Coal Derived Gas

Most experts now agree that low-and medium-Btu gas from coal have great potential as a clean energy source for the U.S. Since natural gas has been widely used as a fuel in utilities, industrial boilers, and industrial processes, it is important to consider the combustion characteristics of low-and medium-Btu gases in potential applications involving replacement of natural gas. Fuel oil combustion characteristics may also be considered, since many processes have capability for firing either natural gas or oil. In the following discussion, combustion characteristics such as gas volume, flame temperature, flame length, flame stability, heating value and ignitability are considered.

Gas Volume Vs. Heating Value

In comparing low- or medium-Btu coal gas to natural gas, one characteristic that is often misinterpreted is the heating value of fuel on a volume basis. When the higher heating value (HHV) is expressed in Btu per SCF of fuel gas, natural gas has a value of about 1,006 versus about 282 for a typical medium-Btu coal gas[1] and about 168 for a typical low-Btu gas from bituminous coal[2] (see Table C-1).

The large difference in heating values as represented by these figures would undoubtedly exert a psychological effect on those considering retrofitting a combustion process but who have previously been accustomed to natural gas. These figures indicate that the low- and medium-Btu gases must be delivered to the point of combustion at 5.99 and 3.57 times the flow rate of natural gas, respectively, to achieve the same heat input. Long distance transport of these coal gases is obviously uneconomical since the pressure drop through existing mains is roughly proportional to the square of the flow rate. The increase in pumping cost alone would be prohibitively high.

For in-plant applications, however, it is more appropriate to examine the heating values in terms of the volume of stoichiometric air-fuel mixture, especially when the burner is of the premix type where air and fuel gas are mixed prior to being burned. In any combustion process it is not the pure fuel gas that is being burned but rather the air-plus-fuel gas mixture. As can be seen in Table C-1, the heating value of natural gas, oxygen-blown gas and air-blown gas are, respectively, 96.1, 89.5, and 73.1 Btu per SCF of air-fuel mix. The heating capacities of all three gases at the burner are therefore not so widely different as generally supposed. In normal firing with 10% excess air these values become even closer due to the high air-fuel ratio for natural gas. In terms of relative flow for a given heat input, the ratio of fuel gas to natural gas is 1.07 for the oxygen-blown gas and 1.31 for the air-blown gas produced from a bituminous

Table C-1

Comparison of Gas Combustion Characteristics

	Natural Gas	Coke Oven Gas	Two-Stage Cyclic Gas	Med-Btu Gas (Oxygen-Blown)	Water Gas (Coke)	Low-Btu Gas (Air-Blown, Bituminous Coal)	Producer Gas (Anthracite)	Blast Furnace Gas
Analysis %								
CO	-	6.3	28.5	37.9	37.0	28.6	27.1	23.4
H_2	-	46.5	52.2	38.4	47.3	15.0	16.6	1.6
CH_4	99.0	32.1	6.5	3.5	1.3	2.7	0.5	0.1
C_2H_6	0.2	-	-	-	-	-	-	-
C_2H_4, C_6H_6	-	4.0	0.6	-	-	-	-	-
CO_2	0.2	2.2	8.0	18.0	5.4	3.4	5.0	15.6
O_2	-	0.8	-	-	0.7	-	-	-
N_2	0.6	8.1	4.2	2.2	8.3	50.3	50.8	59.3
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Volume								
scf Air/scf Fuel	9.47	4.99	-	2.15	2.10	1.30	1.09	-
Fuel Mix, scf/MM Btu	10406	10471	-	11173	10834	13680	14285	-
Flue Gas, scf/MM Btu	10482	10101	-	9823	9479	12500	12920	-
HHV								
Btu/scf Fuel Gas	1006	572	335	282	286	168	146	81
Btu/scf Air-Fuel Mix	96.1	95.5	-	89.5	92.3	73.1	70.0	-
Btu/scf Flue Gas	95.4	99.0	-	101.8	105.5	80.0	77.4	-

Table C-1 (Continued)

Comparison of Gas Combustion Characteristics

	Natural Gas	Coke Oven Gas	Two-Stage Cyclic Gas	Med-Btu Gas (Oxygen-Blown)	Water Gas (Coke)	Low-Btu Gas (Air-Blown, Bituminous Coal)	Producer Gas (Anthracite)	Blast Furnace Gas
Flame Temp.								
°F	3560	3610	-	3600	3670	3200	3100	-
Relative Flow Rate (Fuel Gas/Natural Gas)								
Fuel Gas	1.0	1.76	-	3.57	3.52	5.99	6.89	-
Air-Fuel Mix	1.00	1.01	-	1.07	1.04	1.31	1.37	-
Flue Gas	1.00	0.96	-	0.94	0.90	1.19	1.23	-

coal. The increased volume of gases (7 and 31%) can be a positive benefit because it gives faster circulation of the combustion products and, hence, better heat distribution throughout the furnace. The pressure drops at the burner would still be higher than the case with natural gas, however.

