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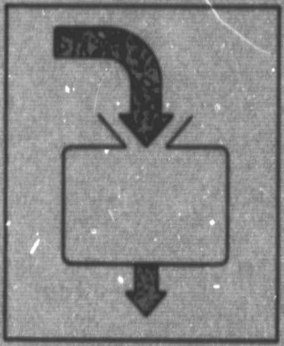

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Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

ABSTRACT

This is the final report on the Coal Pump Development task undertaken by the Jet Propulsion Laboratory for the Department of Energy. The report summarizes the previously documented Phases I and II efforts and continues the narrative description of the Phase III effort. The objectives of the task have been to (1) establish a base of engineering experiences in the continuous extrusion of coal in the plastic state using modified thermoplastic extruders and to (2) assess the feasibility of developing large commercially applicable coal feeding systems based on this approach.

Plastic state coal pumping of 12 different bituminous coals has been demonstrated on thermoplastic extruders of five different designs. The twin corotating continuous screw extruder has been found to be the best prototype for a large coal pump of commercial coal feeding size. Studies of application to a high pressure hydrogasification coal process show the advantage of using the coal pump over other feed methods. New data on the plastic state viscosity of coal, sliding friction of coal, and reactivity of extruded coal is reported.

In the Phase III studies, techniques for achieving continuous coal sprays were studied. Coaxial injection with gas and pressure atomization were studied. Coal particles, upon cooling, were found to be porous and fragile. Reactivity tests on the extruded coal showed overall conversion to gases and liquids unchanged from that of the raw coal. The potentials for applications of the coal pump to eight coal conversion processes were examined.

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SECTION I

INTRODUCTION

This report describes the effort which has taken place under Subtask 5 of Modification 009 of Interagency Agreement DE-AI 21-77 ET 13032, formerly EF-77-A-01-2616. The Interagency Agreement is between the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA).

This phase of the effort covers the period from September 1979 through June 1980.

The DOE program manager is Mr. Robert G. Gall of the Morgantown Energy Technology Center.

SECTION II

OBJECTIVES

The objective of the Coal Pump Development subtask is to verify the capability of the plasticating coal pump to spray into a pressurized environment.

The technical approach has set four goals: (1) develop a coal injector configuration for the continuous spray of finely divided particles, (2) demonstrate the reactivity of the coal after the coal is pumped, (3) demonstrate the spray of coal into a pressurized environment, and (4) investigate various coal conversion processes to which the coal pump may be applied.

SECTION III

SUMMARY

A. PROJECT DESCRIPTION

The objective of the JPL Coal Pump Development project is to develop a new method of feeding coal into high pressure coal conversion reactors. The technique depends on the property possesed by some kinds of coal to become plastic when heated to temperatures between 740 and 860°F. It has been found that plasticating screw extruders, of types widely used in the thermoplastics industry, can be used as prototypes of the plasticating coal pump. The feasibility of using this method for pumping coal into a high pressure environment is investigated in this project.

In the Phase I study, described in Reference 3-1, experience in coal pumping was obtained by using an existing 1.5-inch coal pump and an acquired 2.5-inch coal pump, which were both of the single-screw continuous extrusion type. Studies of the viscometric, thermal, chemical, and physical properties of plastic coal and extruded coal (i.e., after pumping) and the coefficient of sliding friction were undertaken. Analytic studies of coal pump processes were done using an existing computer program for a single-screw extruder.

In the Phase II study, which is described in Reference 3-2, operations on four different coal pumps were accomplished. The studies on the viscometric properties of coal and on the coefficient of sliding friction were completed. The investigation of thermal, physical, and chemical properties is continued. A study on the application of the coal pump to the short residence time hydropyrolysis process was also reported.

In the Phase III study, which is reported here, continuous spray of plastic state coal was obtained using a coaxial injector with an annular flow of hot nitrogen gas. A mean size of 1- to 2-mm coal particles was obtained by this injector. Pressure spray techniques were investigated by using a coal pump-fed piston and die extruder ("expulsor"). Operation of this apparatus into a pressurized collection chamber was accomplished at the project's close. The coal pump extrudate was also subjected to laboratory liquefaction and gasification tests to ascertain if there is any change in reactivity. Coal pump application studies were extended to cover a number of coal conversion processes.

This is the final report on the Coal Pump Development project. Summaries of the Phase I and Phase II reports are included, and a bibliography of all reports, publications, and dissertations prepared under this contract is given. This report continues the narrative account of the research and development studies with a description of the Phase III effort.

B. THE COAL EXTRUSION CONCEPT

With the increasing need to produce synthetic gas and oil from coal, coupled with the economic advantages of large high-pressure gasifiers, the problem of reliably feeding coal into reaction vessels at a high rate has become acute. There are several techniques for feeding coal into reactors that operate near ambient pressure; but there are fewer techniques as the pressure increases. Low-pressure units use lock hoppers, which must be operated at low temperature, with batch feeding of the coal. Slurry-feed techniques used in high-pressure gasifiers require energy to extract the liquid used to transport the coal. Both techniques introduce inefficiencies that may be tolerated in small-scale gasifiers, but are undesirably costly in commercial scale operation.

Although the plastic properties of coal are known and used in connection with coking, these phenomena have not been extensively used for other purposes. In fact, the plastic temperature range of coal has been avoided in coal-feeding systems to prevent the formation of coke. Through the coal extrusion concept, however, the plastic-state of coal may become the key to solving the problem of continuously feeding coal into high-pressure reactors. The concept of extruding coal is supported by the fact that a well developed industry is based on the continuous extrusion of thermoplastics for sheet, film, pipe, and similar extruded products. Ultimately, the extrusion of coal may not be too different from the extrusion of plastic and, consequently, much of this existing technology may be used to aid in solving the coal-feeding problem.

Not only is there a probability that plastic-state extrusion of coal may solve the problem of feeding coal into high pressure reactors, but extrusion may also become a part of the coal conversion process. The mixing of plastic coal with reagents (e.g., H_2O, H_2, and O_2) at the elevated temperatures and pressures within the coal pump may be liquefying or gasifying coal more efficiently and at lower costs than in the conventional methods.

Soon after the idea of extruding coal in its plastic-state was conceived, preliminary experiments with a small piston and die extrusion device were undertaken. In this experiment, a machined one-inch diameter cylinder of coal (a Utah bituminous) was inserted into a cylindrical die, heated to 390°C (734°F), and pressurized to approximately 5000 psi by a hydraulically actuated piston. A stream of fine coal particles was extruded through a 0.020-inch diameter orifice in the die into the atmosphere.

Having confirmed that coal could be extruded through a small orifice, a small, used, thermoplastics extruder was procured and modified by increasing the size of the heaters. The plastication temperature range for coal is between 370° to 450°C (698° to 842°F), whereas for plastics it is between 120° to 240°C (248° to 464°F). Using the 1.5-inch i.d. screw to extrude at throughputs ranging between 12 and 38 lb/hr, pressures up to 1650 psi were generated within the extruder. The extrudate expelled from the extruder was either in the form of long, curly, thin (1/4 in.) spaghetti or large, expanded, foamy billowy masses. Work continued with the 1.5-inch extruder to aid in the determination of the feasibility of plastic-state extrusion method.

C. PHASE I COAL PUMP DEVELOPMENT TASK

The Phase I program was implemented by the Department of Energy to expand the engineering base of extrusion. A standard 2.5-inch single-screw extruder was procured from the Egan Machinery Company. The machine was identical to that used for plastics except that maximum capacity heaters were installed and the profile of the screw was modified slightly based on the 1.5-inch experience. Additional off-the-shelf hardware was procured and assembled into a feed system with the extruder. The coal pump feed system was operated using Pittsburgh No. 8 coal at throughputs up to 200 lb/hr and generated pressures up to 2000 psi. The feed operation was into an atmospheric pressure receiver.

Two main difficulties have been experienced during testing. These are blockage of the feed to the extruder as a result of backstreaming volatiles condensing on the incoming feed, and overload of the drive motor resulting from instabilities in the melting zone of the screw. As a result, runs have been limited to 1-to-3 hours duration. New configurations of screws and feed section are expected to overcome the blockage problem and eliminate the screw jamming.

Studies were initiated to characterize the properties and rheology of coals and their extrudates, and to model the coal pump to aid in understanding the fundamentals of coal extrusion and to help in scaling to pump sizes suitable for use in commercial-size coal conversion plants. The apparent viscosities of coal heated to the plastic state ranged from a low of one poise for Pittsburgh No. 8 (equal to viscosity of SAE 10 oil at 60°F) up to 1000 poise for Kentucky No. 9 coal. Both of these coals have been extruded through the 1.5-inch coal pump. Characterization by the Institute of Mining and Minerals Research (IMMR) (Reference 3-3) of several coals and extrudates show that the calorific value of the coal is relatively unchanged after extrusion. Data on the viscosity and density of plastic-state coal have been obtained for several coals. These data are being correlated with proximate and ultimate analyses, calorimeter analyses, thermal gravimetric analyses, Gieseler plastometer measurements, and fast neutron absorption analyses. The data show that useful degrees of plasticity to exist in many coals of economic significance (Pittsburgh No. 8, Ohio No. 9, Kentucky No. 9, and Kentucky No. 11, to name a few), but the variations in apparent viscosity with time, temperature, pressure, shear, and thermal history are quite large. The study of the solid friction characteristics of several coals is reported as a function of pressure, temperature, and velocity.

The modeling effort was able to utilize a computer program, developed by Scientific Process and Research, Inc., for the thermoplastics industry, to model coal extrusion. This model was used in the design of the screw profile for the 2.5-inch coal pump and has been used to correlate performance of the JPL 1.5-inch plasticating extruder with the Ingersoll-Rand Research, Inc., 1.5-inch dry feeding screw extruder. Analytical modeling without program modification shows good correlations, provided the differences in coal properties are included. The computer model was used to aid in scaling studies for larger size extruders.

The investigations conducted during Phase I demonstrate that the plasticating screw extruder is a technically and economically feasible method for feeding bituminous coals into high pressure reactors. The pump demonstration has been scaled up from a 1.5-inch research screw extruder (10 to 40 lb/hr) to a commercially-obtained, higher-speed, 2.5-inch screw extruder (with a capacity of 50 to 200 lb/hr). Preliminary economic studies show coal pump annual operating cost estimates to be comparable to those for a lock hopper ($26 million versus $25 million for a 625 t/hr plant), though the initial cost of the coal pump is slightly lower. This comparison did not take into account the real possibilities of reductions in the high pressure reactor sizes and simplifications in the flow streams due to the delivery of coal in its very reactive plastic state (temperatures of 800° to 850°F and initially high pressures of 1000 to 3000 psi). In taking into account only the energy saving resulting from heating the coal to its plastic state temperature, the operating costs may be credited with an increase in thermal efficiency which thus reduces the operating costs to $20 million versus $25 million for the lock hopper.

D. PHASE II COAL PUMP DEVELOPMENT TASK

The 2.5-inch coal pump operation was characterized by deposition of volatile condensates on the feed port which prevented long duration runs and by unstable operation of the screw extrusion process. Runs of up to 5 hours duration and flow rates up to 220 lbm/hr were recorded. The principal cause of unstable through-flow of coal in the screw was traced to poor performance of the solid feed part of the screw extrusion process.

The Werner and Pfleiderer Corporation demonstrated plasticating extrusion on their ZSK-57 twin corotating screw extruder in an early test, done at their expense. An extended run has been completed on a JPL subcontract under this task. The twin-screw extruder has overlapping screw flights with complete wiping of each surface by the other screw. There is positive forward feed of solid particles as contrasted to the feed by drag force differentials in the single screw; hence, plugging by particles collecting on tar condensation is eliminated. Steady operation at a variety of conditions for over 8 hours was accomplished at feed rates of up to 350 lbm/hr and with die pressures of up to 650 psi for 2 hours. The twin corotating screw extruder is considered to be the best prototype for scaling the plasticating coal pump to commercial sizes of 50 tons/hr.

Research studies on the old 1.5-inch coal pump centered on overcoming some of the stability problems plaguing the 2.5-inch coal pump. Conditions for smooth starts were established. Venting the gases was found to solve the tar condensation problem in the smaller extruder, but this solution did not work on the larger one. Using the barrel gas vent, a run of 34 hours with voluntary run termination was obtained with the 1.5-inch pump. Coals of several different types were found extrudable. Pocahontas No. 3, which was not extrudable by itself, could be extruded as a 25% mixture in Pittsburgh No. 8 coal. Complete energy and material balance around this coal pump was obtained.

A new 1.5-inch coal pump was installed in a barricaded test cell to develop new techniques for spraying the plastic coal into high pressure. Continuous sprays into atmospheric pressure using a low pressure drop injector was demonstrated.

The apparent viscosity of the plastic state coal was determined as a function of time and temperature. The samples were completely enclosed during heating to retain all gases and vapors inside the sample chamber; hence, the capillary viscometer measured an overall or bulk viscosity. The apparent viscosity of coal decreases very rapidly with time until a minimum is reached, and then can increase, all at constant temperature. The lowest apparent viscosity was that of Pittsburgh No. 8 which had a measured viscosity of 2.5 poise at 473°C that was still decreasing at the limit of measurement. Ohio No. 9 coal is an order of magnitude less fluid than Pittsburgh No. 8 at comparable temperatures. Illinois No. 6 coal is about two orders of magnitude less fluid than Pittsburgh No. 8. Viscosities of mixtures of coal were also determined.

The change in properties of several coals before and after coal pumping (or "plastic state extrusion") has been determined by the University of Kentucky Institute of Mining and Mineral Research (Reference 3-4) under a subcontract from JPL. Changes in properties are small and are in the direction to be expected from mild heating (400° to 500°C) for a short time. The volatile matter is generally 3 to 6% lower than the parent coal. The calorific value is nearly unchanged, typically down by less than 1%. The free swelling index is generally increased by 1 unit and the ash content is increased slightly.

The coefficient of sliding friction of coal against smooth hot steel surfaces has been measured over a range of temperatures from 70° to 600°F, with surface speeds of 2 to 32 inch/sec, and normal forces of 10 to 1500 psi. This work was done by Prof. C. I. Chung at the Rensselaer Polytechnic Institute under a subcontract from JPL (Reference 3-5). From 70° to 300°F, the coefficient of sliding friction is approximately constant with temperature; it is independent of the sliding speed and decreases slightly with increasing normal force. At temperatures between 375° to 425°F, an abrupt decrease in the friction is attributed to the presence of oils released by the coal which lubricate the sliding surface. Plastication or melting rates were measured for surface roll temperatures of 770° to 835°F. The point of initiation of plastication, 770°F, is higher than the softening point, 736°F, from Gieseler plastometer measurements. The behavior of the plastication rate as functions of temperature, surface speed, and normal force is not the same as that found in conventional polymers. Coal plastication has some of the character of a mixture of polymers and particles, but it is more complex.

The application of the plasticating coal pump to the Rockwell/ Cities Services hydrogasification process was studied. This is the commercial embodiment of the Hydrane process developed originally at the Pittsburgh Energy Technology Center. The coal pump fits well into the requirements of a feed system for the process. The coal pump can deliver coal at high pressures (1000 to 1500 psi), at elevated temperatures (900°F), without dilution with slurry agents or transport gases, and with spray formation. The price of the product SNG could be lowered as much as 6.6% by using a coal pump instead of a slurry feed system.

E. PHASE III COAL PUMP DEVELOPMENT TASK

Techniques for achieving continuous sprays of coal were tested in a 1.5-inch coal pump. Gas atomizing injectors were investigated since these operate with lower pressure drops than the pressure atomizing injectors. The four gas jets on one coal jet injector yielded spray particle sizes ranging from 1/4 to 3/8 inch long. The coaxial injector, where a central coal jet was surrounded by an annular flow of hot gas, yielded mean particles sized about 0.10 inch. Hot gaseous nitrogen was used as the atomizing fluid. Pressure atomization of coal was tested in a coal pump feed piston-and-die apparatus ("expulsor"). Short duration flow rates up to 700 lb per hour were obtained. Qualitative indications of good atomization were obtained.

A mixing section incorporated into the screw of the 1.5-inch coal pump stabilized pressure fluctuations and seemed to homogenize the plastic coal. In all 38 tests, over 30 hours of total test time were accumulated.

Some tests were run on the reactivity of the extrudate during liquefaction from a coal pump. In two different tests with Kentucky No. 9 coal, the test data would indicate that the extrudate would suffer a 4 to 9% decrease in the first stage liquefaction conversion fraction. However, if the loss of volatiles which occurs during the collection of coal pumped samples is taken into account, the actual change in reactivity is negligible.

Tests on the reactivity of pulverized coal and pulverized extrudate with hot steam, synthesized by the explosion of a stoichiometric H_2-O_2 mixture, were run. The parent coal reacted more extensively than the extrudate but differences were not expected to be significant in process applications.

Applications of the plasticating coal pump to seven gasification processes and to one liquefaction process were found to be favorable. These are the Hygas, Bigas, Rockwell hydrogasification, Shell-Koppers, Bell, Texaco, Exxon, and the SRC-II processes.

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SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Continuous sprays of plastic state coal have have been obtained using a gas-liquid coaxial injector. The atomizing fluid of nitrogen at 650°F was able to spray the coal into particles with a mean size generally less than 2 mm. The coal particles, when examined upon cooling, were porous and fragile. Lower coal viscosity should enable somewhat smaller size spray to be obtained. Experiments to obtain smaller particle sizes using high mass flow pressure atomization were initiated. Qualitative indications of small particle sizes were obtained in a high mass flow pressure atomization injector suitable for coupling to a high pressure gasification reactor. Smooth, continuous, and trouble free plasticating extrusion of coal continues to be demonstrated, with considerable reduction in outlet stream pressure fluctuations when a special mixing section is incorporated into the screw.

The reactivity of extruded coal has been compared to its parent coal both for liquefaction conversion and for gasification. In liquefaction tests, the conversion to preasphaltenes (pyridine-soluble fraction) based on the mass charged to the reactor is from 1 to 9% lower for the extrudate than for the raw coal. If the volatiles lost during the extrusion process and the subsequent quenching are counted, then there is substantially no loss in the liquefaction conversion fraction. In gasification tests, using reaction with the combustion products of stoichiometric mixture of H_2 and O_2, raw pulverized coal was converted to volatile products more completely (~ 92% conversion) than extruded pulverized coal (~ 78% conversion). These tests indicate some decrease in the reactivity of extruded quenched coal compared to raw coal. Experiments in gasification using hot sprayed coal were inconclusive due to poor spray quality.

Application of the coal pump to eight coal conversion processes were examined. These are the Hygas, Rockwell/Cities Service, BiGas, Texaco, Shell-Koppers, Exxon, Bell, and SRC-II. These include both gasification and liquefaction processes, entrained bed and fluid bed, and raw and catalyzed reaction processes. It is concluded that further examination of the plasticating coal pump is worthwhile for these applications and other processes similar to them.

B. RECOMMENDATIONS

Further development of larger coal pumps should use the twin-corotating screw extruder. Scaling to 350 lbm/hr has proven successful so increases in sizes from 1 to 5 ton/hr can be tested. This is a size compatible with several projected or current coal conversion pilot plants. The twin-screw corotating coal pump overcame the two difficulties of steady solid transport and of control of the tar/oil deposition on screw surfaces.

Research on the apparent viscosity of coal should be continued. The nature of plasticity and pyrolysis of coal seems intimately related to the coal conversion processes. It is intriguingly suggestive that plastic behavior peaks at about 425°C, a temperature that is also the optimum reaction temperature for several coal-to-oil conversion processes. This is believed not to be fortuitous. The interaction between the high shear inherent in a coal pump with hydrogenation should be beneficial to a coal hydroliquefaction process.

SECTION V

COAL SPRAY STUDIES

A. OBJECTIVE

A coal pump will be used to study means for achieving continuous sprays of plastic state coal. Initial experiments will be done at atmospheric pressure; later tests will be conducted at higher pressures, first with gaseous nitrogen pressurization and then with gaseous hydrogen. Several means of obtaining fine atomization of coal will be investigated.

B. INTRODUCTION

In this report, spray atomization of plastic state coal from several injector configurations is discussed. All spray experiments were done at nominal one atmosphere conditions. Design of a high pressure hydrogasification test section to couple to the coal spray injector was completed. The quality of the spray achieved in the reported experiments did not justify tests at simulated process conditions.

Spray from extrusion of coal heated to its plastic state has been demonstrated by Ryason and England (Reference 5-1). Spray of plastic state coal was reported by Ingersoll-Rand Research Co. personnel (Reference 5-2) using a reciprocating screw injection machine. Sprays of Pittsburgh No. 8 coal were reported from the coal extrusion reactor apparatus in the Phase I coal pump report (Reference 3-1). In these cases the spray was always formed using very high pressure drop (> 3000 psi) across small orifices (~ 0.020 to 0.050 in.).

The possibility of having the coal pump spraying coal into a high pressure short residence time hydrogasification reactor was seen as an important application. The ability of the coal pump to operate continuously and to spray continuously has been the goal of this development.

There are several methods of atomizing a fluid so that a spray of small droplets is obtained. Pressure atomization is obtained when a fluid is accelerated rapidly by its passage through a small orifice across a high pressure drop. This technique has been used successfully as noted above. In a two-fluid atomizer, the fluid stream is shattered by the action of a secondary, usually gaseous, stream moving at a relatively high velocity. A single-fluid swirl atomizer causes fluid breakup to occur because the swirl action forces the fluid to form a thin film that eventually becomes unstable and then breaks up. The thin film may also be formed by allowing the fluid to flow onto a whirling disk or cup. However, pressure atomization is relatively less desirable since high pressure drops cause a high velocity flow of the coal through the orifice. This high velocity (~ 200 to 500 fps) probably causes high wear rates on the orifice material. Since secondary gas flow is available in a hydrogasifier in the form of the hydrogen stream, the two-fluid atomizer was selected as being a promising option for plastic state coal.

Two-fluid atomization depends on the transfer of momentum from the secondary fluid moving at high speed to the slower moving fluid. If the slow moving fluid is coal, then the injection velocity can be much lower, hence presumably lessening the wear relative to that obtained in pressure atomization.

The objective of the program was to spray coal into a high pressure environment. However, due to the undesirably large size particles created by two fluid atomizing injection, another approach to the spray atomization was adopted. This was to return to the use of pressure atomization. The scale of expulsion rates was increased above what was previously obtained in the piston and die apparatus.

A design to use sprayed coal for a hydrogasification test reactor operating at 1000 psi was prepared. Detailed stress and safety calculations and fabrication were deferred until a later phase of the project (not currently funded).

C. DESCRIPTION OF THE SYSTEM

1. Vibra Screw

The Vibra screw (Figure 5-1) is a unit for precision metering of dry coal, and consists of these major components: (1) a 3-cubic foot capacity live bin that holds approximately 120 lbs of coal; (2) a vibrating trough and a 1-inch diameter screw capable of feeding up to 112 lbs of coal per hour; and (3) a mechanical variable speed drive. The vibrating trough is electrically heated and preheats the coal to 350°F prior to entry into the extruder feed hopper. The live bin is blanketed with nitrogen at all times. The raw coal feed stock, after crushing and sieving, is generally run once through the Vibra screw in order to dry it. Additional coal is added during a run to the live bin through a closed container affixed to a port on top of the live bin lid.

2. Coal Pump

The coal pump shown in Figure 5-1 was built by Davis Standard (Model 1505). It has a 1.5-inch diameter screw with a length to diameter ratio of 24 to 1. A variable speed 10-HP motor turns the screw through a gear reduction system.

After a run, the screw may be removed by a ram assembly affixed to the end of the extruder gear drive. The screw is pushed through the barrel and out of the extruder for cleaning. This is done after every run.

The barrel, die/adapter, and clamps are electrically heated by band and cartridge heaters as shown in Figure 5-2. In the case of the barrel the watt density is 48 watts/square inch which provides a heat-up time of 25 minutes from ambient to 850°F. For the adapter, the watt density is 24 watts/square inch with a 30 minute heat-up time. The die

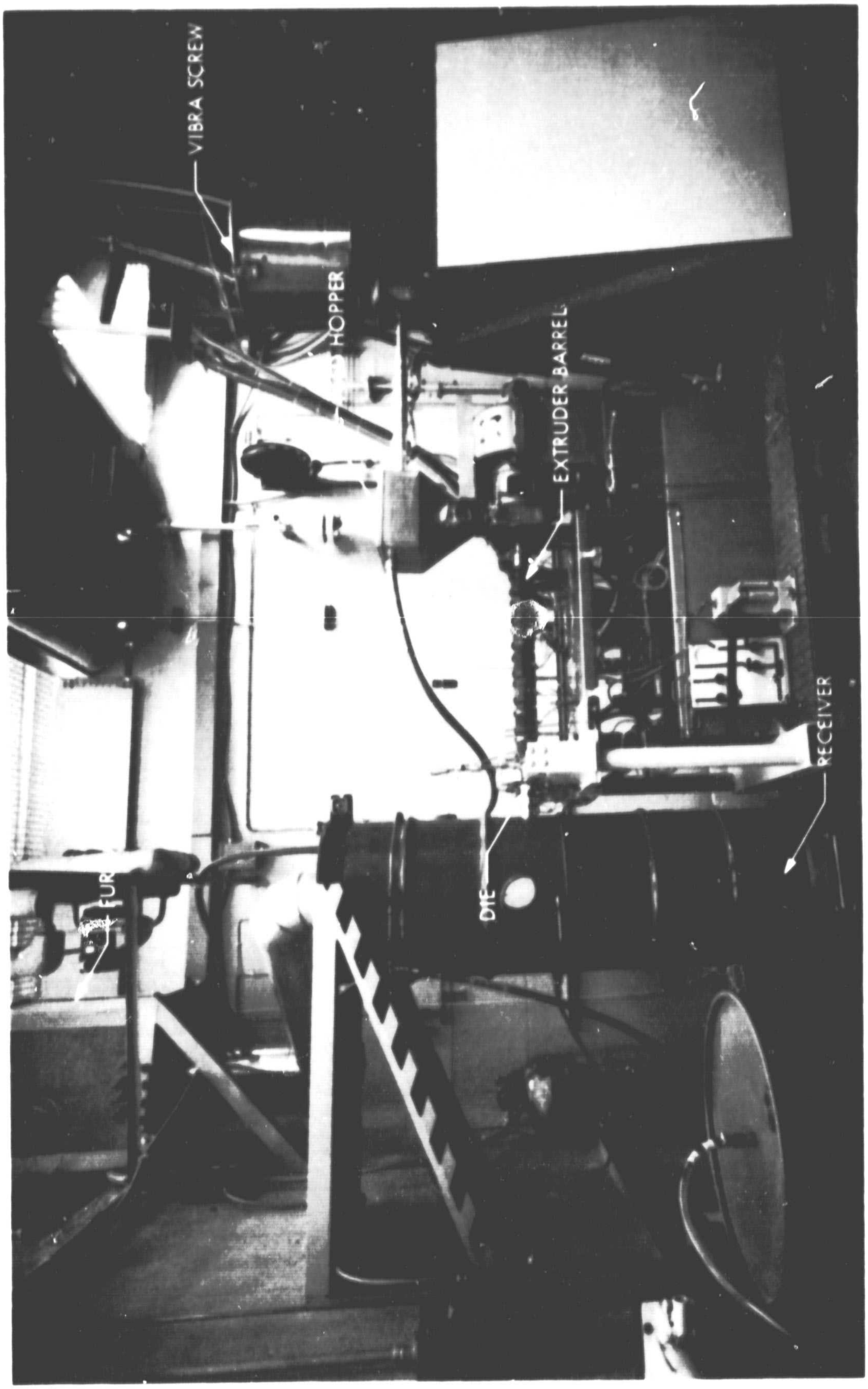


Figure 5-1. A Photograph of the 1.5-inch Coal Spray Research Apparatus in its Nonpressurized Spray Configuration

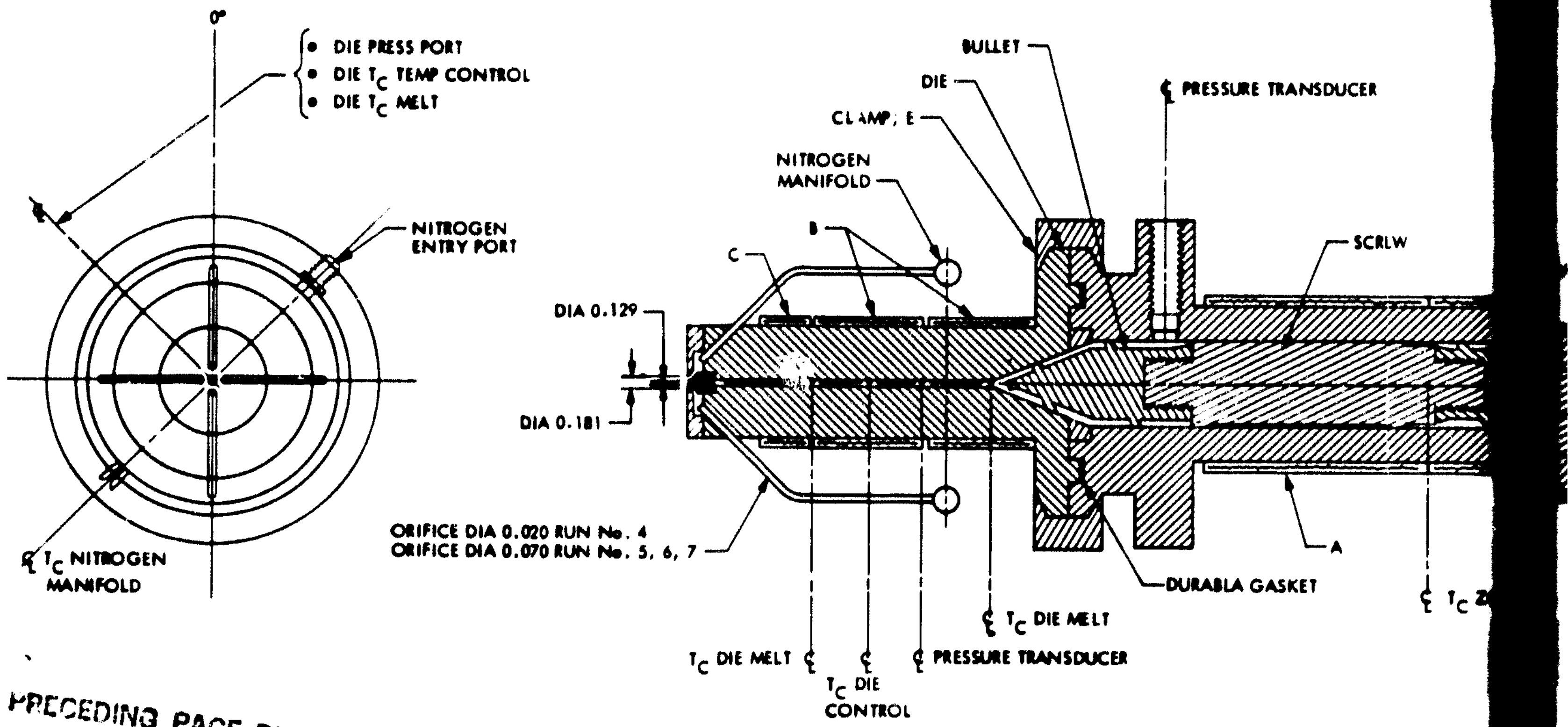
A - BAND HEATERS 4" LONG 2 7/8" I.D.
1000 WATT, 120 VOLT

B - HEATER 2" LONG 2" I.D., 240 VOLT,
300 WATT

C - BAND HEATER 1" [illegible]G 2" I.D., 240 VOLT
300 WATT

D - BAND HEATER 1 [illegible]NG, 1 1/2" DIA,
120 VOLT, 275 WA[illegible]

E - CARTRIDGE HEATER 3/8" DIA, 300 WATT,
240 VOLTS, 4 HEATERS



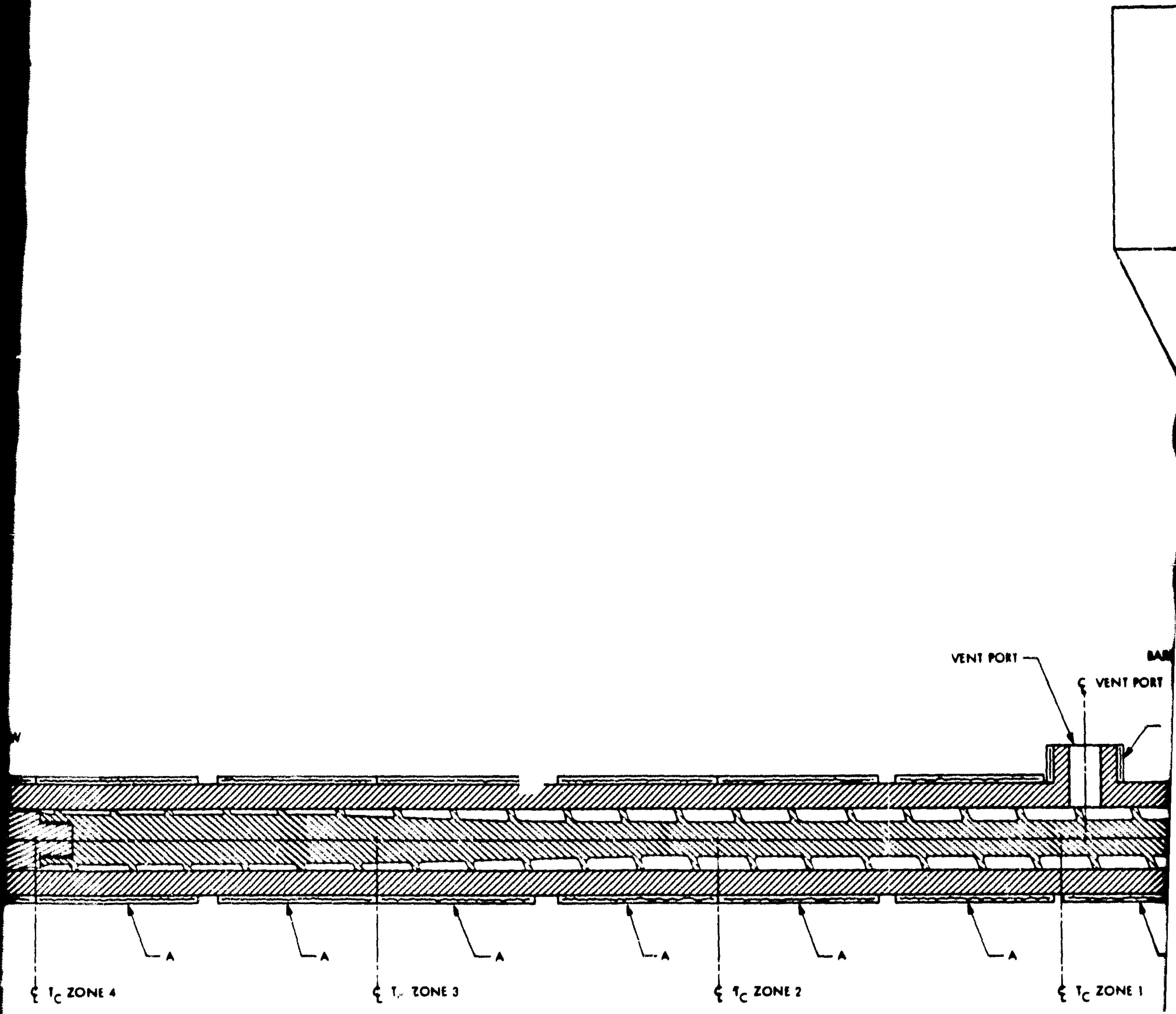


Figure 5-2. A Drawing of
Coaxial Inje
Locations of
Indicated

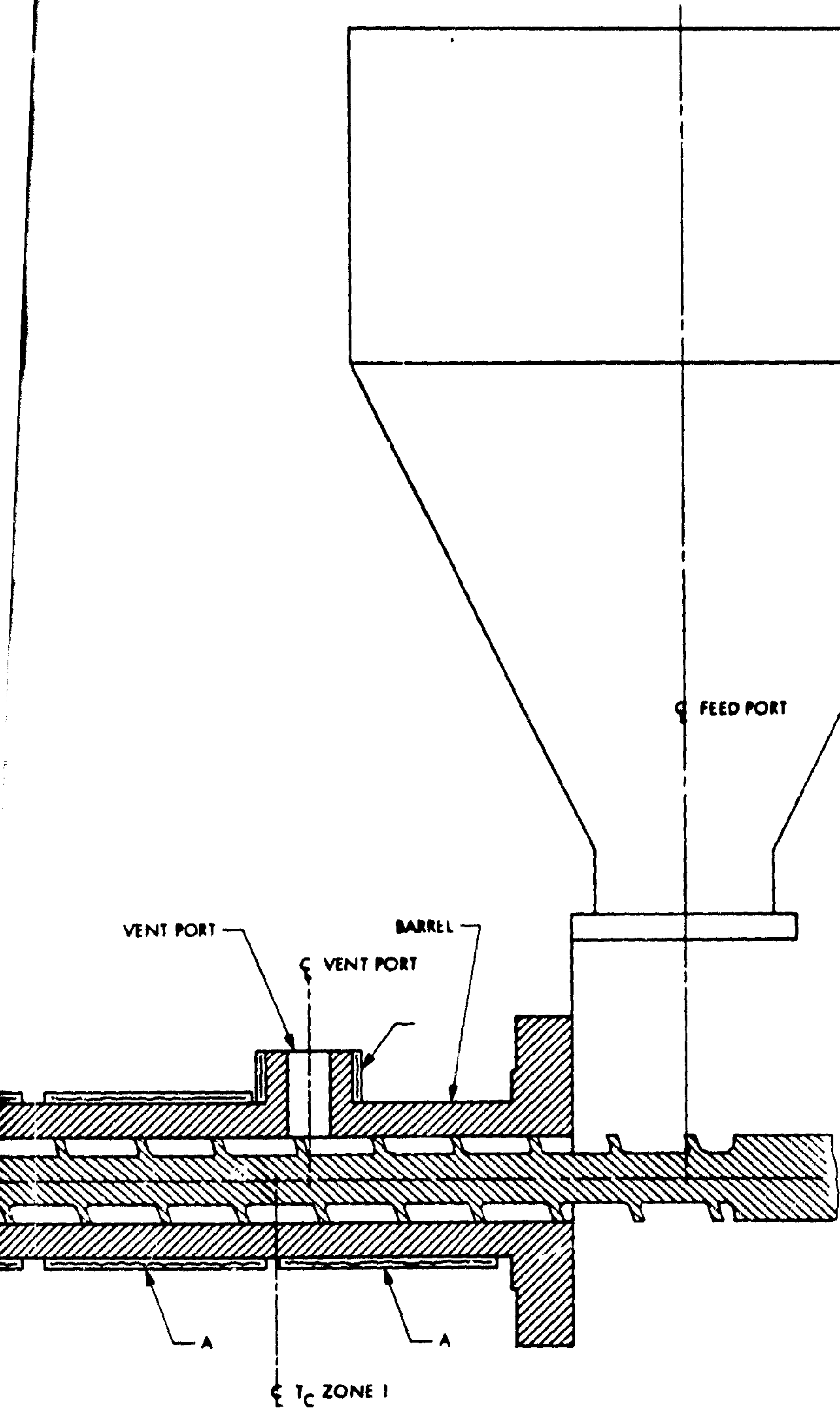


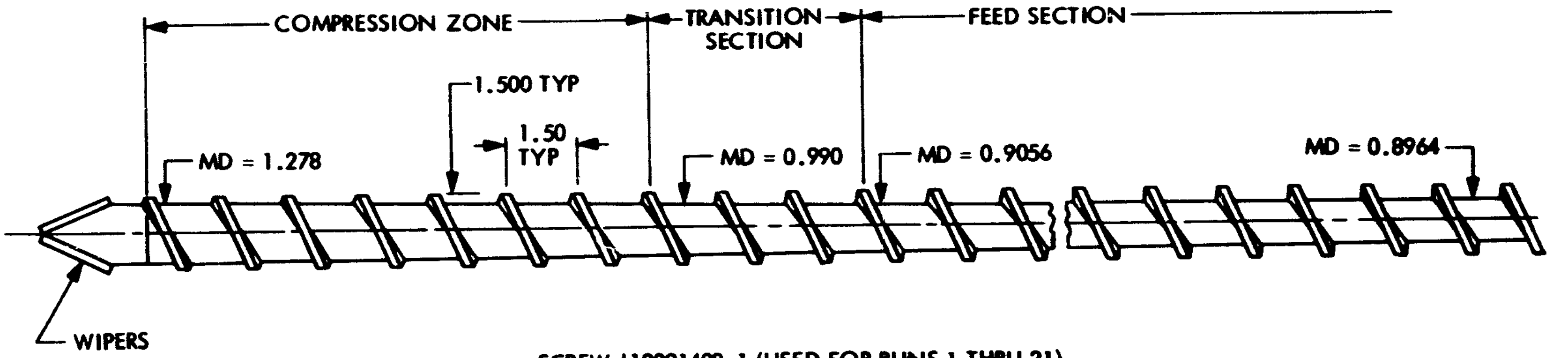
Figure 5-2. A Drawing of the Coal Pump Barrel, Screw, Clamp, and Coaxial Injector. The Heater Characteristics and the Locations of Thermocouple and Pressure Transducers are Indicated

clamps are heated with cartridge heaters. Originally they were 1/4-inch diameter, 2.5-inch length, and 200 watts but since the heatup time proved to be too long, these were changed to 3/8-inch diameter by 2.5-inch length and 300 watts. Four heaters were used per clamp half providing a heat-up time of approximately 45 minutes. The barrel is vented at a port 6 inches downstream from the centerline of the feed hopper which allows the backstreaming gases and tars to be carried off by positive draft ventilation to the furnace. The die/adapter assembly is held in place by clamps which are hydraulically operated and may be opened remotely in case a barrel overpressure is caused by blockage in the die.