In terms of flue gas volume the differences are even less pronounced. As shown in Table C-1, the flue gas volume per MM Btu is 12,500 scf for low-Btu gas and 9,823 scf for medium-Btu gas which is actually slightly lower than the value of 10,482 for natural gas. In a retrofit situation with medium-Btu gas, equipment downstream of the combustion zone (e.g., a flue-gas heat-recovery system) may thus require little or no modification. In the case of low-Btu gas which increases the volume of flue by 19%, removal of some tubes of the heat exchanger with some loss in heat recovery capacity appears to be the simplest approach if it is desired to maintain constant fan duty.

Flame Temperature Vs. Heating Value

The adiabatic flame temperatures of various gases are also presented in Table C-1. The flame temperature of medium-Btu gas, approximately 3,600°F, is somewhat higher than that of natural gas which is 3,560°F. The flame temperature of low-Btu gas, 3,200°F, is lower because of its high nitrogen content in the fuel. The lower flame temperature air-blown gas will significantly reduce the rate of radiative heat transfer in, for example, furnace applications. To raise the flame temperature to a desirable level the fuel and the combustion air, or the air alone, may be preheated. Figure C-1 shows the effect of feed preheating on the flame temperature of the three gases. As can be seen, the low-Btu gas can give a flame temperature of 3,560°F if both the stoichiometric air and the fuel are preheated to about 650°F.

The flame temperature, however, is not the sole factor that affects the overall radiative heat transfer in a furnace. The thermal radiation properties of the combustion products vary with each different fuel, and consequently the radiation from hot gases could be less or more than that from natural gas even if the flame temperatures are identical. As shown in Table C-2, combusted natural gas, medium-Btu gas, and low-Btu gas contain varying amounts of nitrogen, carbon dioxide, and water vapor. Nitrogen radiates no heat and is perfectly transparent to foreign radiation; however, carbon dioxide and water vapor are good radiators having different emission characteristics. The individual emissivity of these two radiating species varies not only with the concentration (or partial pressure) but also the temperature level and the length of radiation path as well. Furthermore, the individual emissivities interact in a complex manner to affect the total emissivity for CO_2 and H_2O as a whole.[3] For the purpose of comparing the relative radiant flux from the three combusted gases, the emissivities at 3,600°F, 1 atm, and for 1 ft of radiation path are calculated and summarized in Table C-2. As can be seen, the combustion products from the medium-Btu gas will radiate 2% more than would the combusted natural gas under identical conditions. In contrast, the combusted low-Btu gas will radiate 10% less even if the feed is preheated to produce a 3,600°F flame. Again, this can partly be attributed to the relatively high inert nitrogen content in its combusted gas, which suppresses the total concentration of CO_2 and H_2O.