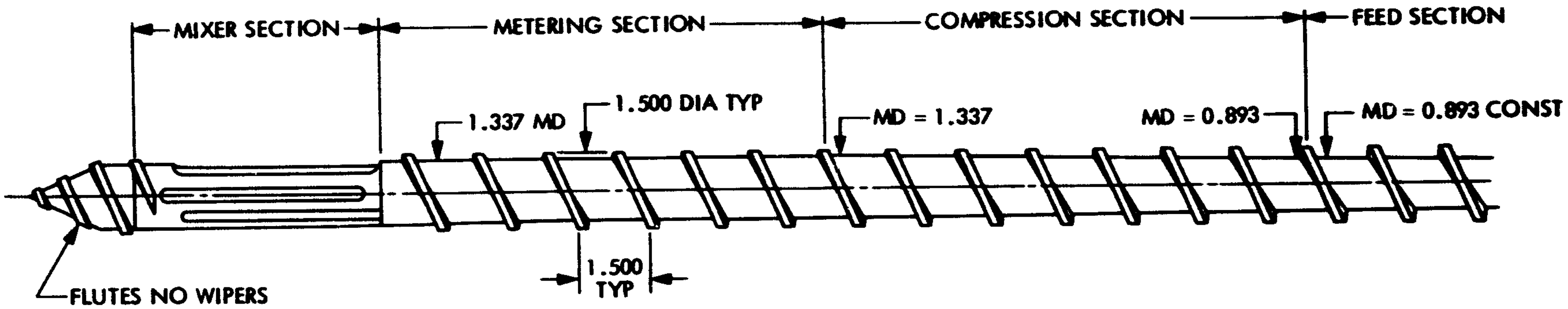
Both the coal pump and the Vibra screw are mounted on rails and moved with a winching system at both ends which allows movement of the complete system approximately 15 feet.

3. Screw and Mixer Section

The screw used in early tests had a standard configuration (designated by JPL drawing number J10091048-1, or -1 for convenience) consisting of a feed zone, a transition section, a compression zone, and a bullet as shown in Figure 5-3. The second screw (-2) consisted of feed, metering, and compression sections plus a Maddock mixer section and a bullet (Figures 5-3 and 5-4). The mixer section, -2 configuration, was designed on the basis of a patented design by B. H. Maddock (Reference 5-3). It has been shown to accelerate melting, improve mixing, and separate solids from melt phase in thermoplastics extrusion. Figure 5-4 is an overall photograph. Figure 5-5 is a cross-section dimensional drawing. Figure 5-6 is a closeup photograph. Dimensions in inches of these screws are listed in Table 5-1. Screws are made of 4140 steel with flame hardened flights. The mixer section is made from 4140 steel flame hardened to Rockwell 55. (Screw configurations for each run are called out in Table 5-6 as either the -1 or -2 configuration.)



SCREW J10091408-1 (USED FOR RUNS 1 THRU 21)



SCREW J10091408-2 NEW MIXER SCREW USED RUN 22 AND 23

Figure 5-3. Schematic Drawings of the Screws Used in the 1.5-inch Davis Standard Coal Pump

Figure 5-4. A Photograph of the -2 Screw Configuration Showing the Mixer Section in Place

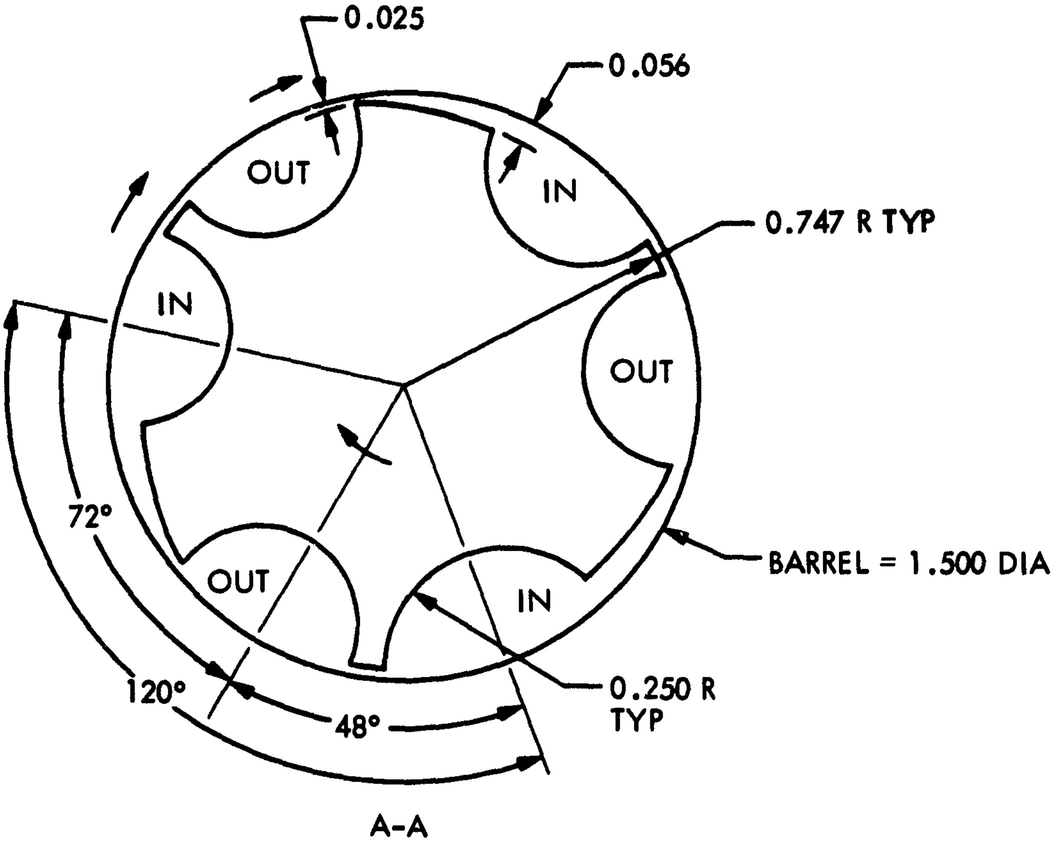


Figure 5-5. A Cross-Section View of the Mixer Section Which is Designed Following the Concepts Discussed by Maddock (Reference 5-3)

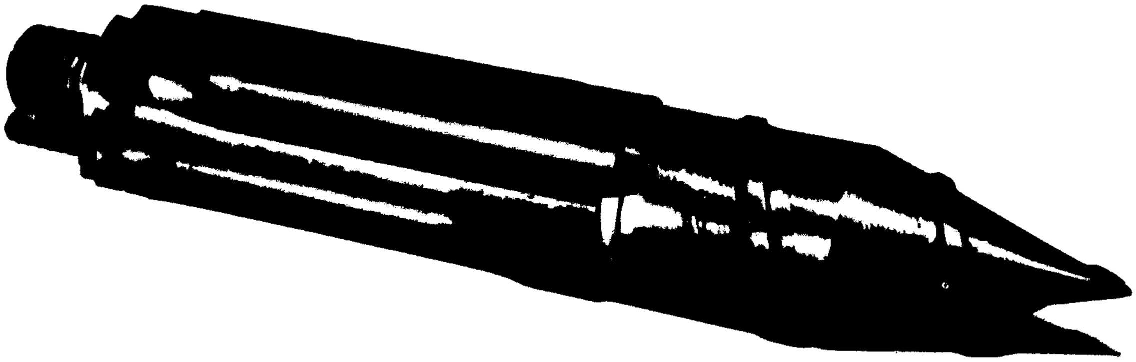


Figure 5-6. A Close-up Photograph of the Mixer Section

Table 5-1. Dimensions of Coal Pump Screws (inch)

Dimension	Drawing No.	
	J10091048-1	J10091048-2
Total length of screw	51.062	51.062
Channel depth feed zone	0.302	0.302
Channel depth-end of compression zone	0.082	0.082
Compression ratio	3.7	3.7
Length to start of mixer section[a]		6.250
Length to end of mixer section[a]		1.750
Length to start of compression[a]	24.250	24.250

[a] Measured from exit end of screw.

In one test, the 40° conical bullet on the end of the screw was replaced by a 40° conical bullet with two narrow clearance collars ringing the circumference. This was termed the -3 configuration. The theory was that melted coal would be pushed through the 0.030-inch clearances and thus be assured of some additional shear and mixing. However, in the -3 configuration's only test there was no evident improvement in smoothing the pressure profile. Subsequent tests with the Maddock mixer section (-2) screw proved so successful that further experiments with the -3 configuration were cancelled.

4. Dies

The various dies and configurations are described in Table 5-2, with a basic die shown in Figure 5-7. Typically the die capillary or orifice is the smallest diameter through which the coal was extruded or sprayed and was placed at the exit end of the die. In the case of the expulsor an adapter was used to connect the extruder and bypass valve which has an inside diameter of 0.189 inch. The orifice, through which the coal was sprayed, was placed in the bypass valve at the entrance to the coal spray receiver.

5. The Receiver/Collector System

This receiver (shown in Figure 5-1) accepts the extrudate from the extruder die or expulsor. Either dry collections of the extrudate may be made or a water quench of the hot extrudate sprays and hot gases can be done. The lower section (55 gal drum) collects all solid and spray samples. It is designed for quick change in collecting samples. The upper plenum chamber section exhausts the hot gases into the incinerator for burning before dissipation into the atmosphere. There are water spray nozzles inside the upper section. In addition, gases and fine particles from the vent port, replacement receiver barrels, and the extruder feed hopper are scavenged off through a series of transvectors (aspirating nozzles) to the furnace, there to be burned.

The high pressure gas heating system consists of a 18 kW Chromalox electric gas heater of stainless steel and Incoloy construction capable of heating gaseous nitrogen to 1000°F at 60 cu ft/min and 600 psi. The hot gases are piped to the injector orifices through thermally insulated and electrically heated conduits.

6. Expulsor

Figure 5-8 is a photograph of the coal pump and expulsor system. The expulsor consists of (1) an adapter which connects the extruder to the expulsor, (2) a bypass valve, (3) coal conditioner, (4) coal spray receiver, (5) extrudate receiver (not shown), and (6) piston actuator. A schematic diagram of these components is shown in Figure 5-9. The manually operated electrically heated bypass valve allows coal to be extruded into the coal conditioner which is also heated. The coal is held in the conditioner for some specified time period (up to 4 min)

Table 5-2. Configuration of Dies Used in 1.5-inch Davis Standard Coal Pump (inch)

Die No.	Run No.	A	B	Die Capillary D	L/D
1	1-7	0.189	6.612	0.189	27
2	8	0.189	1.689	0.073	5
3	9	0.189	3.50	0.073	5
4	10,12	0.073	1.940	0.073	6.02
5	11	0.189	4.612	0.073	6.02
6	13	0.100	2.112	0.100	4.4
7	14,24	0.189	4.612	0.073	5.0
8	15,17	0.189	6.924	0.136	3.7
9	16	0.189	4.612	0.189	16.5
10	18,19,20, 21,22,23	0.129	6.924	0.129	40
11	25	0.189	6.612	0.100	40
12	26,27	0.189	6.924	0.073	6.84
13	31[a]	0.189	6.612	0.030	0.5
14	32-38[a]	0.189	6.612	0.073	0.5
15	39	0.189	6.612	0.189	35

[a] Expulsor runs.

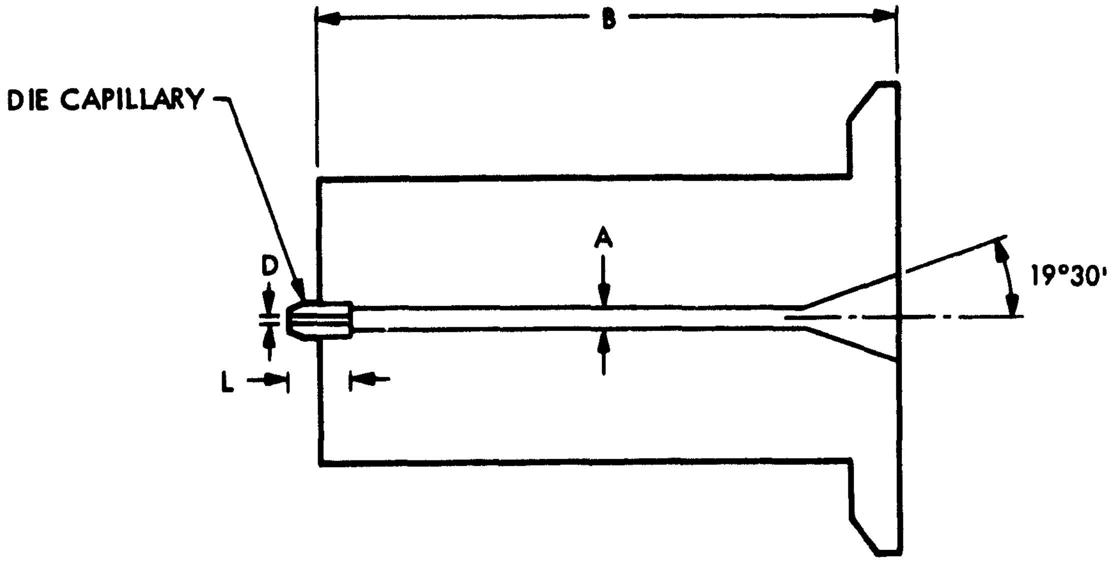


Figure 5-7. A Schematic Diagram of the Injection Die for Dimension Callout

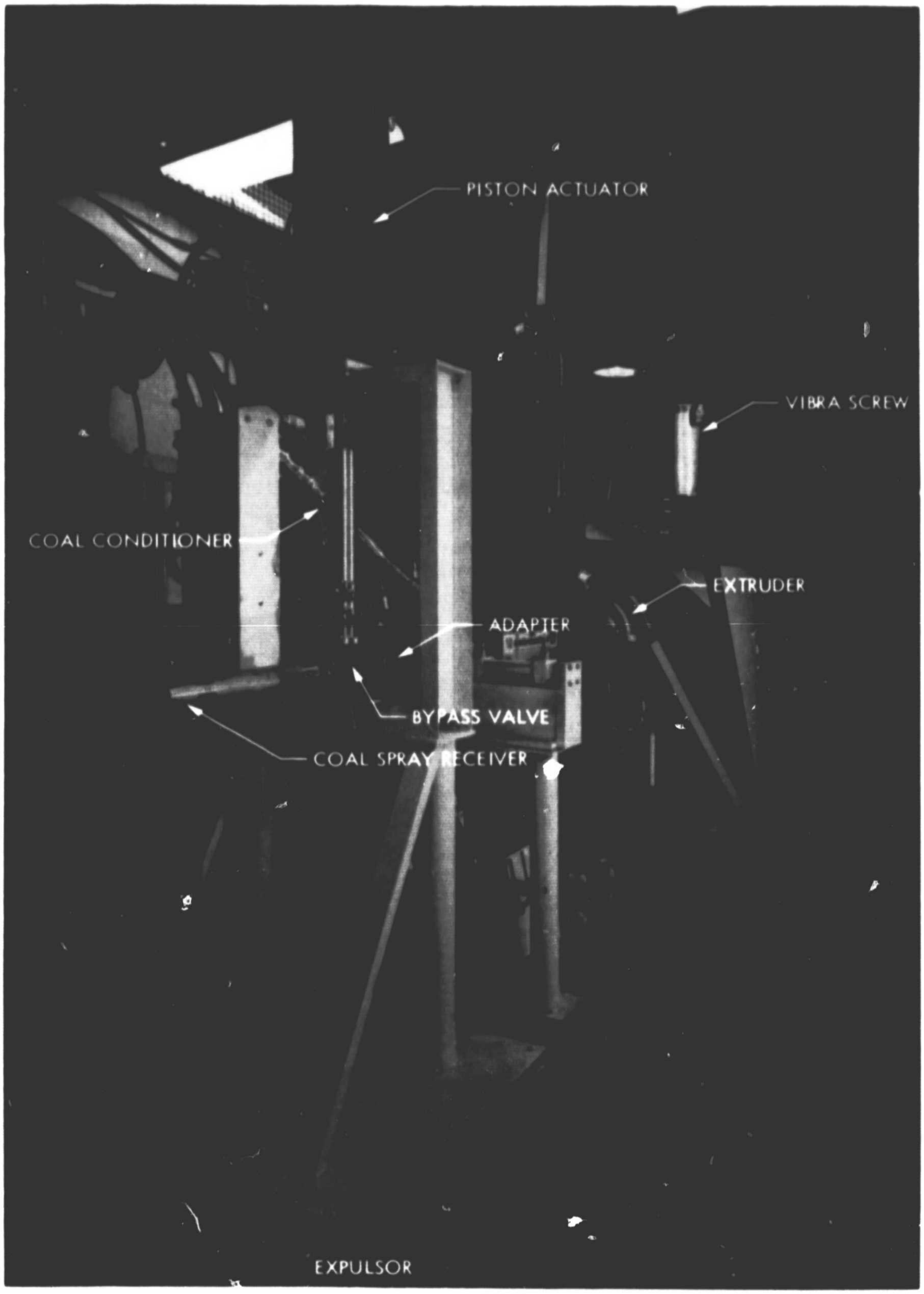


Figure 5-8. A Photograph of the Coal Spray Apparatus in its Expulsor Configuration

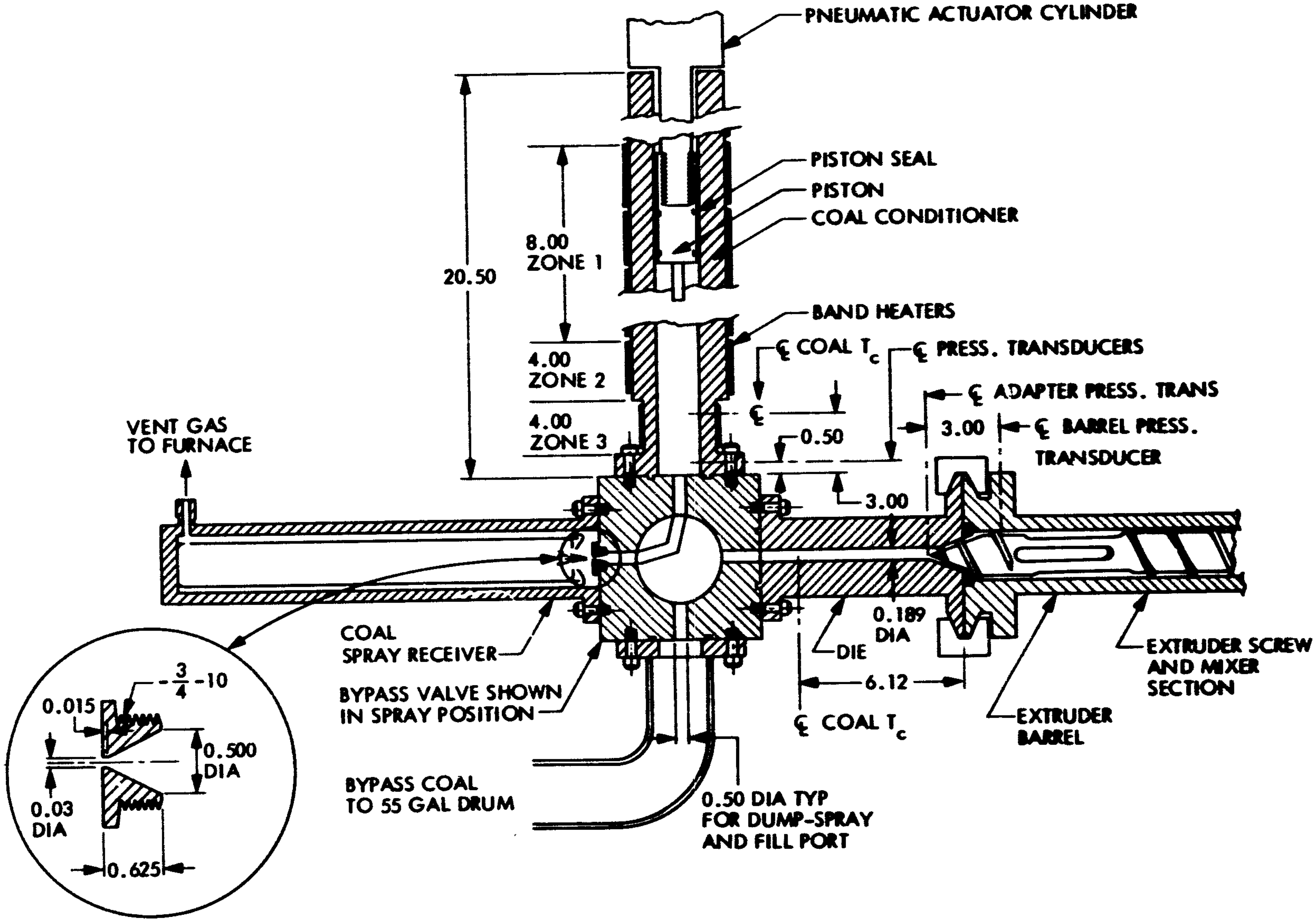


Figure 5-9. A Schematic Diagram of the Expulsor

and later sprayed by a pneumatically actuated piston through a small orifice (see Table 5-2, and the inset diagram in Figure 5-9.) into a coal spray receiver. During the period the coal is being held in the conditioning mode, the bypass valve is switched to the dump position and the coal is extruded into the extrudate receiver in a normal way.