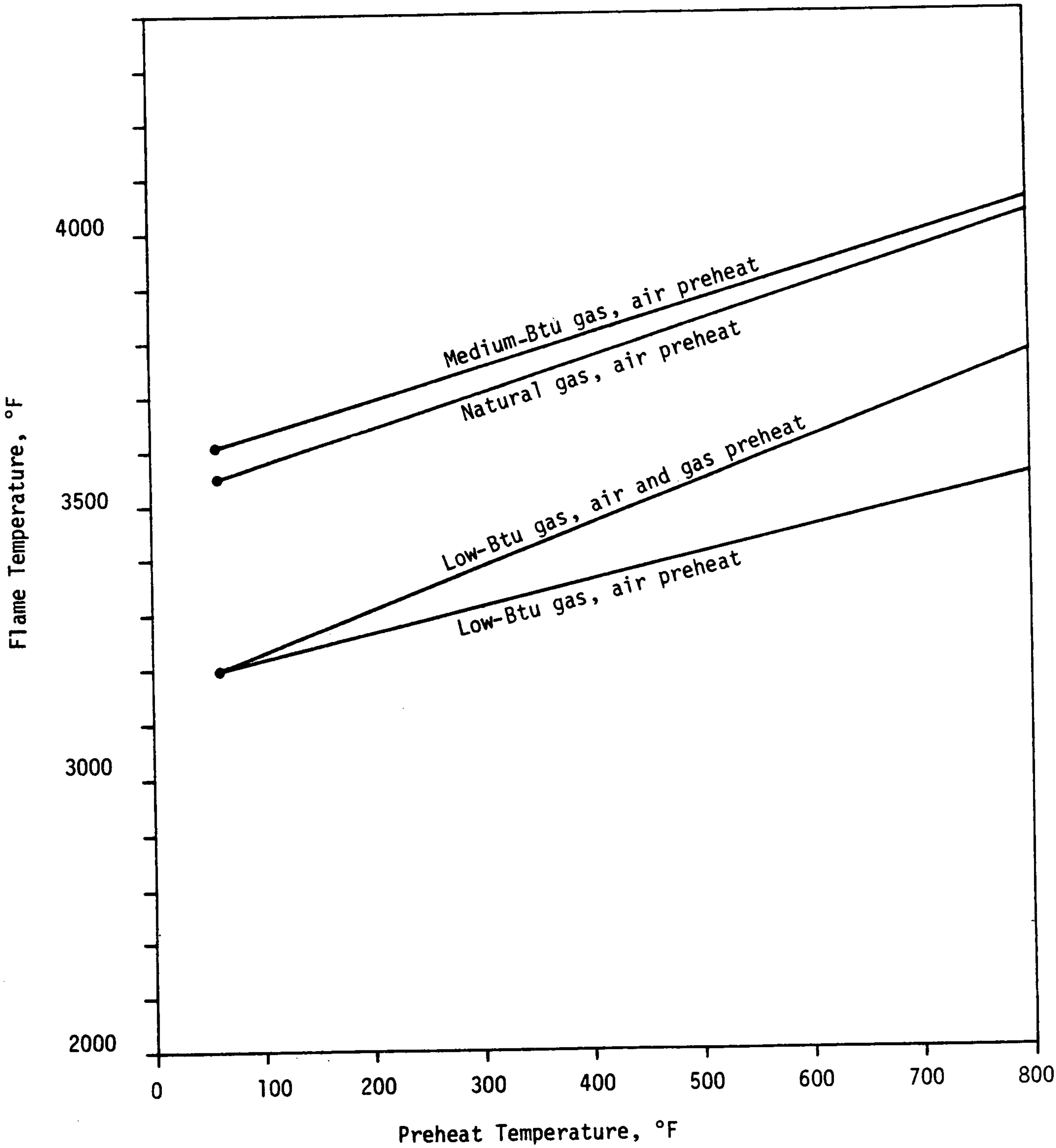

Figure C-1 Flame Temperature vs Feed Preheat Temperature

Table C-2

Comparison of Combustion Products

	Natural Gas	Medium-Btu Gas (Oxygen-Blown)	Low-Btu Gas (Air-Blown)
Composition (Vol. %)			
CO_2	0.0952	0.2145	0.1671
H_2O	0.1898	0.1640	0.0982
N_2	0.7150	0.6215	0.7347
Emissivity ($3600^{o}F$, 1 atm, and 1 ft. path)			
ε_{CO_2}	0.025	0.038	0.035
ε_{H_2O}	0.031	0.026	0.015
$\varepsilon_{CO_2 + H_2}$	0.051	0.052	0.046
Relative Radiant Flux From Combusted Gas (Nat. Gas = 1)	1.00	1.02	0.90

It should be cautioned, however, that the real condition in a furnace may be quite different from what was implicitly assumed in arriving at the above figures. The combusted gases may not be well mixed, and large gradients in the water and carbon dioxide concentrations may exist in various areas. As noted earlier, the increased volume of combusted low-Btu gas may actually change the combustion pattern which will affect convective as well as radiative heat transfer. Furthermore, the overall radiative heat transfer consists of flame radiation as well as gas radiation. Potential controls on flame radiation, such as on the luminosity of flame by injecting a small amount of oil or pulverized coal, can be used appropriately to at least partially offset the change in the gas radiation.[4]

Flame Length Vs. Heating Value

Consideration of the change in flame length as a function of fuel heating value is also important in evaluating the performance within a furnace, because the size and shape of the flame affect the rate of radiative heat transfer (flame radiation). When changing fuel gas, it has been observed experimentally that the flame length generally decreases as the higher heating value (expressed in Btu/scf of pure fuel gas) decreases. As can be seen in Figure C-2, when the ratio of flame length (L) to nozzle diameter (d) is plotted against the higher heating value (HHV), the relationship is nearly linear for a number of fuel gases, including the low-Btu gas.[4] For a given burner, therefore, the low-Btu gas will give a flame only one-fifth or one-sixth in length compared to that of natural gas. The oxygen-Blown medium-Btu gas can be expected to show a proportionate decrease to about one-third or one-fourth.

The flame length can be increased by enlarging the burner diameter; however, this is a costly procedure and may encourage flame instability due to flash back (see below). A simpler procedure could be to vary the amount of air swirl if the burner is of the type that uses swirling (tangential) air flow and radial gas injection. By reducing the tangential-to-radial flow components of combustion air, i.e., by increasing the momentum of air-and-fuel gas mixture in the radial direction, the flame length increases. Thus, by changing the air register vanes or baffles to decrease the amount of air swirl (but not the total amount of combustion air) it may be possible to hold a fixed flame length when switching from natural gas to coal gases having lower heating values.[4][7]

Flame Stability Vs. Heating Value

The flame instability is often characterized in terms of its flashback and blowoff limits.[5] The phenomenon of flashback, or the passing of flame into the port through which a fuel-air mixture flows, occurs when the stream velocity is reduced to a certain critical value. Similarly, the phenomenon of blowoff occurs when the velocity is increased about a certain limit. These characteristic limiting values vary from fuel to fuel, and can be summarized in a flame stability diagram for a range of fuel-to-air ratio.

Figure C-3 is such a diagram for 100% methane which may be taken to represent natural gas.[5] Plotted on the abscissa is the fuel gas concentration expressed in fraction of stoichiometric, so that a rich mixture will have a value greater than unity while a lean mixture a value less than one. The ordinate represents