7. Instrumentation

The barrel pressure, die/adapter pressure, coal conditioner pressure, piston actuation pressure, position transducer, motor current, and voltage were continuously recorded on Mosley strip charts. All other parameters were printed out by a Monitor Labs Model 9400 Digital Data System at 30-second intervals. (See Table 5-3.)

Table 5-3. Coal Pump Instrumentation

Parameter	Transducer
Temperature: barrel, die, adapter, clamps, bypass valve, coal conditioner	Chromel-alumel K type closed end thermocouples
Temperature: barrel, die, adapter, coal conditioner	Chromel-alumel K type exposed junction thermocouples
Pressure: barrel, die, adapter, coal conditioner	Strain gage type, water-cooled Gentran transducers
Gaseous nitrogen supply	Tabor pressure transducers with flow control by orifice and valves

8. Sieving

Two systems were used to determine the sprayed coal particle size: dry and wet sieving systems.

In the dry system, coal was sprayed into the receiver while being sprayed with water. This was to prevent damage to the particles through impact with the wall of the receiver barrel and by heat or fire. The collected sample was then removed from the water and dried in an oven. After drying, the coal was mixed and then sieved through screens to determine particle sizes.

In the case of wet sieving, the wet sample was mixed in the receiver to obtain a representative sample. The sample was then wet sieved through a column of screens. Each screen was washed individually using a low velocity stream of water to facilitate movement of coal through the screens and to prevent damage to the particles. The wet sample was then dried in an oven and weighed.

9. Test Operation

A test with the extruder begins by bringing the barrel, clamps, and die up to the required temperatures. For a run with Pittsburgh No. 8 coal, the required barrel temperatures are as follows: Zone 1, 500°F; Zone 2, 650°F; Zone 3, 820°F; and Zone 4, 850°F. The clamps temperature is at 650°F, the die at 850°F, and the barrel vent port at 400°F. The time generally required to reach operating temperatures is about 30 minutes. At this time if the test was to extrude coal, the Vibra screw is started at the desired feed rate and the vibrating-trough heaters are turned on to provide a coal temperature of approximately 350°F at the coal pump feed port.

During this time the pressure transducers are calibrated and a final check of the instrumentation is made. If all temperatures are correct, the extruder rpms are brought up and the Vibra screw is pushed into the extruder feed hopper. Within 45 seconds coal is extruded.

In the case of coal spraying, hot gaseous nitrogen (GN_2) is used and the operating sequence is as follows: (1) bring the extruder and injector up to temperature; (2) turn on GN_2 at required flow rate and set GN_2 bypass valves; (3) turn on electrical power to GN_2 heater when the gas temperature comes up to the required temperature (approximately 700°F); (4) turn on the Vibra screw along with its heaters; (5) check the instrumentation along with the temperatures and pressure; (6) position the Vibra screw (after reaching the required temperature of 350°F) over the feed port while the extruder rpms are being brought up, and (7) start the run.

For tests with the expulsor, the sequence is as follows: (1) set extruder temperatures as in an extrusion run; (2) set adapter, bypass valve, and all coal conditioner temperatures to 850°F, in this case the time required to reach operating temperature will be about 1 hour; (3) turn on the Vibra screw along with its electrical heaters when the set temperatures have been achieved ; (4) move at this time the expulsor actuation piston to the down position, put the bypass valve in the dump position, bring up the extruder to 120 rpm, and position the Vibra screw over the feed port. In 45 seconds coal will be extruding. After the extruder reaches steady state (approximately 15 minutes), the bypass valve is moved to the fill position. Pressure is applied to the top of the piston, and the piston movement is monitored. When the coal conditioner is full, the bypass valve is moved to the dump position and the coal is held in the conditioner for some specified period. At the end of this period the bypass valve is moved to the spray position, the piston is actuated, and the coal is sprayed into the receiver. On completion of the spray cycle, the bypass valve is moved to the fill position to start another cycle.

10. Coal

Pittsburgh No. 8 coal supplied by the Morgantown Energy Technology Center was used for this study. The characteristics of this coal were determined by W. G. Lloyd (Reference 3-4). The data are shown in Table 5-4.

Table 5-4. Characteristics of Pittsburgh No. 8 Coal (Sample #789352)

	Basis		
Property	As Received	Moisture Free	Moisture and Ash Free
Moisture %	0.25	---	---
Ash %	8.08	8.10	---
Volatile matter %	39.61	39.71	43.21
Fixed carbon %	52.06	52.19	56.79
Carbon %	77.17	77.36	84.18
Hydrogen %	5.16	5.14	5.59
Nitrogen %	0.97	0.97	1.06
Sulfur %	2.36	2.36	2.56
Oxygen (by difference) %	6.26	6.06	6.59
Forms of Sulfur			
Pyritic %	0.81	0.81	0.88
Sulfate %	0.02	0.02	0.02
Organic (by difference) %	1.53	1.53	1.66
Gieseler Plastometry			
Softening temperature	403°C		
Maximum fluidity temperature	423°C		
Solidification temperature	382°C		
Maximum fluidity	15,576 ddpm		
Low Temperature Ashing Analysis %		10.14	
SiO_2	51.8		
Al_2O_3	25.9		
Fe_2O_3	14.4		
TiO_2	2.59		
P_2O_5	0.49		
CaO	3.16		
MgO	0.82		
Na_2O	1.19		
K_2O	1.28		
SO_3	4.17		

This coal is used in the bulk of the experiments reported herein. It is essentially the same as the previous batch of Pittsburgh No. 8 reported in References 3-1 and 3-2, as far as proximate and ultimate analysis. However, the fluidity as measured by the Gieseler plastometer is substantially less than that reported previously. The comparison is shown in Table 5-5. The new batch is still a highly fluid coal.

Table 5-5 Comparison of Pittsburgh No. 8 Coals

	Pittsburgh #8 (Phases I and II)	Pittsburgh #8 (this report)
Softening temperature	372°C	403°C
Maximum fluidity	>> 25,000 ddpm	15,600 ddpm
Solidification temperature	483°C	485°C
Plastic temperature range	111°C	82°C

D. TEST RESULTS

1. Run Summary

A summary of all test runs on the coal spray apparatus is given in Table 5-6. There were 39 tests with coal extrusion conducted over a period of 14 months of which 25 runs ended in voluntary terminations. Six of the involuntary terminations occurred during a run series to determine the smallest orifice size for continuous low pressure drop flow. Three out of the four runs with Kentucky No. 9 and No. 11 coals ended involuntarily. There were two cases of involuntary termination which occurred when a recessed coaxial injector configuration was being tested. These cases will be discussed later. In all, there was a total of 32 hours of run time accumulated on the 1.5-inch Davis Standard coal pump. The performance of the coal pump with Pittsburgh No. 8 coal was reliable.

2. Orifice Flow Tests

The pressure rise attainable by a single screw drag pump is determined by a balance of the mass rate of coal melted by viscous dissipation of heat, by the pumping action of viscous drag of the rotating screw acting on the molten coal, and by the pressure drop occurring in the discharge through the injector orifice (or die). The theoretical relations were discussed in the Phase I report (Reference 3-1). In a

Table 5-6. Coal Pump Applications Laboratory Run Summary

Summary of Test Runs Conducted on the 1.5-Inch Coal Pump (Davis-Standard)
Test Period February 2, 1979, to June 6, 1980

Run No.	Date	Test Objective	Screw Conf. No.	Die Conf. No.	Expulsor Conf. No.	Coal Type	State Wet Dry/Mesh/T°F	Gas Type
1	2-23-79	Shakedown	-1	1	-	Pitt #8	Dry 6/40/294	--
2	3-5-79	Shakedown	-1	1	-	"	" /282	--
3	3-15-79	Shakedown	-1	1	-	"	" /349	--
4	4-17-79	4-on-1 injector .020" x .189"	-1	1	-	"	" /350	N_2
5	5-1-79	4-on-1 injector .073" x .189"	-1	1	-	"	" /350	N_2
6	5-2-79	4-on-1 injector .073" x .189"	-1	1	-	"	" /350	N_2
7	5-7-79	4-on-1 injector start w/out cleaning screw	-1	1	-	"	" /350	N_2
8	5-15-79	Smallest orifice determination .073"	-1	2	-	"	" /350	--
9	5-22-79	" " .073"	-1	3	-	"	" /350	--
10	6-6-79	" " .073"	-1	4	-	"	" /350	--
11	6-17-79	" higher die temp .073"	-1	5	-	"	" /70	--
12	6-19-79	" " .073"	-1	4	-	"	" /70	--
13	6-21-79	" " .100"	-1	6	-	"	" /70	--
14	6-26-79	" change orifice diaphram	-1	7	-	"	" /70	--
15	7-2-79	Coaxial injector 1 L/D recess	-1	8	-	"	" /350	N_2
16	7-17-79	Ky coal	-1	9	-	Ky #9	Dry 6/40/64	--
17	7-26-79	Ky coal 4 on 1 w/nipple	-1	8	-	Ky #9	" /64	N_2
18	8-9-79	Spray size Coaxial flush	-1	10	-	Pitt #8	" /344	N_2
19	8-23-79	Spray size Coaxial flush	-1	10	-	"	" /350	N_2
20	9-13-79	Spray size Coaxial mixing bullet	-1	10	-	"	" /354	N_2
21	10-13-79	Movies for PIO	-1	10	-	"	" /354	N_2
22	10-25-79	Coaxial injector-mixing section	-2	10	-	"	" /350	N_2
23	11-6-79	Duplicate run #22	-2	10	-	"	" /350	N_2
24	11-28-79	.073" (run #8)	-2	7	-	"	" /350	--
25	12-12-79	Viscometer run 0.1 x 4"	-2	11	-	"	" /350	--
26	1-15-80	Spray coaxial (run #24)	-2	12	-	"	" /350	N_2
27	1-23-80	Coaxial injector 1 2/0 recess	-2	12	-	"	" /350	N_2
28		No run						
29	2-20-80	Expulsor shakedown	-2	--	91412	---	------	--
30	3-12-80	Expulsor valve test	-2	--	91412	"	" /350	--
31	3-27-80	Expulsor test .030"	-2	13	91412	"	" /350	--
32	4-3-80	Expulsor test .073"	-2	14	91412	"	" /350	--
33	4-9-80	Expulsor test .073"	-2	14	91412	"	" /350	--
34	4-24-80	Expulsor test .073"	-2	14	91412	"	" /350	--
35	5-5-80	Expulsor test .073"	-2	14	91412	"	" /350	--
36	5-16-80	Viscosity run	-2	14	91412	"	" /350	--
37	5-21-80	Viscosity run	-2	14	91412	"	" /350	--
38	6-4-80	Ky #11	-2	14	-	Ky #11	Wet 6/40/350	--
39	6-5-80	Ky #11	-2	15	-	KY #11	Dry	--

Table 5-6. Coal Pump Applications Laboratory Run Summary (Continuation 1)

Summary of Test Runs Conducted on the 1.5-Inch Coal Pump (Davis-Standard)
Test Period February 2, 1979, to June 6, 1980

Run No.	Dur. Min.	Mode of Termination	Extrudate Collection Mode	Post Run Tests	Comments
1	23	Voluntary	Dry		
2	184	Voluntary	Dry		
3	55	Voluntary lost P_B	Dry		Movie by PIO, stop/start
4	97	Voluntary	Dry		Movie high speed
5		No extrudate	---		
6	77	Voluntary	Wet sample	Sieving data	Movie high speed
7	15	Voluntary	---		Lost P_B
8	10	Over-torque	---		Coal came out vent port
9	2	Bolt failure on die	---		Need welded die plate
10	6	Over-torque	---	Coal in screw exam	Bad speed controller
11	3	High barrel pressure	---	Coal in screw exam	
12	1	No extrusion	---		
13	45	Voluntary	---		Video tape
14	10	Plugged orifice	---		
15	20	High barrel pressure	No extrusion		Coal in gas manifold
16	43	Voluntary	LN_2 collection	IMMR sample	Coal shipped to IMMR
17	13	Stopped extruding	LN_2 collection	"	"
18	50	Voluntary	Water spray	Dried & sieved	
19	144	Voluntary	Water spray	"	
20	30	Voluntary	Water spray	"	Mixing bullet not effective
21	120	Voluntary	---	---	
22	110	Voluntary	Water spray	Dried & sieved	High speed movie 4000 fps
23	160	Voluntary	Water spray	"	" (stop/start)
24	135	Voluntary	---	---	Long run to ck plugging
25	250	Voluntary	---	---	Screw and barrel bent during cooling
26	64	Voluntary	Water spray	Wet sieve	
27	23	High barrel pressure	---	---	Mixer section stripped screw coal in gas manifold
28				---	
29		--------		---	Run w/no flow
30	17	Voluntary		---	Valve rotation checkout
31	17	Voluntary	Collector	---	One cycle no spray
32	23	Voluntary	"	---	Two tests
33	31	Voluntary	Atmosphere	---	Movies at 4000 fps
34	15	Voluntary	"	---	One cycle
35	35	Voluntary	"	---	
36	31	Voluntary	No spray	---	Lost O-ring
37	30	Voluntary		---	One data point
38	0	Jammed	Dry sample	---	
39	17	Jammed	"	---	Started w/Pitt #8, screw stripped mixer section threads

metered (or starved) feed mode of operation, the controlling pressure increment occurs in combinations of the solid transport section, the melting section, and the pumping (or metering) section of the screw. Theoretically, if a high pressure drop die is installed in the flow circuit the combined pressure rise capabilities of the solid feed, the melting, and the metering sections of the screw should provide balancing pressure rise capability. For a metered (or starved) mode of feeding, which was used at all times, the length of the solid compaction region should vary to accommodate the pressure rise demand. This mode seemed to be excessively sensitive to upsets when the discharge orifice diameter was too small. Therefore, tests were conducted to determine if there was a minimum die diameter for steady flow.

Flow tests without simultaneous gas flows were conducted to determine the smallest orifice size that can accommodate continuous plastic coal flow using -6/+40 mesh Pittsburgh No. 8 coal. An orifice diameter of 0.073 inch proved susceptible to flow blockage and intermittent plugging. An orifice diameter of 0.100 inch did not plug for a one-hour run. These tests were run using the standard screw configuration.

In a later run with a mixing section installed in the screw (-2 screw configuration), more homogeneous mixing of the plastic state coal was obtained. Evidence of this was observed when the 0.073-inch orifice was tested with the mixing section in the screw. There was no flow blockage and the barrel pressure trace was smooth, showing much less evidence of unmelted clumps.

It should be possible to obtain continuous flow through orifices even smaller than 0.073 inch. The momentary blocking of the orifice by an inclusion slows the flow rate, thereby forcing a pressure build up in the solids transport segment of the screw. However, for some types of interaction of solid friction coefficients and drag forces, this feedback to create high pressure does not proceed smoothly through transients. It is believed that a pumping section which acts on already melted (or plasticized) coal, rather than on the solid particle transport section, would be stable. A gear pump, for example, between the melting section and the die would probably solve the problem. A twin-screw co-rotating extruder should also not have this type of difficulty.

3. 4-on-1 Injector Tests

The configuration of four gas jets impinging on a single axially directed liquid jet has been investigated for use in developing a low pressure drop coal atomizing injector. The gas used in the experiments was heated nitrogen.

In Run 4, the gas jet diameter was 0.020 inch and the center jet diameter was 0.189 inch. The gas temperatures ranged between 340° to 390°F. This run showed the gas jet had too high a dynamic pressure for the coal stream. The linear velocity of the coal stream was about 0.2 to 0.4 ft/sec, hence the coal was deflected around the gas jet's impingement point. In Runs 5 and 6, the gas jet diameter was increased to

0.073 inch. Atomization of the coal stream was obtained. The coal spray particles were about 1/4 to 3/8-inch long. The injector configuration is depicted as Figure 8-3 of Reference 3-2 and a sample of the collected coal is shown as Figure 8-4 of Reference 3-2.

Elverum and Morey (Reference 5-4) reported on an empirical criterion for obtaining uniform mixing in the spray of a 4-on-1 injector when all streams are liquid. This is expressed as

$$(W_4/W_1)^2 = 2.75\ (\rho_4/\rho_1)\ (A_4/A_1)^{1.25} \tag{5-1}$$

In the case of four liquid jets impinging on a central gas jet, Mehegan, et al (Reference 5-5), derive an equation which predicts the penetration depth, X_p, of the impinging stream on a central gas jet of diameter D_1. This is given by

$$(W_4/W_1)^2 = (0.64/\cos^2\theta)\ (X_p/D_1)^2\ (\rho_4/\rho_1)\ (A_4/A_1) \tag{5-2}$$

In these equations, W_1 and W_4 are the total mass flows in the central and impinging jets respectively, A_1 and A_4 are the total flow areas in the central and impinging jets, ρ_1 and ρ_4 are density of the fluids, and θ is the angle between the impinging jet and the center jet axes. For the jet diameters of interest, an impingement penetration distance of about $X_p/D_1 = 1.0$ would yield the same numerical results for both Equations 5-1 and 5-2. If these results are extrapolated to the present case of 4-gas jets on 1-liquid jet illustrated in Figure 5-2 , it would be concluded that the penetration is excessive and poor atomization would result. These conclusions are in fact supported by the tests. Unfortunately, the limiting flow rates and minimum orifice sizes prevented use of the optimum sizes.

The configuration of four jets of high velocity gas impinging on a central slow moving liquid jet is in fact a poor atomizing injector. It is not possible in this configuration to reverse the gas and liquid jets because of the limitation on these diameters. The coaxial jet configuration was used instead.

4. Mixing Section Results

The mixing section in the screw is based on a design described by Maddock (Reference 5-3). The purpose of the mixing section is to complete the melting process which starts in the feed compression and metering section (see Figure 5-3), by mixing the last remnant of unmelted coal with molten product. When the Maddock mixing section is inserted in the screw, a drastic reduction in the barrel pressure fluctuation resulted. The "before" and "after" pressure traces are shown in Figure 5-10. Long-term drift of the barrel pressure measurements were still observed however.