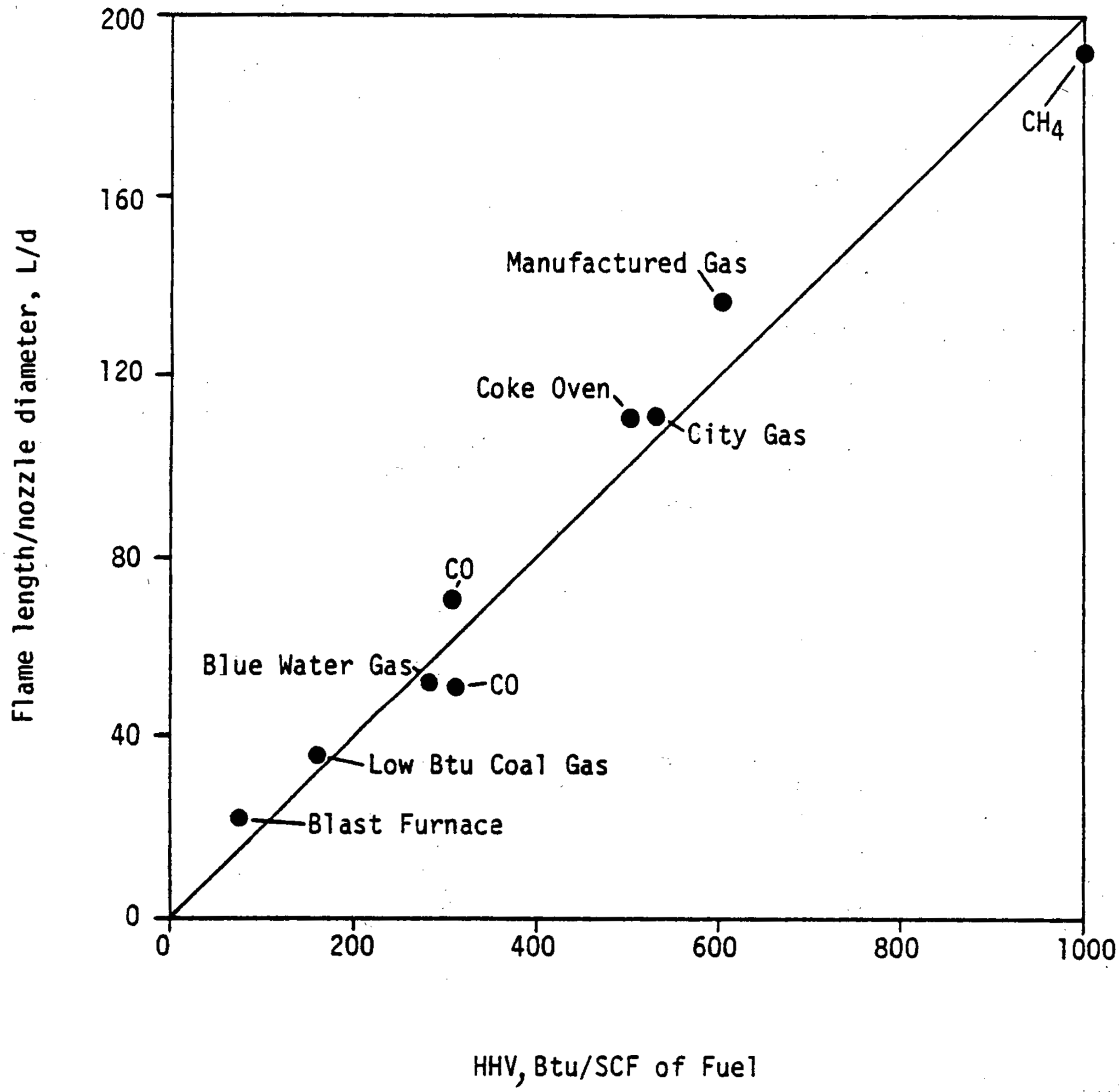

Figure C-2 Ratio of Flame Length to Nozzle Diameter vs Heating Value of Fuel

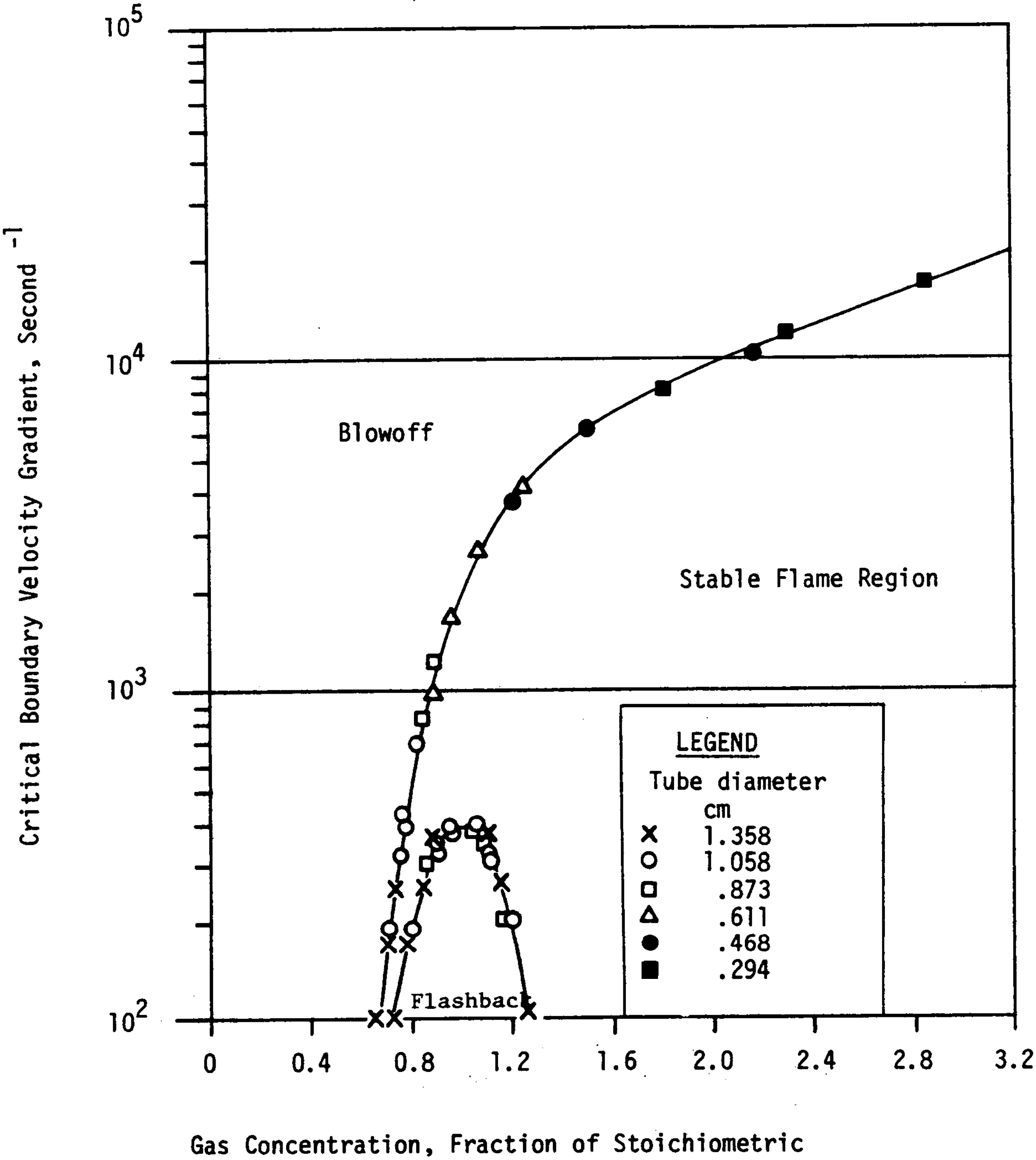

Figure C-3 Flame Stability Diagram for 100% CH_4

the quantity termed critical boundary velocity gradient defined as the rate of change of stream velocity at the edge of the exist plane of the burner port when flashback or blowoff occur. This quantity is roughly proportional to the average flow velocity divided by the characteristic burner diameter.[6] Thus, for a given burner, the critical velocity gradient at flashback is closely related to the burning velocity of the flame. It is also considered to be related to the ignition delay time and the peak frequency of the combustion roar spectrum.

As can be seen in Figure C-3, the two critical curves define a region in which the natural gas (methane) can be burned to produce a stable flame. For comparison, the flame stability diagram for a fuel containing 83.3% of CO and 16.7% of H_2 is shown in Figure C-4. Clearly, the stability region for this fuel is substantially different from that for natural gas mainly because H_2 burns much faster than natural gas. Note also that, in the case of natural gas, the flashback curve nearly reaches the maximum value when the fuel air mix is stoichiometric. In the case of $CO-H_2$ fuel, the maximum occurs at a fuel-rich composition.

Since coal gases contain mostly CO, H_2, and very little methane (N_2 and CO_2 are considered as diluting inert gases), the characteristics of coal gases should behave much like that of the $CO-H_2$ fuel just shown. To construct flame stability diagrams for the low- and medium-Btu gases under consideration, a procedure developed by Grumer et al[5] for multicomponent systems was used. The coal gas is first treated as a mixture of a $CO-H_2$ hybrid (of appropriate composition) and a small quantity of methane, which is then diluted with N_2 and CO_2 to give the fuel composition presented in Table C-1. The limiting curves obtained by this procedure for the medium- and low-Btu gases are plotted in Figure C-5 and Figure C-6, respectively, where the curves for natural gas (broken lines) are also superimposed for direct comparison. As can be seen, both coal gases (solid lines) would burn much faster than natural gas because of the presence of hydrogen which is known for its very high burning velocity. For a given burner, therefore, it is necessary to supply coal gas air mixture at much higher stream velocity and richer in fuel than the case with natural gas to prevent flashback and maintain a stable flame. The deviation from natural gas is slightly less pronounced with low-Btu gas partly due to its lower hydrogen content and partly due to its high nitrogen content which tends to suppress the curves.

Ignitability

The much wider flammability limits of hydrogen than natural gas facilitate ignition of low-Btu and medium-Btu gas. Little difficulty was encountered in spark ignition of very lean fuel air mixtures of low-Btu gas during experimental tests sponsored by a Gilbert industrial client.

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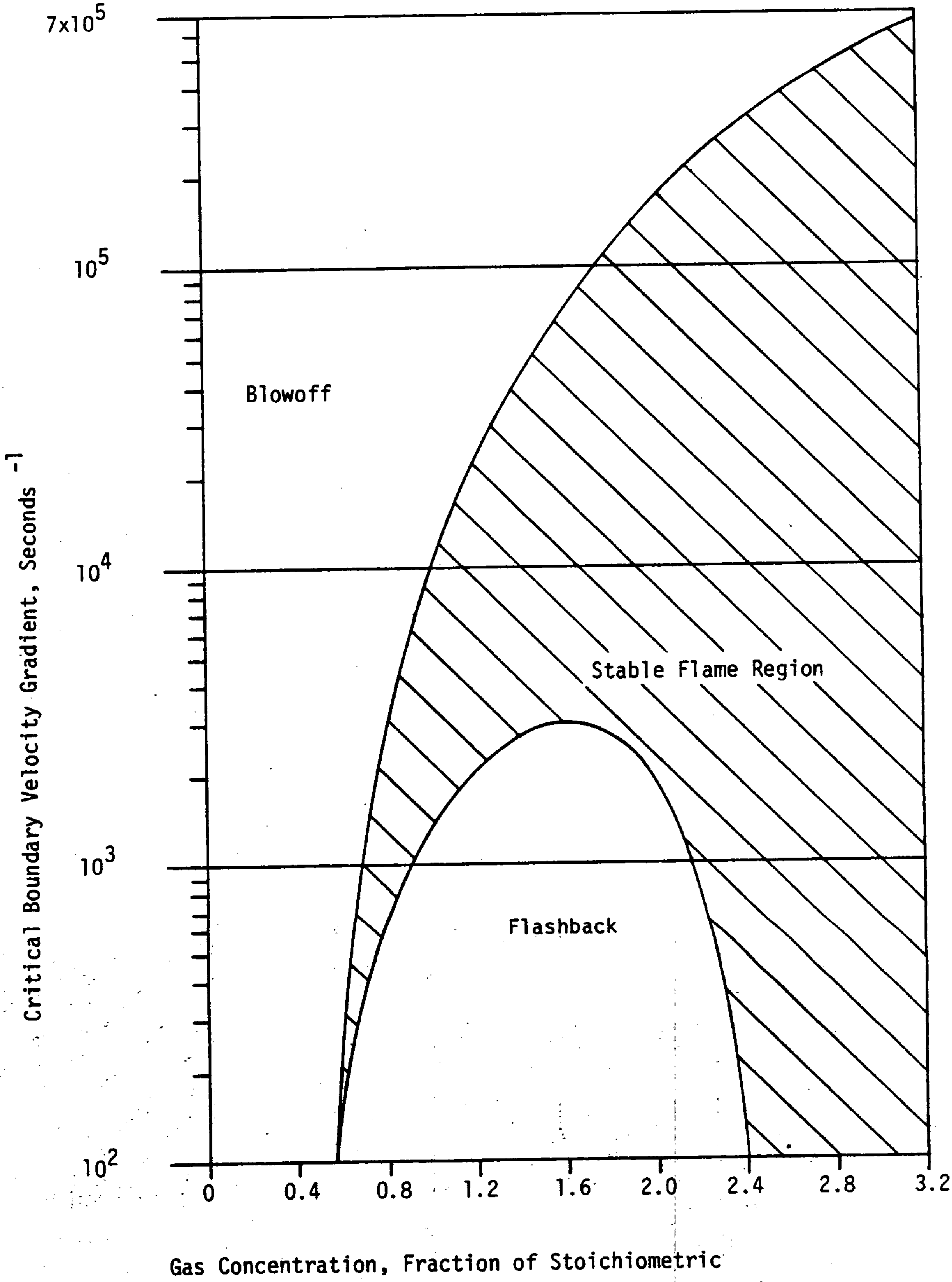