The flow through a Maddock mixing section can be analyzed using the theory of drag flow (Reference 5-6). The cross section of the mixing section is depicted in Figure 5-5. A schematic version for the purpose of this analysis is shown in Figure 5-11. The partially molten

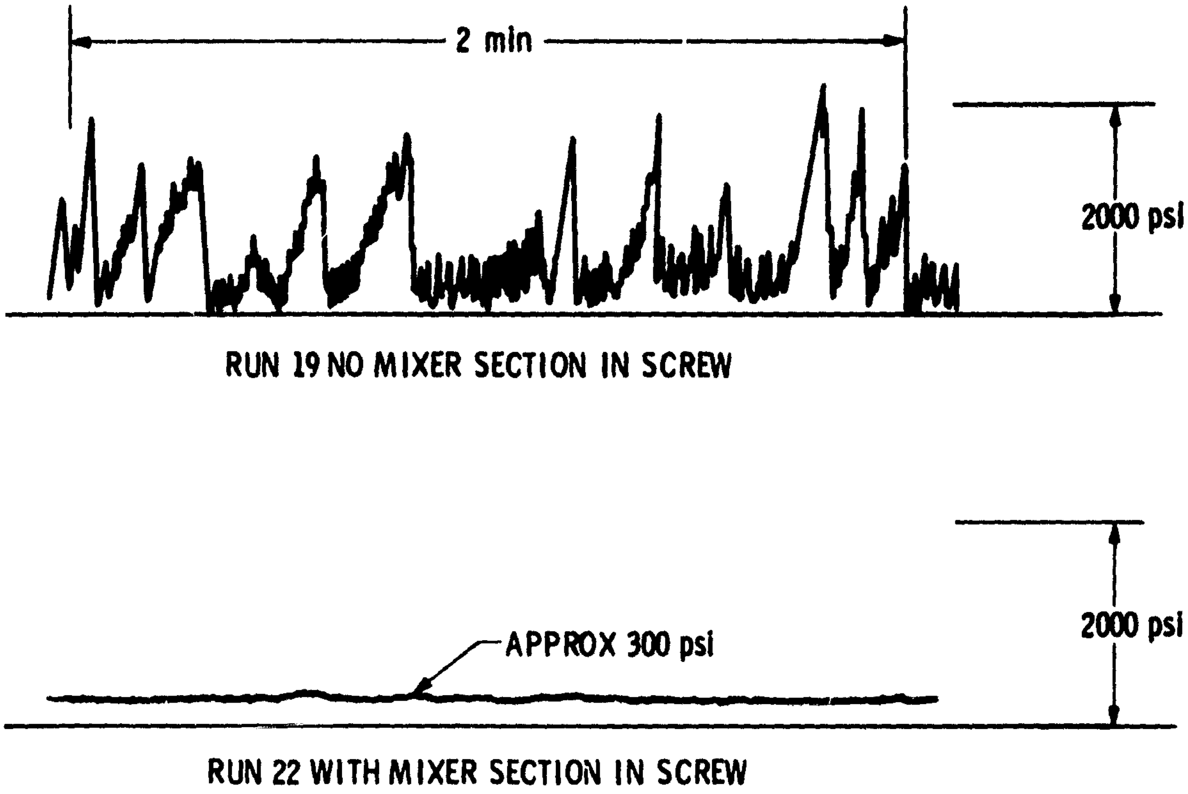


Figure 5-10. Effect of the Maddock Mixing Section (-2 configuration) on Barrel Pressure Fluctuations

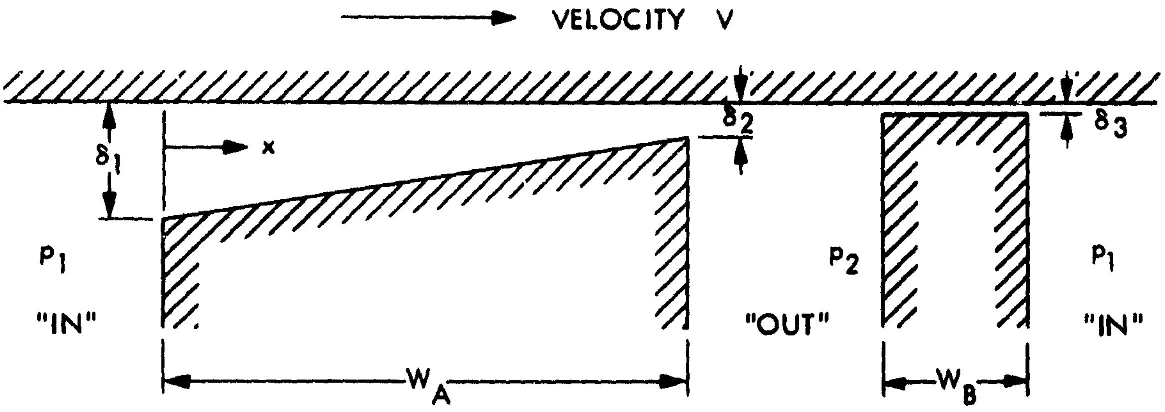


Figure 5-11. Diagram of Flow Configuration Used in the Analysis of the Pressure Rise Characteristic of the Maddock Mixing Section

coal flows into the section through the "in" groove, and is forced through a tapered slot into the "out" groove. There is also a non-tapered slot between the "out" groove and the "in" groove. This slot opening height is very small compared to the height of the tapered slot; hence less coal flows through it. In Figure 5-11, the convention is adopted that the screw is stationary and the barrel surface (i.e., the upper plane surface depicted in Figure 5-11) translates in its own plane at a velocity V. This distortion is defensible since the convective terms (including the centrifugal term) are negligibly small in the Navier-Stokes equation compared to the viscous flow terms. For the case of Newtonian viscosity μ and constant density, the laminar flow equation for low speed drag flow is simplified to:

$$\frac{dp}{dx} = \mu \frac{\partial^2 u}{\partial y^2} \tag{5-3}$$

where u is longitudinal flow velocity. The pressure p is constant across the slot height, but varies along the length. Integrating this equation and combining with the equation for mass conservation, an expression for the pressure rise between the "in" and "out" grooves in mixing section is obtained. This equation is:

$$p_2 - p_1 = \frac{[(\delta_m/2 - \delta_3/2)\, V - G]}{[\delta_1 \delta_2 \delta_m/(12\mu_A W_A) + \delta_3^3/(12\mu_B W_B)]} \tag{5-4}$$

where we have defined the mean slot height δ_m as:

$$\delta_m = 2/(1/\delta_1 + 1/\delta_2), \tag{5-5}$$

μ_A and μ_B are the viscosity of the fluid in slot A and slot B, and G is the net volumetric flow rate per unit groove length.

For conditions encountered in a typical mixing section, the pressure p_2 is higher than p_1 indicating that the mixing section is acting as a pump albeit an inefficient one. A plot of pressure rise as a function of mass flow is shown in Figure 5-12. The viscosity function is the same as that used in the computer model of Reference 3-1. Higher viscosity at lower temperature causes higher pressure rise. Increasing the mass flow rate through the mixing section decreases the pressure rise slightly. The magnitude of the pressure rise is relatively small, compared to other pressure sensitive mechanisms discussed in Reference 3-1.

Wear on the mixing section observed after about 16 hours of operation proved quite low. Weight loss was not measurable to a precision of 0.2 grams indicating a wear rate of less than 3 lbm metal lost per 10^6 lbm of coal flowing.

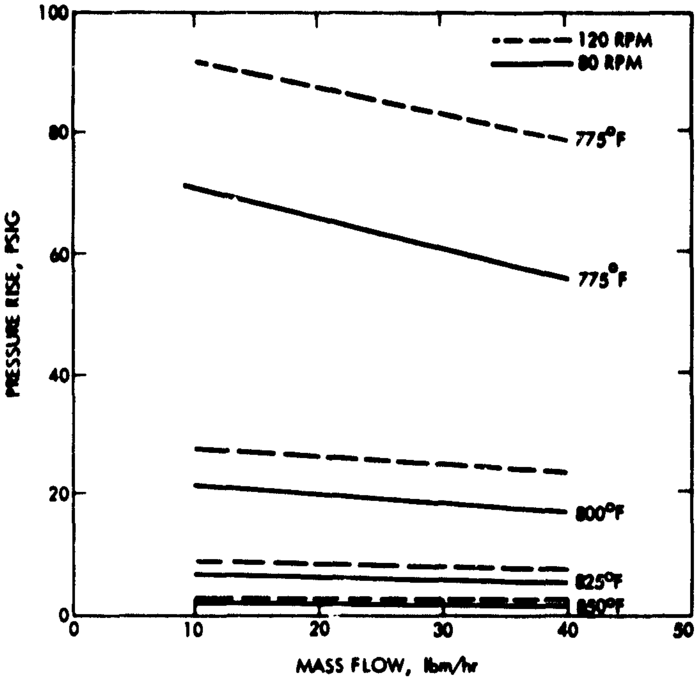


Figure 5-12. Pressure Rise Through a Maddock Mixing Section: density 60 lbm/ft^3, viscosity μ lbm/in-sec, μ = exp (34.10 - 0.428 ln (γ - 0.0477 t) where γ = $|du/dy| sec^{-1}$, t - temperature °F

5. Coaxial Injector

The design of the coaxial injector has been depicted (see Figure 5-2). Hot nitrogen gas is used as the atomizing gas in all runs. Continuous sprays of plastic state coal were obtained and a series of runs were made in an attempt to develop correlations.

A summary of spray runs with the coaxial injector is given in Table 5-7. It presents all results obtained with a coal flow rate of 18 lbm per hour, and a screw speed of 120 RPM. The last three lines of the table summarize the particle sieve data by presenting the cumulative mass present of particles retained on a given sieve. It may be seen that from 17 to 53% of the mass of the particles are retained on a 10 mesh (2 mm) sieve. Run 19 is with a standard screw, Run 20 is with a mixing bullet, and Runs 22 and 23 are with the mixing section. As seen by comparing the data for +10 mesh, there is a size decrease in going to a mixing screw. However, replicate runs, Runs 22 and 23, did not verify the results, showing that some variability existed run to run.

Table 5-7. Summary of Coal Spray Runs

Run No.	19-1	19-2	20-1	22-1	22-2	23-1	23-2
Coal, lbm/hr	18	18	18	18	18	18	18
Gas, lbm/hr	31	45	32	36	47	33	45
Gas Temperature, °F	597	617	587	543	581	565	565
Die Temperature, °F	865	865	852	776	801	810	810
Zone 4 Temperature, °F	806	806	801	831	810	823	823
N, RPM	120	120	120	120	120	120	120
Screw Configuration, #	-1	-1	-1	-2	-2	-2	-2
Net Shaft Specific Power, hp-hr/lbm	.045	.038	.048	.034	.034	.061	.051
Barrel Pressure, psi	---	---	---	300	200	400	420
Mass greater than:							
+50 mesh, %	92	93	89	91	82	95	94
+30 mesh, %	85	86	83	78	83	90	88
+10 mesh, %	45	51	52	22	25	45	49

Table 5-7. Summary of Coal Spray Runs (Continuation 1)

Run No.	19-3	19-4	22-3	22-4	23-3
Coal, lbm/hr	10	10	10	10	35
Gas, lbm/hr	31	32	35	36	45
Gas Temperature, °F	591	537	548	539	559
Die Temperature, °F	865	750	814	750	810
Zone 4 Temperature, °F	806	776	814	823	823
N, RPM	80	80	80	80	120
Screw Configuration, #	-1	-1	-2	-2	-2
Net Shaft Specific Power, hp-hr/lbm	---	.047	---	.028	.036
Barrel Pressure, psi	---	---	200	400	650
Mass Greater than:					
+50 mesh, %	93	91	87	94	92
+30 mesh, %	88	84	77	89	86
+10 mesh, %	53	43	17	46	39

These data are presented in Figures 5-13 to 5-17. Increasing the gas mass flow did not cause a significant change in the particle size. Probably the most significant aspect of these spray measurments is that the particle size distribution is relatively independent of the changes in conditions. Inherent variability from run to run, and from time to time, due to unknown causes have more of an effect than the controlled parameters.

In an effort to obtain a more representative coal spray sample, the collection technique was changed to collect all the spray for a shorter time. It was not possible, however, to sieve all the spray coal collected in even a short interval as 5 minutes, using either the wet or the

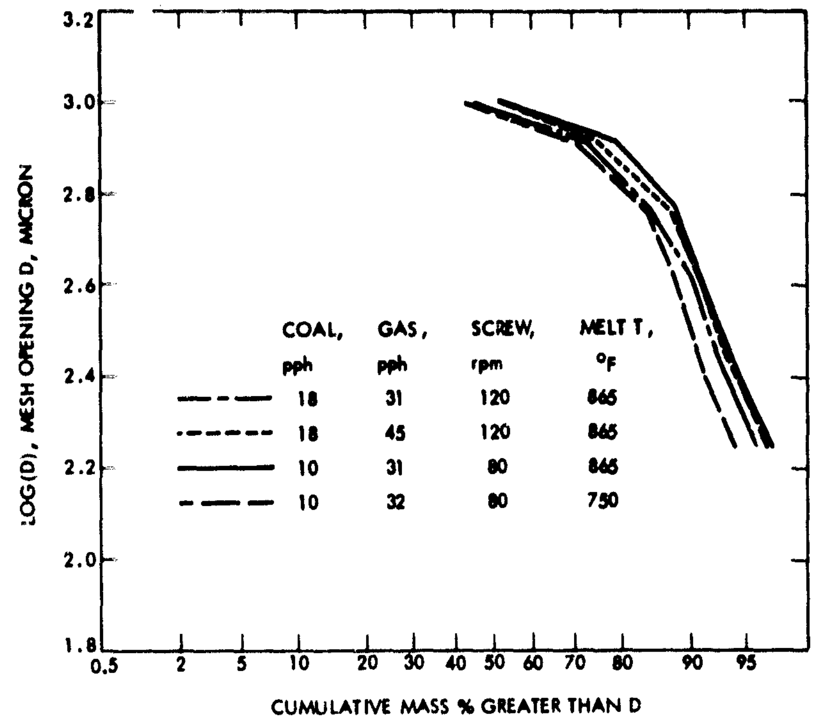


Figure 5-13. Coal Spray Particle Size Distribution for Run 19 (dry sieve method) Standard (-1) Screw Configuration

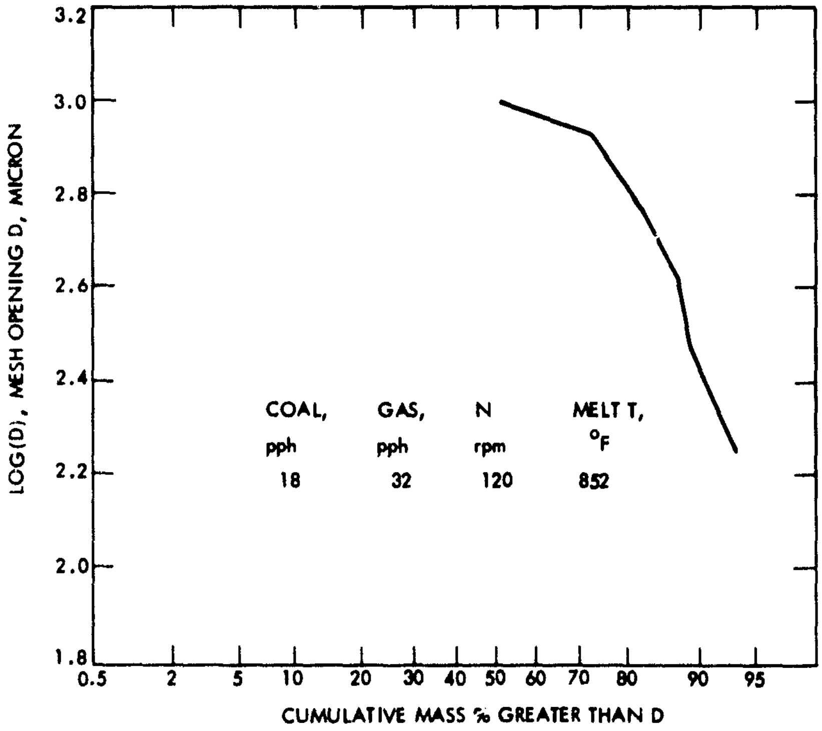


Figure 5-14. Coal Spray Particle Size Distribution for Run 20 (dry sieve method) Mixing Bullet (-3) Screw Configuration

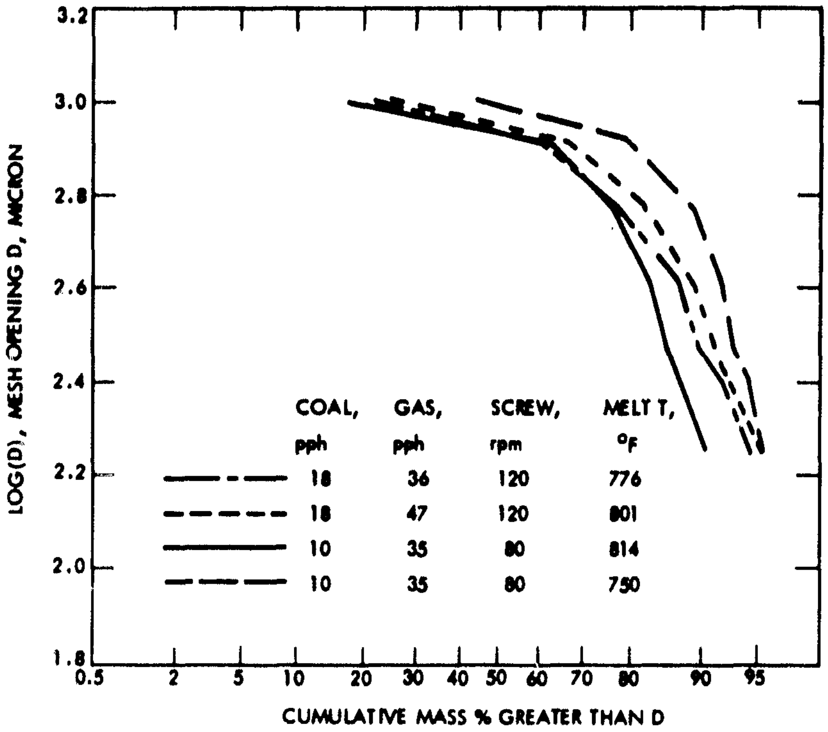


Figure 5-15. Coal Spray Particle Size Distribution for Run 22 (dry sieve method) Mixing Section (-2) Screw Configuration

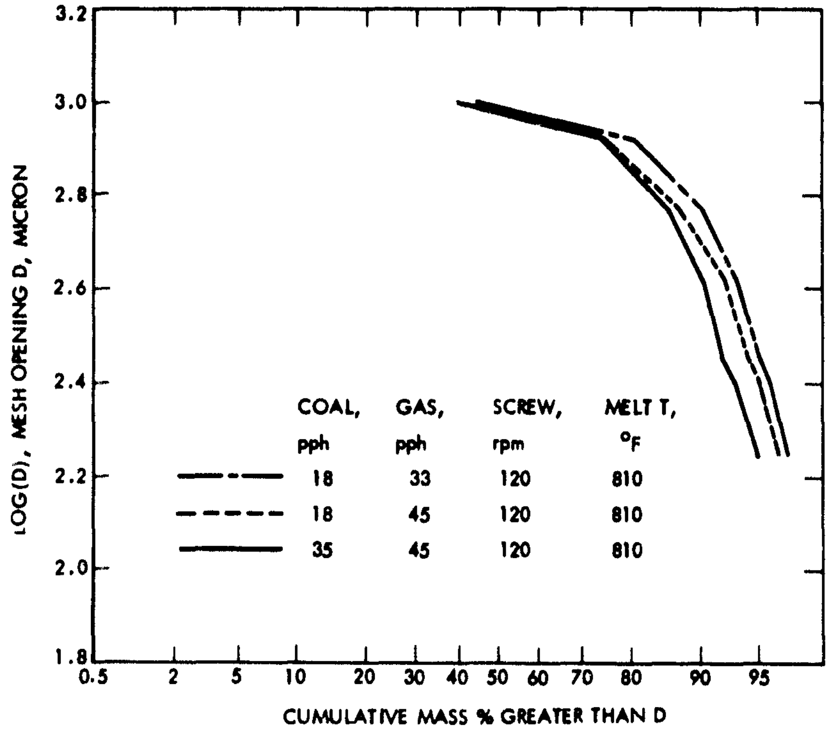


Figure 5-16. Coal Spray Particle Size Distribution for Run 23 (dry sieve method) Mixing Section (-2) Screw Configuration

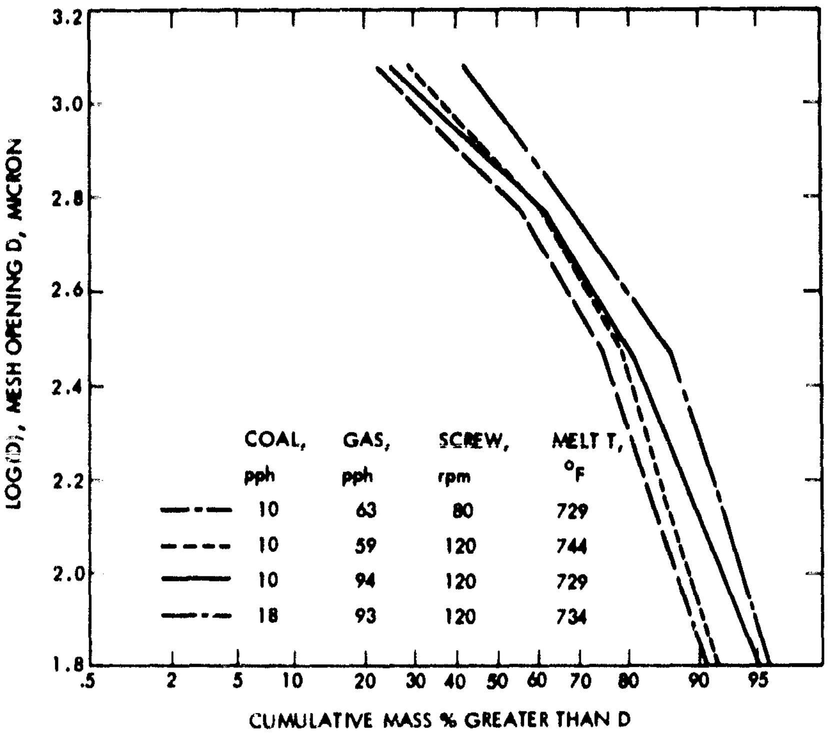


Figure 5-17. Coal Spray Particle Size Distribution for Run 26 (wet sieve method) Mixing Section (-2) Screw Configuration

dry technique. The wet sieve technique was developed to get a more complete accounting of smaller particles. It was not used extensively with the coaxial spray; hence, the data are not reported.

6. Spray Theory

Several empirical correlations of spray size for the concentric jet or air blast atomizer have been proposed. One of the earliest and still one of the best documented correlations is that given by Nukiyama and Tanasawa (Reference 5-7) which is

$$S_{MD} = 5.85\ \sigma^{0.5}\ v_r^{-1} \rho_\ell^{-0.5} + .0597\ (\mu_\ell (\rho_\ell \sigma)^{-0.5})^{0.45}\ (1000\ Q_\ell/Q_a)^{1.5} \qquad (5\text{-}6)$$

where S_{MD} is the Sauter mean diameter (volume-number mean) in centimeters, σ is the surface tension in dyne/cm, v_r is the relative velocity in cm/s, ρ_ℓ is the liquid density in g/cm^3, μ_ℓ is the liquid viscosity in g-s/cm^2 (or poise) and Q_ℓ/Q_a is the ratio of liquid to gas volumetric flow rate. Kim and Marshall (Reference 5-8) and Lorenzetto and Lefebvre (Reference 5-9) have presented similar correlations. The three correlations are quite similar, in that all express the mean drop size correlation as the sum of two terms. One term is dominated by the reciprocal relative velocity of the gas compared to the liquid velocity and the other term is dominated by the ratio of liquid to gas flow. The liquid viscosities used in these experiments were all in the range of 0.01 to 1.0 poise whereas plastic state coal has a viscosity range of about 100 poise and higher. Nevertheless, theoretical drop sizes are computed using the following data (corresponding to Run 22-1):

ρ_ℓ	1.2 g/cm^3
σ	30 dyne/cm (similar to heavy hydrocarbon)
ρ_a	0.6×10^{-3} g/cm^3
v_r	470 m/s (sonic velocity in N_2)
W_a/W_ℓ	1.91 (mass flow of air to mass flow of liquid ratio)
D_ℓ	3.3 mm (diameter of the liquid jet orifice)
μ_ℓ	100 poise

The Nukiyama-Tanasawa correlation gave 271 microns. The Kim-Marshall correlation gave 230 microns and the Lorenzetto-Lefebvre correlation gave 25,000 microns as the estimated drop sizes. It should be pointed out that in the last referenced correlation, very viscous fluids were better correlated by the Nukiyama-Tanesawa relation than by their own proposed correlation. The observed mean drop size is about 1500 microns. This is considered reasonable correspondence considering the gross uncertainties in effective viscosity and the gross extrapolation of the correlation equations. The conclusion drawn from these tests and correlations was that it would be impossible to achieve very fine droplet formation from plastic coal using the gas-liquid atomizing technique.

7. Viscosity Correlations

Run 25 was set aside to obtain data on the effective viscosity of extruded coal using the coal pump. The die configuration No. 11 of Table 5-2 was used. This was basically a capillary of 0.1-inch diameter and 4-inch length.

The apparent viscosity computed from the measured pressure drop and the known mass flow are shown in Figure 5-17 as a function of the die melt temperature. The data are presented for various coal feed rates and screw speeds. It is apparent that aside from falling within a broad range from 10 to 100 poise, there is no apparent correlation with any of these variables.

As a basis of comparison, coal viscosity data obtained in earlier work (Reference 3-2) are plotted on Figure 5-18. Those data are strongly time dependent so only the lowest viscosities measured are presented in Figure 5-18, and are joined by a dashed line. The apparent viscosities observed in the coal pump are within the same range as that observed in the laboratory viscometer, but these values were obtained at lower temperatures.

We conclude that the gross variations in the properties of the feed coal and the unsteadiness of the flow process in the screw extruder prevent a rational correlation of the viscosity data. It is clear that the viscosity is adequately low.

8. Power Correlation

The net shaft specific power expended by the coal pump in plasticating coal extrusion is defined as:

$$\text{Net shaft specific power} = \frac{(\text{total shaft power}) - (\text{no load shaft power})}{(\text{mass flow rate})} \qquad (5\text{-}7)$$

We have measured but not reported the heating load power because most of the runs were too short to get a good baseline for averaging the data. The data obtained during coal spray runs are reported as part of Table 5-7. Each specific power data point is an average of at least five readings obtained over a period of 30 minutes.

The net specific shaft power ranged from 0.028 to 0.061 hp-hr/lbm with an average of about 0.04 hp-hr/lbm. This is substantially lower than the values of about 0.08 to 0.10 hp-hr/lbm reported previously for the old Centerline Machine Co. 1.5-inch coal pump (Reference 3-2). It is about equal to the results of 2.5-inch coal pump running at its rated mass flow with the standard 3:1 compression screw (Reference 3-1, Figure 5-15).

The theoretical power consumption if all the shaft power were to be converted into thermal energy within the coal is 211 Btu/lbm or about 0.083 hp-hr/lbm. The conclusion is that in the 1.5-inch coal pump about half the energy required for plastication comes from the heaters and

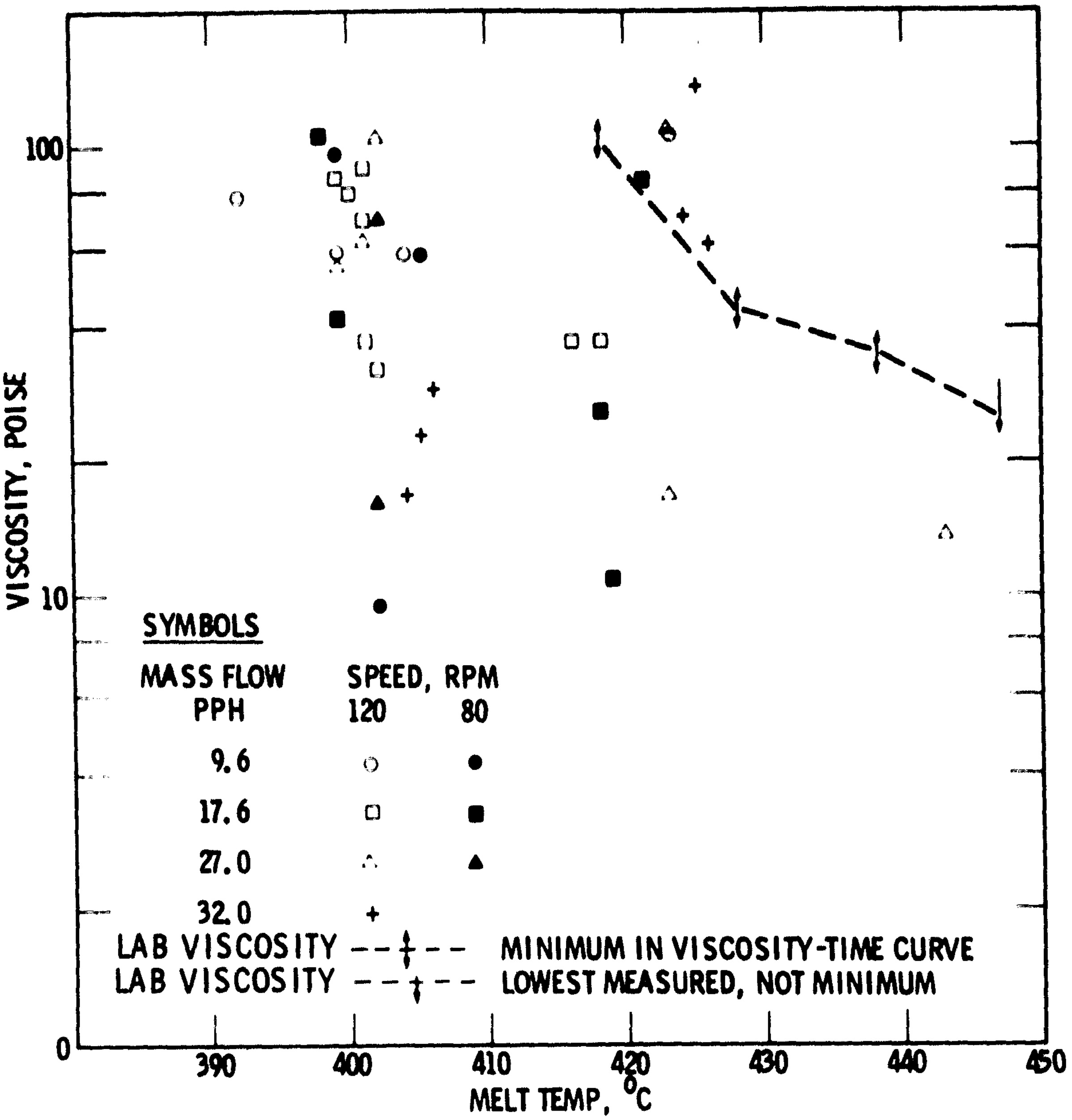


Figure 5-18. Apparent Viscosity of Pittsburgh No. 8 Coal As Observed in a Capillary Die, Attached to the Coal Pump and As Measured in a Laboratory Viscometer

half from dissipation of mechanical power. Scaling studies have shown that larger machines would have higher net specific shaft power consumption.

9. Expulsor Tests

The purpose of the coal expulsor tests was to investigate designs for pressure atomizers at conditions that simulate operation in a pilot plant scale injector. Flow rates of 500 to 1000 lbm/hr at upstream pressures of 2000 to 5000 psi were targets. Since viscosities of coal in the plastic state vary markedly with time, the coal conditioning chamber is designed to hold the plasticated coal at temperature for short or long durations. The coal conditioner can hold 1.3 lbm of coal.

The operation of the coal expulsor (illustrated in Figures 5-8 and 5-9) was satisfactory. The pressure on the piston was varied from 250 psi to as high as 1100 psi during the filling cycle which indicates the ability of the coal pump to pump against pressure.

The fill cycle took between 5 and 7 minutes at coal pump flow rates of 9.5 lbm/hr. In all spray runs to date, the valve was moved to spray without any delay after accumulation. Expulsion occurred very rapidly. For the cases where the piston motion could be accurately measured, the average flow rates on spray were from 126 to as high as 700 lbm/hr. The discharge time varied from 3 to 10 seconds. Summary data is given in Table 5-8.

Table 5-8. Expulsor Test Run Summary

Run No.	31	32-1	32-2	33	34	35-1	35-2
Coal Pump Feed Rate, lbm/hr	10	10	10	10	10	15	15
RPM	120	120	120	120	120	120	120
Coal Temperature, Adaptor, ^{o}F	814	787	806	829	818	806	813
Coal Temperature, Conditioner, ^{o}F	732	827	823	828	792	843	864
Effective Piston Pressure, psi	1050	1180	6000	400	850	600	6000
Conditioner Pressure, psi	1500	1000	2500	700	no data	1000	8650
Expulsion Time, sec	no data	3	3	no data	no data	10	no data
Coal Mass, lb	no data	.46	.58	no data	no data	.35	no data
Equivalent Flow Rate, lbm/hr	---	550	700	---	---	126	---
Die Diameter, in.	.030	.073	.073	.073	.073	.073	.073

The temporary spray receiver (shown in Figure 5-8) compacted the spray so thoroughly that no indication of the particle size of the spray could be obtained. Sprays into atmospheric pressure are shown in Figure 5-19 which is a reproduction of a strip of high speed motion pictures taken at 7000 frames per second. Even at this framing rate, particle motion is not stopped. Under high magnification, the particles seem to be much smaller than those previously obtained from two-fluid atomization. These preliminary spray tests were very promising, so a pressurized water quench spray collection device was designed (but not fabricated at the conclusion of the test program).

The final test runs were designed to measure viscosity as a function of residence time in the coal conditioning chamber. Two runs were devoted to this end but data was not obtained because the piston position indicator lost its rubber surface, thereby precluding accurate flow rate measurements. The piston position indicator is a wheel held against the piston shaft. The piston shaft was so hot that it deteriorated the Viton surface of the wheel. There was, therefore, on several tests some uncertainty in the piston position indicator.

The plug valve was designed and fabricated as part of the 2.5-inch coal pump effort reported in Reference 3-2. The plug valve sealed the plastic state coal quite effectively, but excessive force was required to turn the hot valve. The coal leaked into the seal passage so that under most circumstances, a mallet was needed to turn the valve handle. Based on this experience, a slide valve with sliding surfaces, such as that used extensively in thermoplastic practice, would probably be a better prototype for a valve.

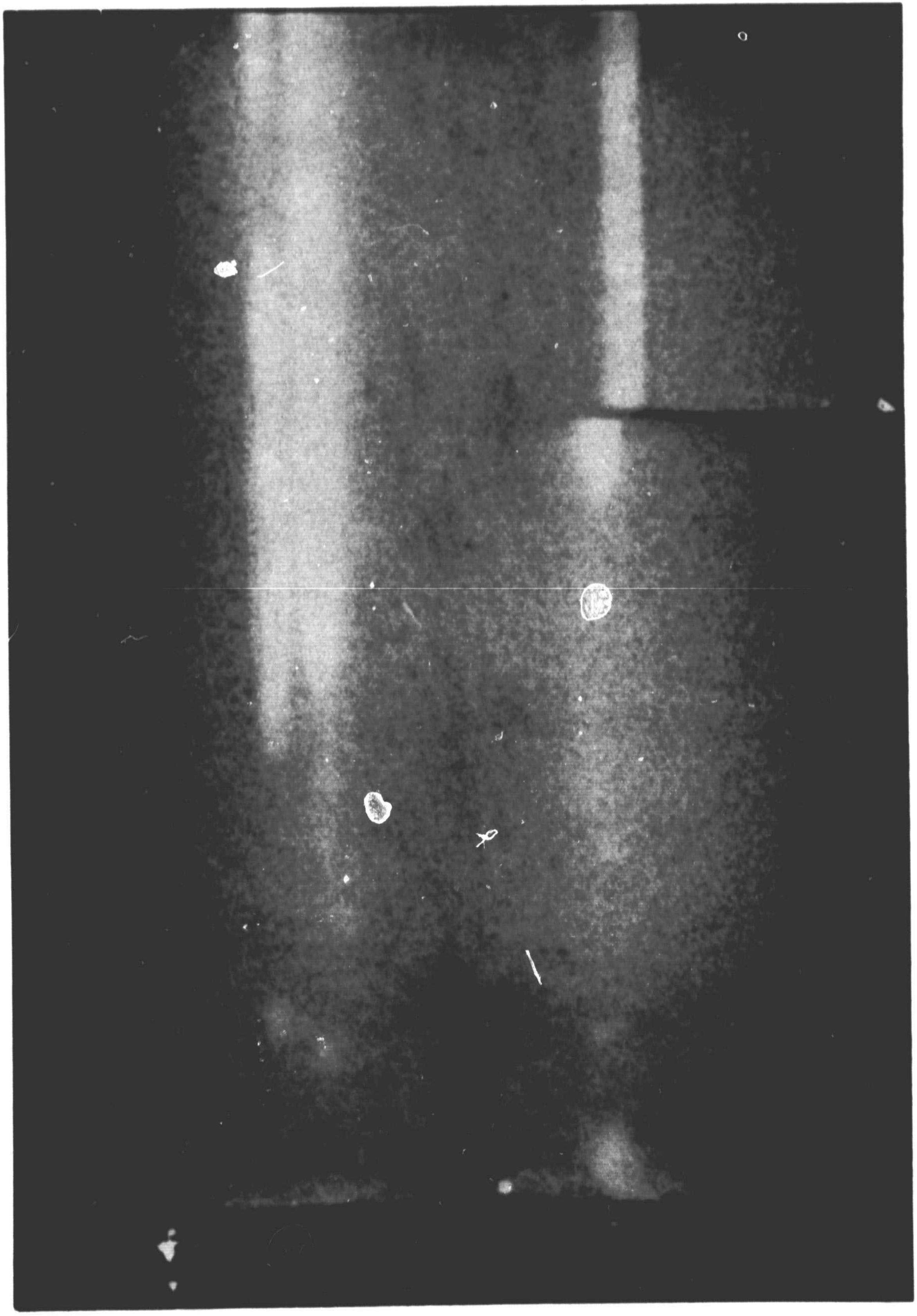


Figure 5-19. Coal Pump Sprays into Atmospheric Pressure

SECTION VI

EXTRUDATE REACTIVITY IN LIQUEFACTION

A. OBJECTIVE

When coal is heated to the plasticating temperature in a coal pump, some measureable changes in coal properties occur. The object of this study is to determine if there are any significant changes in coal reactivity that occur during the plasticating coal pump process.

B. INTRODUCTION

Small but measurable changes in coal properties do occur in the process of coal pumping. It is the purpose of this study to determine if these small changes are reflected in any drastic loss in coal reactivity during a coal liquefaction process. The comparative reactivity of coal extrudate and its parent coal is determined by two different tests of liquefaction activity. In the microclave reaction test, the extent of hydrogenation of coal is determined as a function of time. In the standard autoclave study, the comparative effect of a widely used catalyst is determined.

During coal pumping, the coal is first preheated to 350°F in the metering feeder, and then is heated by heat conduction, shear, work, and frictional energy dissipation to temperatures between 750° and 880°F. As shown in the studies on thermal and physical properties of coal and extrudate done by IMMR (References 3-3 and 3-4), some changes are observed. Data for Pittsburgh No. 8 coal is summarized in Table 6-1. The volatile matter (on a moisture and ash-free basis) drops by 2.5 to 4.5 percent, and the fixed carbon increases proportionately. The change in heating value is insignificant. Moisture is greatly reduced, as expected, and the ash content increases by 0.1 to 1.1 percent, reflecting loss by pyrolysis. The low temperature ash content increases by 0.1 to 0.5 percent. The free swelling index increases by about 1 unit. Surface area determined by methanol adsorption was 88 ± 43 m^2/g for the raw Pittsburgh No. 8 coal and 96 ± 49 m^2/g for its extrudate. The difference is statistically insignificant. The coal and its extrudate have been subjected to extraction by N, N-dimethyl-formamide (DMF) in an atmospheric pressure Soxhlet extractor at 153°C. For Pittsburgh No. 8, 29.6 ± 1.2% of the coal mass could be extracted. After extrusion 41.3 ± 5.0% could be extracted. Pyrolytic bond breaking reactions predominate in the early stages of heating; hence, the extruded coal is more easily extracted by DMF. This result is expected.

Table 6-1. Characteristics of Coal and Extrudate Pittsburgh No. 8 Coal

	Proximate Analysis and Other Data							
	%M[a]	%A[b]	%VM[c]	%FC[d]	HV[e]	FSI[f]	LTA[g]	SA[h]
Raw coal	0.31	7.22	42.2	57.8	15090	7	9.54	46
Extrudate #1	0.03	7.32	38.3	61.7	15186	8	9.55	71
Extrudate #2	0.46	7.37	37.0	63.0	15092		----	--
Raw coal	0.26	5.66	40.93	59.05	14941	7-1/2	8.89	86
Extrudate #1	0.00	6.79	38.0	62.0	14600	9	9.28	153
Extrudate #2	0.28	6.90	37.6	62.4	15066		----	---
Raw coal	0.14	6.59	42.2	57.8	15104	7-1/2	9.73	132
Extrudate #1	0.03	7.68	39.9	60.1	15191	8	10.27	64
Extrudate #2	0.23	7.98	38.8	61.2	15082		----	---

[a] Moisture, %.
[b] Ash (moisture free), %.
[c] Volatile matter (moisture and ash free), %.
[d] Fixed carbon (moisture and ash free), %.
[e] Heating value (moisture and ash free), Btu/lb.
[f] Free swelling index.
[g] Low temperature ash (moisture and ash free), %.
[h] Surface area by methanol adsorption at 25°C, m^2/g.

C. REACTIVITY TOWARD LIQUEFACTION

1. Microautoclave Study[1]

The results of hydrogenation tests on Western Kentucky No. 9 coal before and after extrusion in plasticating coal pump are reported. These tests were performed in a 20-cc microautoclave. Microautoclaves are useful in comparing the relative reactivity of coals to non-catalyzed hydroliquefaction. Tests are more rapid and reproducible compared to larger, conventionally stirred autoclaves.

a. Experimental Procedure. The microautoclave system consists of the following parts: a tubular steel microreactor of approximately 20-cc capacity, into which is placed before each run a disposable glass liner (13 x 100 mm).

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[1] The microautoclave studies were done by Dr. Shuji Mori of the UK/IMMR. It is reported in Reference 3-4.

The reactor assembly is fitted with a pressure gauge and thermocouple, as shown in Figure 6-1. For a standard liquefaction run, the coal or extrudate is reduced to -60 mesh and a charge of 1.50 g is placed in the reactor along with an additional 1.50 g of inert ceramic (16/36 mesh) which prevents agglomeration of the coal. Tetralin (6.0 g) is added. The reactor is closed and purged several times with nitrogen. The system is then pressurized to 1500 psig with hydrogen for a 30-min pressure test. The system is depressurized to 500 psig hydrogen and placed in position in the fluidized sand bath furnace which is preheated to 435°C (815°F). The hydrogen pressure is 1190 psig at reaction temperature.