Figure C-4 Flame Stability Diagram for 83.3% CO, 16.7% H_2

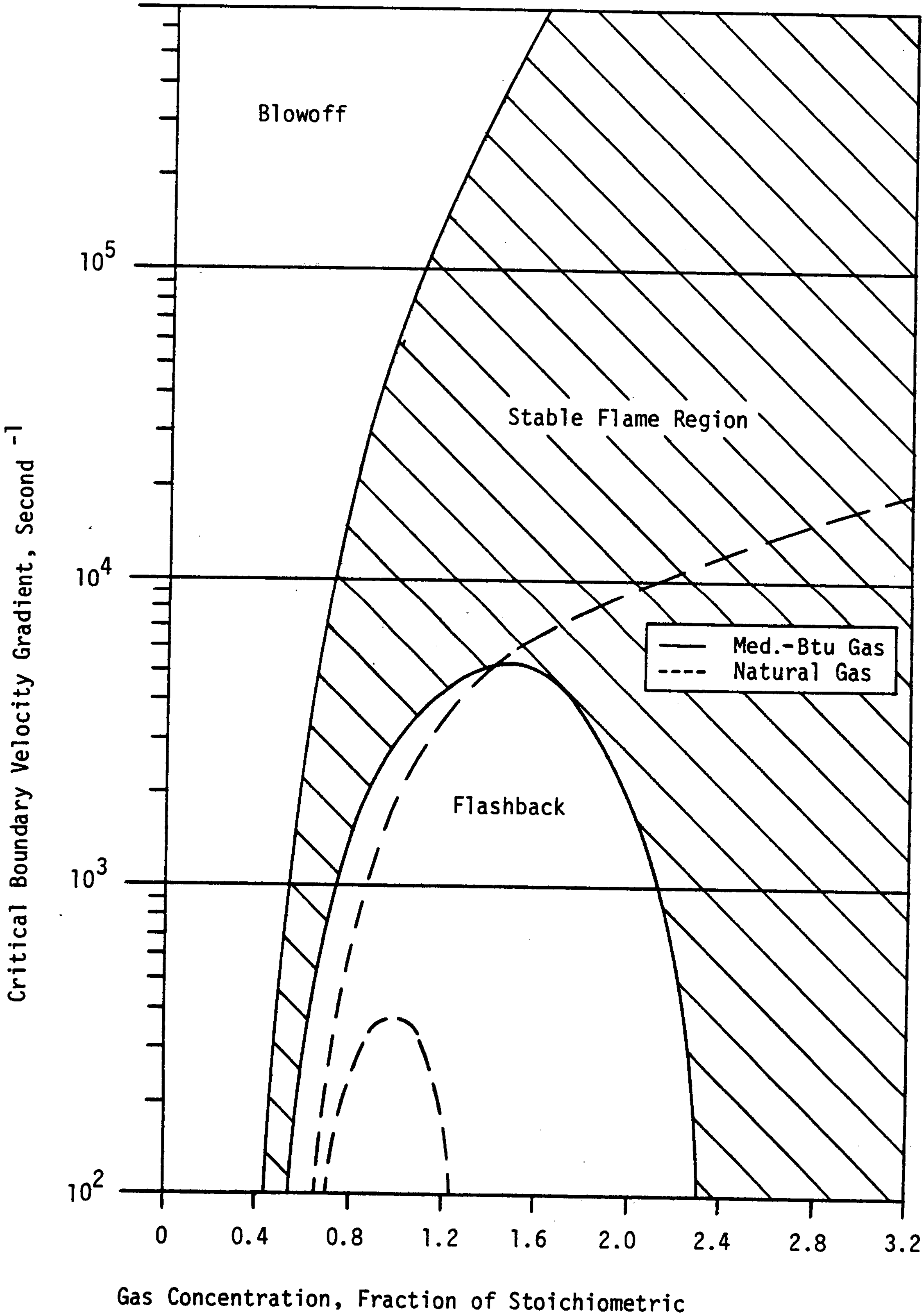

Figure C-5 Flame Stability Diagram for Medium-Btu Coal Gas

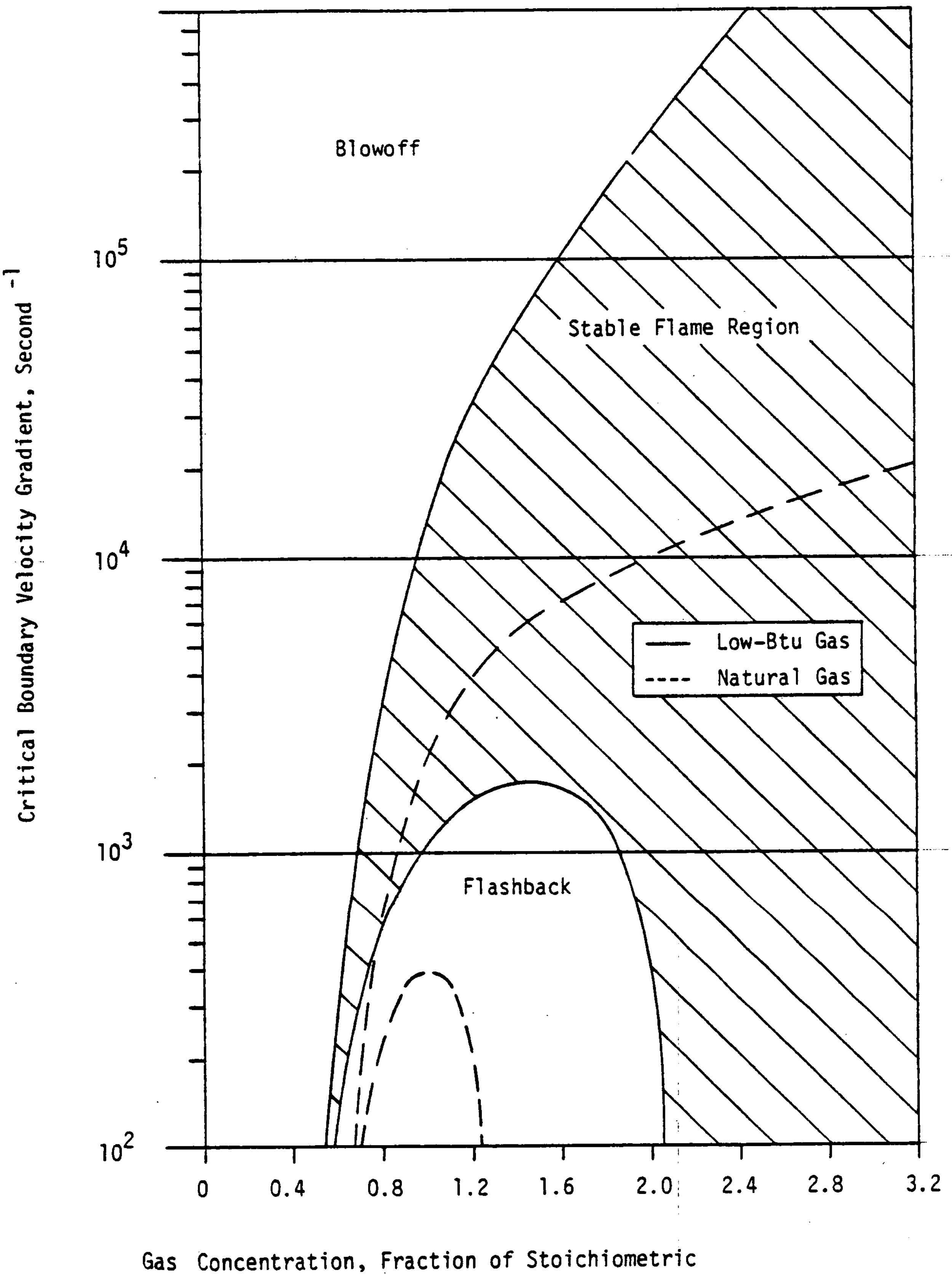

Figure C-6 Flame Stability Diagram for Low-Btu Coal Gas

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