During a run the bath temperature, reactor temperature, and reactor pressure are monitored at 60-sec intervals. Bath temperature is maintained to within ± 2°C by heater adjustments. At the conclusion of a run the unit is removed and placed in a cold sand bath for an initial 60-sec cooldown, and is then quenched in cold running water. In this manner total reaction time is closely defined.

Conversions are determined by hot pyridine extraction, using nitrogen-blanketed atmospheric pressure Soxhlet extractors. The material is subjected to a 42-hour reflux extraction with pyridine, allowed to cool, subjected to a six-hour reflux extraction with methanol to wash out the pyridine; then dried at room temperature and, finally, dried at 60°C under vacuum (less than 1 torr) for six hours. The thimble and contents are then cooled, weighed, heated again under vacuum, cooled and reweighed. If the second weight differs from the first by more than 10 mg the drying cycle is repeated.

b. *Coal and Extrudate Characteristics*. The characteristics of the Western Kentucky No. 9 coal used in the hydroliquefaction tests are summarized in Table 6-2.

c. *Experimental Results*. The microautoclave reactor has been used in this study to compare the reactivities of a plastic coal (Kentucky No. 9 seam, Runs 16 and 17, Table 5-6), with its extrudate from the 1.5-inch coal pump. Runs with the coal and with the extrudate were conducted at 435°C (815°F) for periods of 10, 20, 30, and 60 min. To provide an estimate of repeatability, all runs were carried out in duplicate. The pyridine extraction method provides a measure of total liquids (maltene, asphaltene, and pre-asphaltene fractions combined). Since most coals and all plastic coals contain pyridine-soluble fractions, "zero-minute" dummy runs were also made, in which coal and extrudate were contacted with tetralin, allowed to stand without heating, and then subjected to the extraction analysis.

Table 6-3 presents the results of these runs. Conversions of both coal and extrudate are in the range 52 to 89% in all cases. The repeatability is quite good; the standard deviation for all nine pairs of duplicate data is ±1.8%, and for the best eight pairs is ±1.4%.

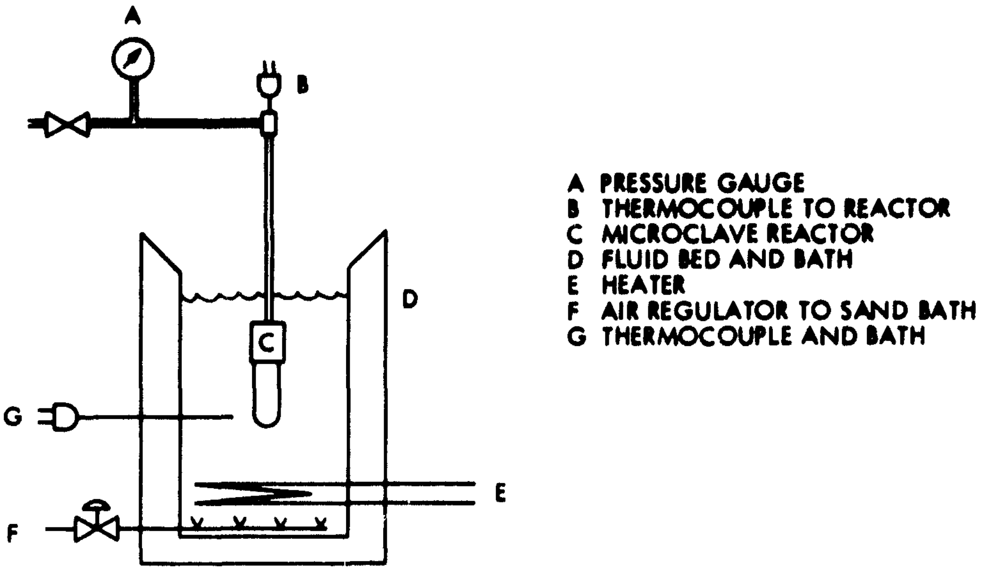

Figure 6-1. The Mori Microautoclave (Microclave) Reactor Setup

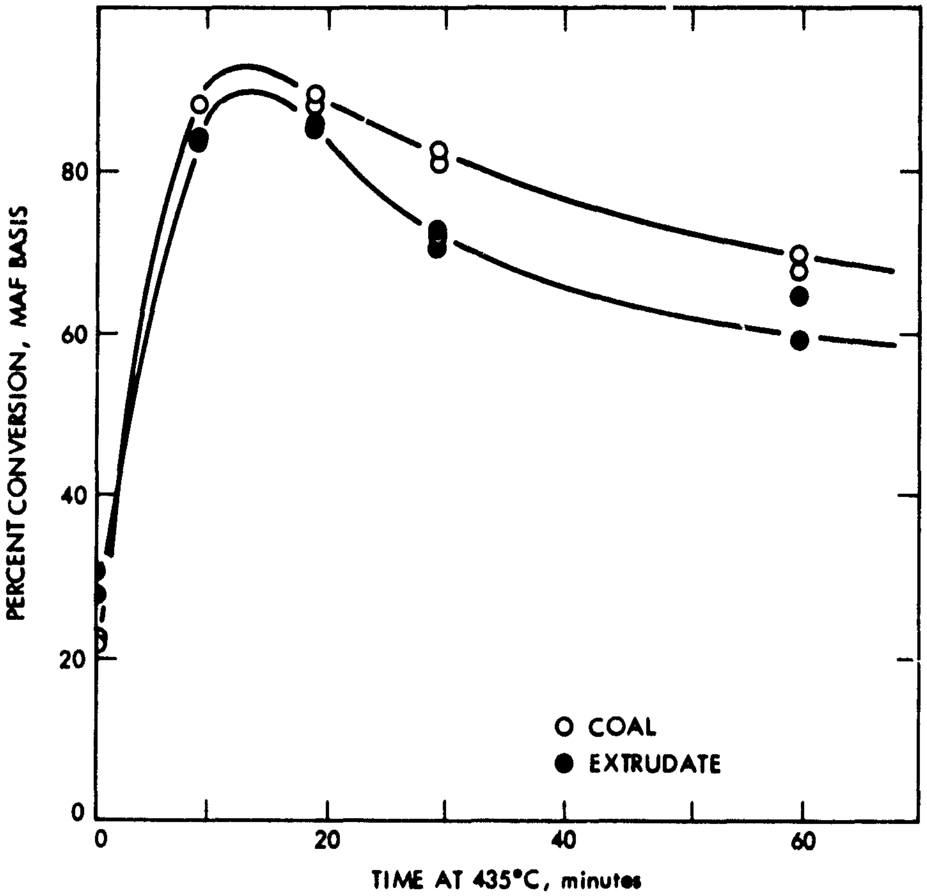

Figure 6-2. Liquefaction Conversion of Kentucky No. 9 Seam Coal and its Extrudate

Table 6-2. Characteristics of Western Kentucky No. 9 Coal and Extrudate Used in Hydroliquefaction Tests (data are on an as-received basis)

	Coal	Extrudate
Moisture, %	1.74	0.55
Ash, %	10.94	12.73
Volatile Matter, %	40.05	34.0
Fixed Carbon, %	45.27	52.72
Heating Value, Btu/lb	12230	12310
C, %	66.54	68.60
H, %	4.88	4.24
N, %	1.17	1.15
S, %	4.33	4.21
O (by difference), %	10.40	8.52
Extracted by DMF, %	16.4	9.6

Table 6-3. Conversions of a Coal and an Extrudate in a Microautoclave at 435°C[a]

Time at 435°C, Min	Coal Converted to Pyridine Soluble Material, %		Extrudate Converted to Pyridine Soluble Material, %	
	As-received basis	maf basis	As-received basis	maf basis
None	21.6	22.7	27.4	31.0
	22.3	23.5	25.0	28.2
10 min	78.7	88.1	73.2	83.8
			72.7	83.2
20 min	79.5	89.1	74.0	84.7
	78.3	87.7	73.9	84.6
30 min	72.0	80.5	61.8	70.6
	72.6	81.1	63.7	72.8
60 min	60.3	67.1	52.0	59.3
	62.6	69.7	57.2	65.3

[a] Kentucky No. 9 seam coal and the extrudate from this coal (Sample M437), received by IMMR September 1979, and reacted with tetralin and 500 psig initial hydrogen at 435°C (815°F) for the indicated periods.

These data provide three bits of information, most easily seen in Figure 6-2. First, it is clear that both coal and extrudate react rapidly, and under these conditions afford maximum conversions of 80 to 90% in approximately 15 min at 435°C. Second, the extrudate is nearly as reactive--but is not quite as reactive--as the parent coal. At any given time the extrudate conversion is running 4 to 9% below that of the coal; or, the extrudate requires about one minute of additional reaction time to attain a given conversion. Third, these data imply the existence of a coking reaction which progressively reduces the overall yield of pyridine solubles as the reaction time is continued beyond about 20 min. [Caution should be used in interpreting this coking reaction, as it may likely be an artifact of the static nature of this method.]

2. Stirred Autoclave Study[2]

Hydroliquefaction tests were conducted to determine the reactivity of coal and its coal pump extrudate. The tests were conducted at approximately the H-Coal Process conditions with and without a cobalt/-molybdenum (Co/Mo) catalyst.

a. Experimental Procedure. A standard Autoclave Engineers 300-cc stirred autoclave which is fitted with thermocouples, pressure gauge, and the facilities for gas input, rupture disc, vent line, trap for condensibles, and head gas sampling is used. The autoclave is charged with 33 to 35 g of pulverized coal or extrudate and approximately 70 g (2:1 by weight) of tetralin. For runs with catalyst a 20-g catalyst charge is used. The autoclave is closed, purged, pressure-tested, and charged with hydrogen to 560 psig at ambient temperature. The autoclave is heated with vigorous stirring to 454°C (850°F), then cooled, vented and opened. The contents are first analyzed for conversion to maltenes and asphaltenes, using a hot toluene extraction procedure. A portion of the residue is then subjected to a hot pyridine extraction, to provide an estimate of total conversion (to maltene, asphaltene and preasphaltenes, as was done in the microvlave runs). Reaction time is calculated from the point at which the warming reactor temperature reaches 399°C (750°F). All runs are for 60 min. The reaction conditions are summarized in Table 6-4.

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[2] The stirred autoclave study was done by Prof. James Watters and Dermot Collins of the University of Louisville under contract to UK/IMMR (Reference 3-4).)

Table 6-4. Stirred Autoclave Reaction Conditions

Coal	[As in Table 6-2]
Temperature	850°F (455°C)
Donor Solvent	Tetralin
Solvent-to-Coal Ratio	2/1 (weight basis)
Catalyst	Commercial H-coal Co/Mo catalyst or none
Organics-to-Catalyst Ratio	5/1 (weight basis)
Initial Gas Pressure	560 psig (±4%)
Reaction Time	60 minutes
Heat-up Time	22 minutes (from ambient to 750°F)

b. <u>Experimental Results</u>. Figure 6-3 shows the results of these runs. Conversions are higher in the stirred autoclave than in the microautoclave--not surprisingly, since the temperature is 16°C higher, the hydrogen pressure is slightly higher, and, perhaps most importantly, the contents are vigorously mixed in these runs.

The data of Figure 6-3 can be looked at with respect to three variables. The effect of extrusion of Kentucky No. 9 seam coal upon its reactivity is moderate but consistent, the extrudate giving 7 to 8% lower conversion to pyridine-solubles (cf., 4 to 9% lower in the microclave runs). The preasphaltene fraction in both noncatalyzed runs is 10-13%, indicating a high quality product, roughly similar to that obtained by Maekawa after three hours at 400°C (Reference 6-1). The effect of the massive charges of commercial Co/Mo H-Coal catalyst appears to be negligible, for both coal and extrudate, with regard to the maltene-asphaltene conversion (toluene-soluble fractions), and to be negative for the preasphaltene fraction (toluene-insoluble but pyridine-soluble). The pre-asphaltene fraction is virtually eliminated in the presence of this catalyst. Data based on pyridine extractions are believed to be inconclusive. Calculations involving pyridine extraction data are often inaccurate due to the fact that small amounts of material are being used. Small errors in measurement usually produce large percentage errors in conversion. These runs should be duplicated with more attention to pyridine extraction.

3. Discussion of Hydroliquefaction Studies

The data reported on the microautoclave and the standard autoclave reactors are in remarkable agreement, considering the marked differences both in liquefaction conditions and in analytical procedures. The Kentucky No. 9 seam coal is readily reacted at 435° to 450°C to 90 to 94% conversion (maf basis) to pyridine-solubles. The extrudate of this coal under the same sets of conditions reacts similarly, but not quite as far or as fast. At the same periods of reaction its conversion may be 4 to 9% lower. Another way of indicating this difference in reactivity (cf.,

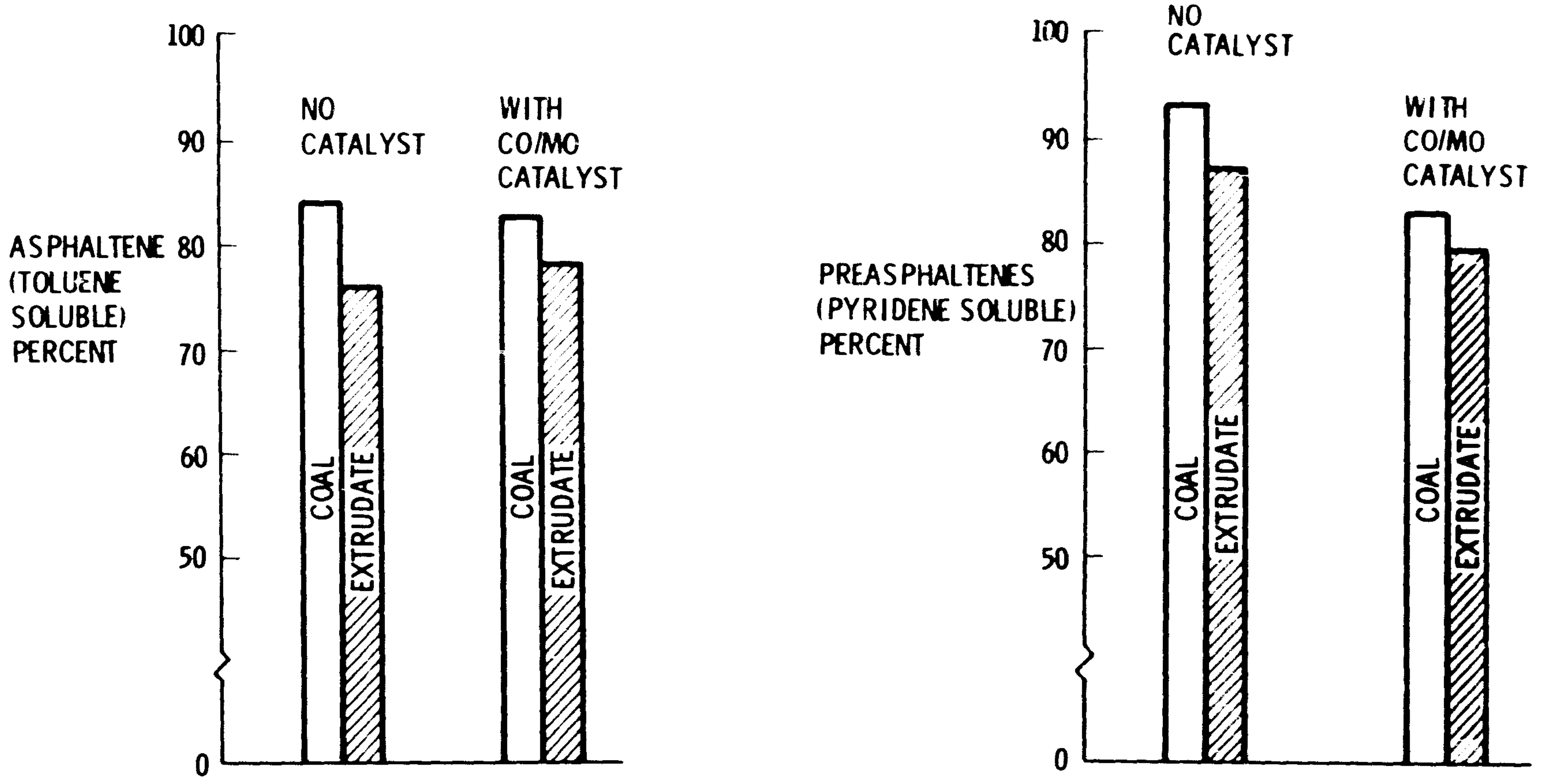

Figure 6-3. Effects on Kentucky No. 9 Seam Coal With and Without a Catalyst

Figure 6-2) is that, during the first ten minutes or so of reaction (when most of the liquefaction takes place), the fresh coal reaches a given level of conversion about one minute ahead of the extrudate.

The fixed carbon content of this coal, as-received, is increased from 45.27 to 52.72% or by about 7.5% as a consequence of extrusion. On a maf basis the fixed carbon increases from 51.84 to 60.79%, or by about 9.0%.

One way of comparing conversions of coals in thermal hydroliquefaction processes is to take it for granted that any material which is capable of escaping the heated coal as volatile matter, in the absence of hydrogen or external hydrogen-donor solvent, is assuredly going to escape the solid matrix to make up a part of the liquefaction product when that same coal is heated in the presence of excess H-transfer solvent and molecular hydrogen. [This argument is not without fault. Most of the pyrolysis weight loss occurs in the 500 to 650°C range, well above that of liquefaction processes.] On this basis, liquefaction begins to count for something as a process only when conversions are well in excess of the volatile matter content of the coal. Conversion can then be viewed in terms of the amount of fixed carbon (AFC) which has been converted:

$$\text{Conversion (AFC)} = \text{Conversion (maf)} - \text{Volatile Matter (maf)} \qquad (6\text{-}1)$$

or in terms of the percentage of fixed carbon (PFC) which has been converted:

$$\text{Conversion (PFC)} = \frac{\text{Conversion (AFC)}}{\text{Fixed Carbon (maf)}} \qquad (6\text{-}2)$$

If the incremental amount of fixed carbon resulting from the extrusion process is viewed as an inert coke-like material, then Equation (6-1) is the appropriate form for comparing conversions in terms of fixed carbon contents. On the other hand, if that incremental amount of fixed carbon is considered to be comparable with the fixed carbon present in the original coal, then Equation (6-2) is indicated. Plots of the microautoclave conversion data, converted to AFC and PFC bases by Equations 6-1 and 6-2, are shown in Figure 6-4. On the AFC basis the extrudate appears to be marginally more reactive than the parent coal; on the PFC basis the reverse is true.

Figure 6-2 shows that on a straight conversion basis the parent coal is measurably more reactive than its extrudate. When conversion is calculated on the basis of fixed carbon contents, Figure 6-4 shows that the conversion curves become very close. If it were possible to include in these calculations the volatile material escaping the screw during extrusion, the differences between conversions of parent coal and extrudate might well become too small to call.

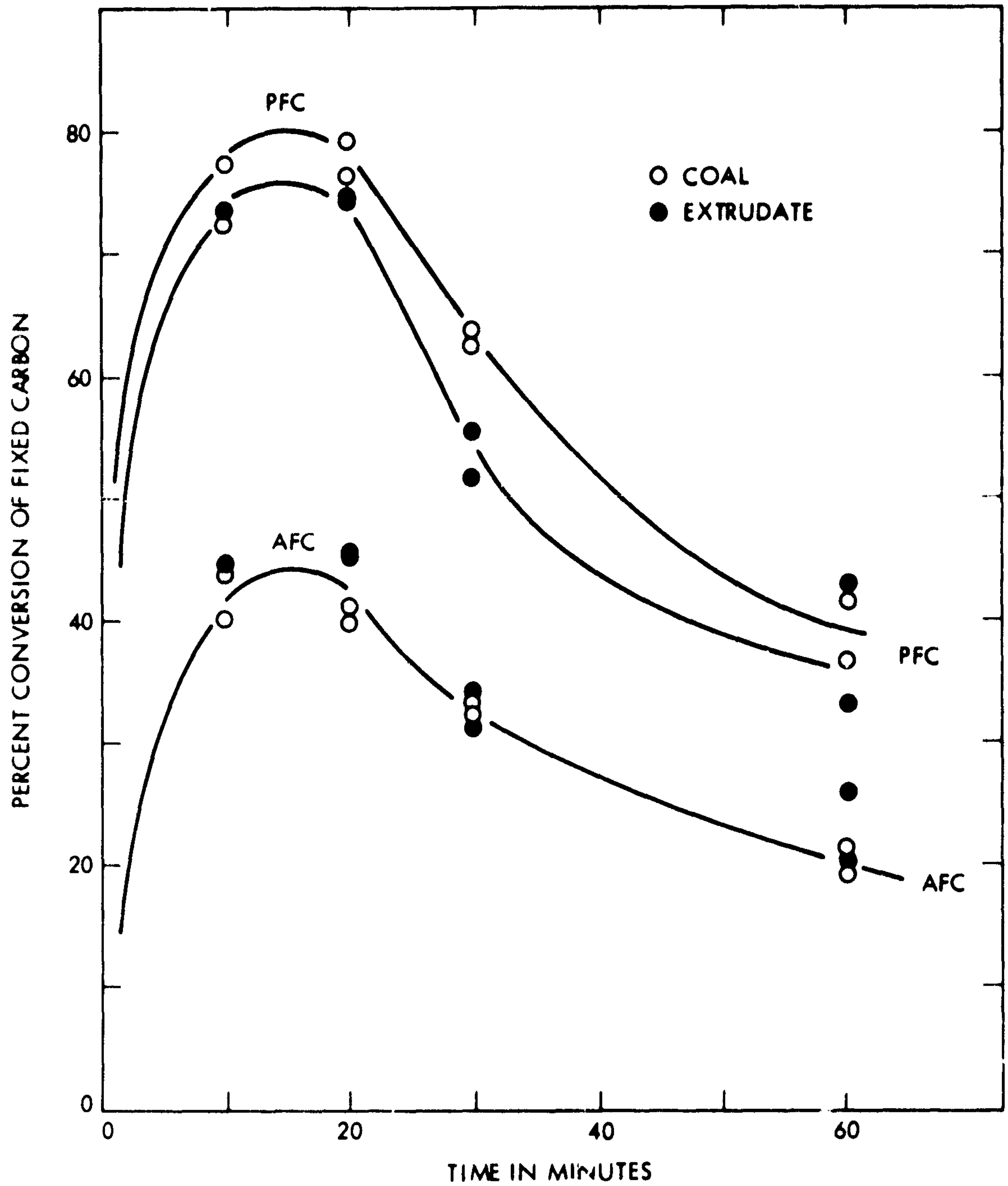

Figure 6-4. Microautoclave Conversions as Functions of Fixed Carbon

SECTION VII

EXTRUDATE REACTIVITY DURING GASIFICATION

A. OBJECTIVE

The direct reaction of coal and steam is an important factor in coal gasification processes. The reactivity of coal sprayed in its plastic state into hot, high pressure steam is compared to the reactivity of pulverized raw coal, of pulverized coal extrudate, and of potassium hydroxide (KOH) impregnated coal.

B. COAL-STEAM REACTION

1. Introduction

It has been demonstrated at JPL that the plastic property of coal can be utilized to pump coal up to high pressures using extruders. Consequently, coal extrusion is a possible feeding technique for high pressure gasification processes that are presently in various stages of development. Previous efforts have shown that the plastic coal forms a very fine spray when subjected to high pressure drops and, moreover, this fine spray is very reactive with oxygen. However, the main reaction in a gasification reactor is between coal and steam. Therefore, the technical and economic feasibility of this technique mainly depends on the reactivity of plastic coal with steam. This research program was undertaken to measure the comparative reactivity of the following forms of coal for steam gasification reaction.

(1) Plastic coal spray.

(2) KOH impregnated plastic coal spray.

(3) Pulverized coal (-40 mesh).

(4) Pulverized extrudate[1] (-40 mesh).

2. Approach

The comparative reactivities of the four forms of coal were evaluated for coal-steam reaction. The reactions were carried out in a batch type reactor. The reaction chamber was filled with stoichiometric hydrogen-oxygen mixtures that were ignited to yield high temperature, high pressure steam. In cases 1 and 2, the plastic coal was sprayed into the chamber simultaneously with the ignition. In cases 3 and 4, coal was blown into the chamber. The reaction chamber was left to cool before the retrieval of reaction products was attempted. After each run, a gas sample was taken for mass spectrometric analysis. The solid

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[1] Extruded on the 1.5-inch Centerline Machine.

products were collected by repeated washings of the chamber and analyzed for ash content. The conversions were calculated using ash content data before and after the reaction.

3. Description of the Apparatus

The experimental set-up for gasification reaction studies is comprised of a piston-cylinder and die system, the batch reactor, and the auxiliary systems for gas injection, ignition, and data acquisition. Figure 7-1 is a schematic of the system as it is used for a coal spray run. Figure 7-2 is a schematic of the system set up for a test of pulverized coal. The various pieces are clamped together by two hydraulic cylinders of 27 square inch area and 9000 psia pressure ratings. These pieces are described in detail below.

a. Piston-Cylinder and Die System. The cylinder is made of stainless steel with a 0.77-in. inside diameter, and has a tight fitting piston. Grafoil piston seals are used to seal the piston surfaces. The cylinder is equipped with band heaters that can heat the cylinder to 1000°F. The piston shaft is driven by a hydraulic slave piston which in turn is driven by a master cylinder motivated by a 60,000 lbf Baldwin testing machine. This combination is designed for piston travel speed of 2 inches per second (corresponds to coal flow rates of 22 g/sec) and 15,000 psia pressures. The coal injector is placed below the cylinder. It is designed to accept a burst disc assembly and an orifice that acts as a die. The burst disc holds the coal during heating and also seals the interface between the coal and the gas-filled reactor volume. The coal spray orifice used in these experiments is 0.020-inch in diameter, and has a length of 0.020 inch.

b. Batch Reactor. The reactor is made of stainless steel cylindrical in shape with the inside dimensions being 6-inch diameter and 11-inches high. The bottom cap is welded to the body. There is a hole in the middle of the bottom cap for liquids recovery. The top cap is designed with matching tongue and groove seals to fit between the coal injector and the reactor. It is equipped with 6 cartridge heaters to minimize the heat losses of the coal injector. Gases are introduced into the chamber through two sonic orifices each of 0.021-inches in diameter and 0.125-inches length. A spark plug is used to ignite the gas mixture. For the pulverized coal and extrudate runs, a shelf that can hold 2 g of pulverized coal was placed in front of the hydrogen orifice.

c. Auxiliary Systems. The gas injection systems for hydrogen and oxygen each consist of a gas pressure regulator, pneumatic valve, and a solenoid valve in series. The solenoid valves are controlled through a digital delay timing apparatus that turns the valves on for a specified time period. These valves, in conjunction with the pressure regulator and the calibrated sonic orifices, specifies the amount of gases let into the chamber. Through calibration runs, the delay between the

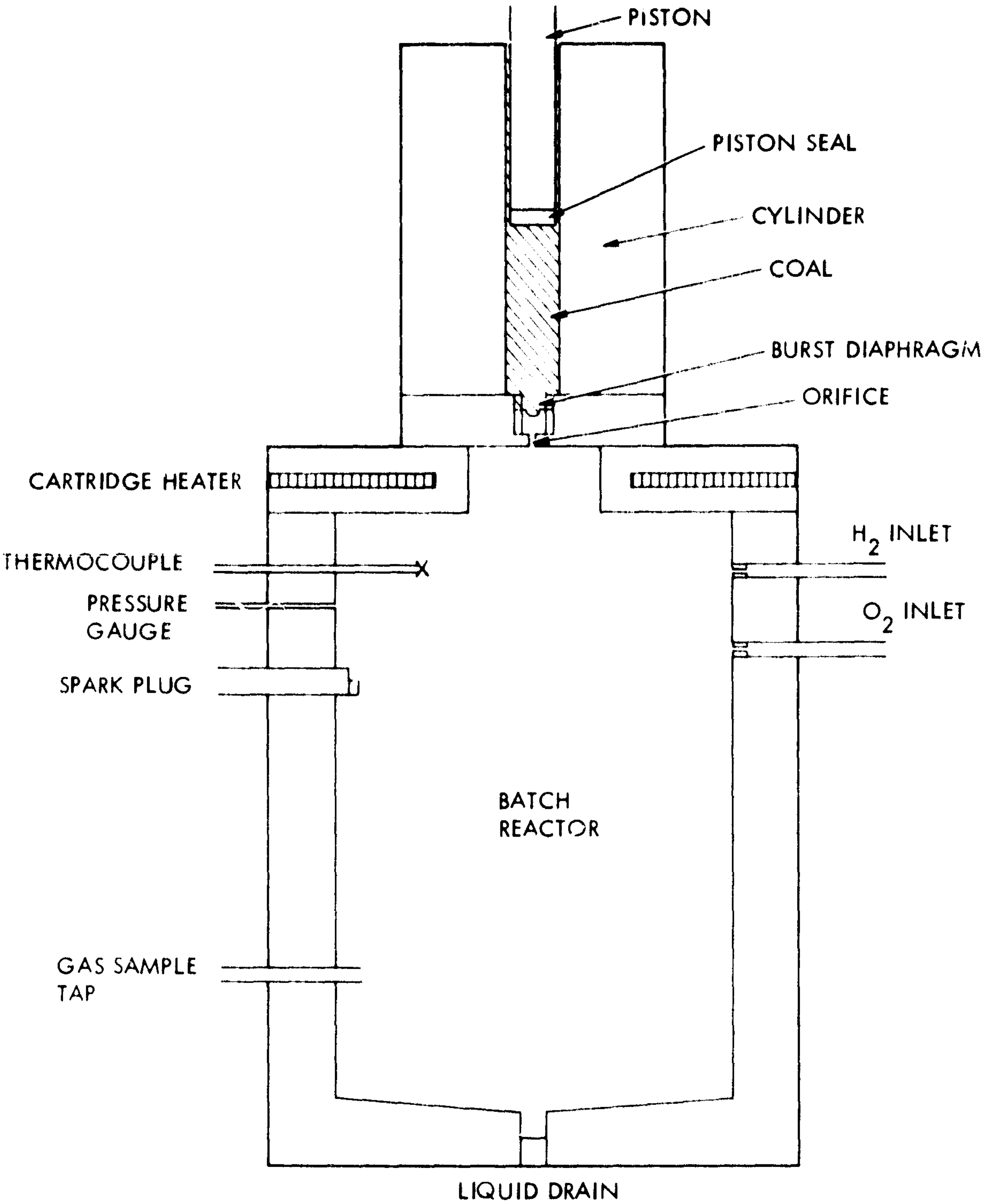

Figure 7-1. Gasification Batch Reactor in Coal Spray Test Configuration

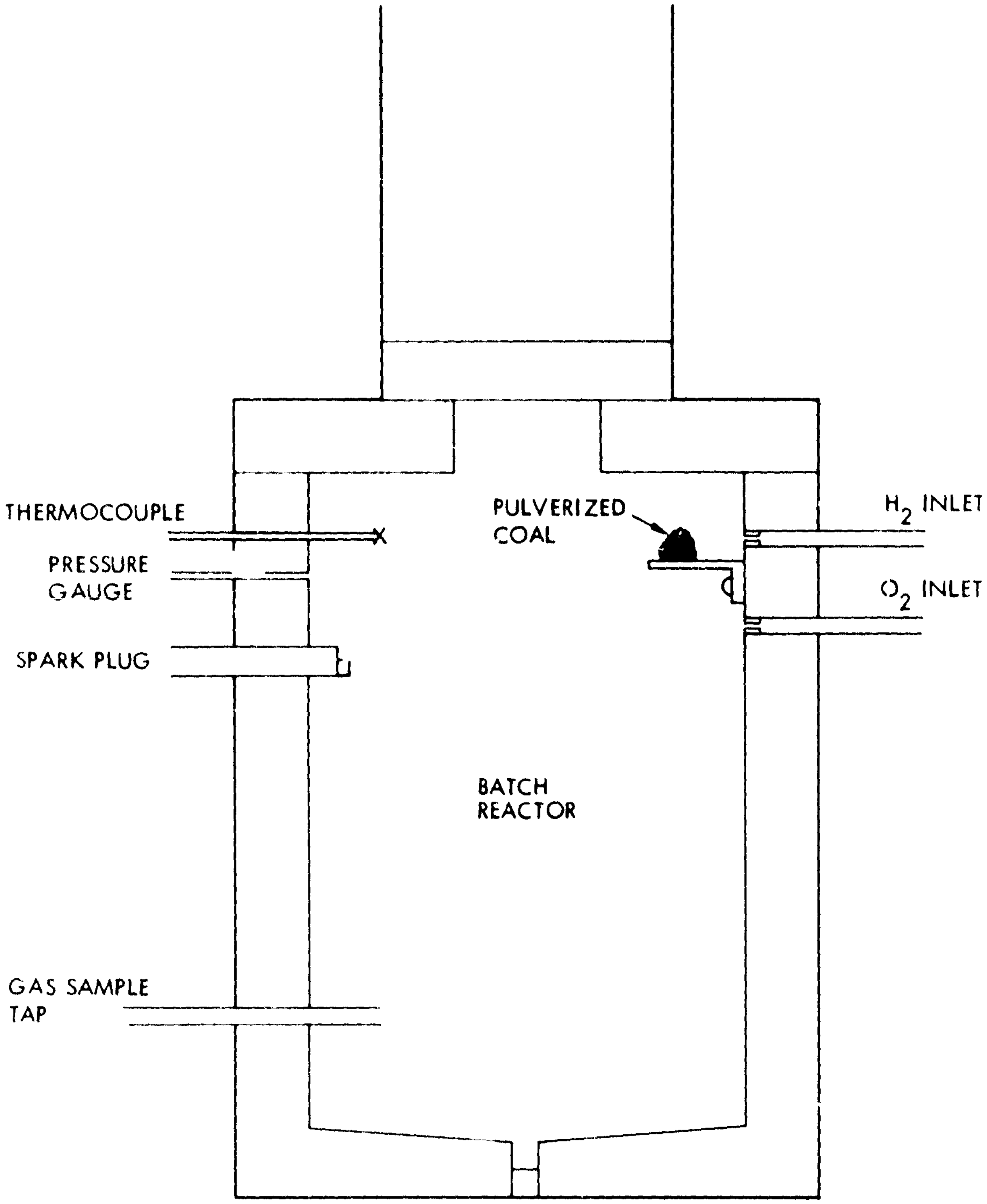

Figure 7-2. Gasification Batch Reactor in Pulverized Coal Test Configuration

ignition and the piston movement that results in simultaneous ignition and spray has been established. All operations mentioned above are remotely monitored from within the control room. The test pit where the actual experiments take place is off limits to personnel after the coal-loading step.

The variables recorded during the experiment are chamber pressure and temperature, coal piston movement, and coal pressure where applicable (Cases 1 and 2). The chamber pressure is measured by two Tabor pressure transducers. The temperature is measured by a bare wire thermocouple. Due to the rather severe conditions in the chamber during ignitions, it had to be made with robust supports; consequently, fast response was not obtained. These and the other variables mentioned above are plotted on an oscillograph during a run and the data is reduced afterwards. A typical run plot is shown in Figure 7-3. The bursting of the coal spray diaphragm is indicated by the fluctuation in the coal pressure and the slight perturbation in the coal piston position indication. The pressure and temperature rises in the reactor when the gas is ignited. Notice that spark ignition, spray, and pressure rise occur in a very closely spaced but distinct sequence. The temperature rise profile shows the effect of a finite time lag caused by the bulk of thermocouple. After each run, the chamber and contents were allowed to cool, and a gas sample was taken for mass spectrographic analysis. Solid products were collected by repeated washing the batch reactor with water. The wash water was filtered and the solid residue was dried and submitted to ash analysis. Conversion of the coal is calculated from the ash analysis.

4. Results

The reactivities of the four forms of Pittsburgh No. 8 coal were measured in the batch reactor under the same conditions. The Pittsburgh No. 8 coal was chosen due to its high fluidity and wide JPL experience in extruding it.

Coal was plasticized by heating in the cylinder at 800°F for 17 minutes. The above conditions were chosen through past experience that showed that the Pittsburgh No. 8 coal became fluid enough to be easily extruded through a 0.020-inch die. KOH is known to be a catalyst for gasification reactions. To investigate the effect of this catalyst on reactivity of plasticized coals, the Pittsburgh No. 8 coal was impregnated in 2M KOH solution for 6 hours. The coal was filtered and dried. Atomic absorption measurements show that it contains 2.1% by weight potassium. The impregnated coal was plasticized as described above.

The ash content for coals before and after reaction was determined by ASTM techniques. Two good runs were made for each of the four forms of the coal listed above except for pulverized coal for which three runs were made. The ash percentages before (A_1) and after (A_2) are given in Table 7-1.

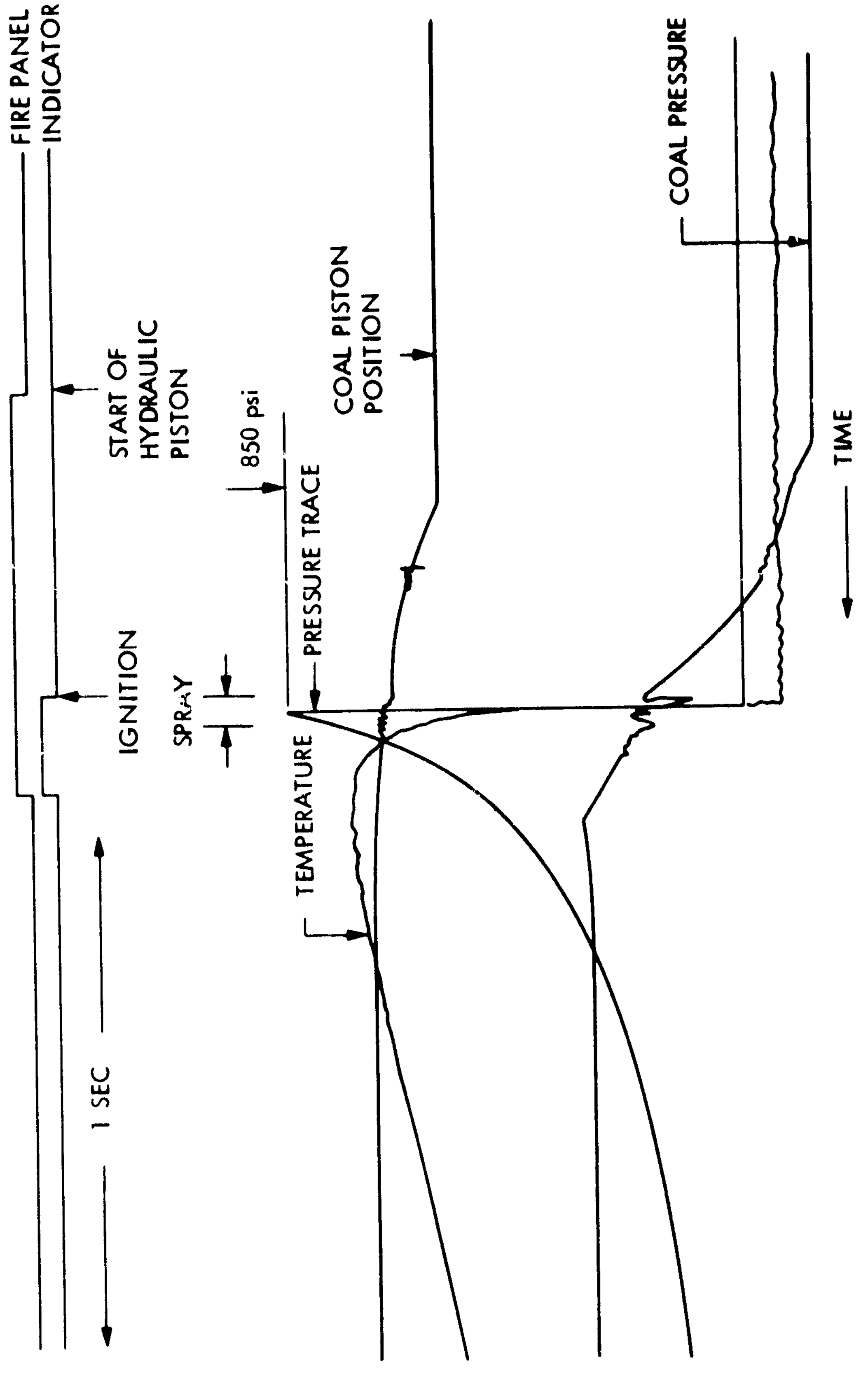

Figure 7-3. Typical Run Data

Table 7-1. Ash Contents Percentage

	A_1	A_2		
		1st run	2nd run	3rd run
1 Plastic Coal Spray	7.3	22.5	20.8	
2 KOH Impregnated Plastic Coal	11.6	34.8	30.8	
3 Pulverized Coal	7.3	58.1	47.6	44.8
4 Pulverized Extrudate	6.7	21.7	28.1	

The percent conversions were calculated from the above ash data using the equation

$$\% \text{ conversion} = 100 \times \frac{(1 - A_1/A_2)}{(1 - A_1/100)} \qquad (7\text{-}1)$$

The percentage conversions are given in Table 7-2.

Table 7-20. Percentage Conversions

	Run 1	Run 2	Run 3	Average
1 Plastic Coal Spray	72.9	70.0	----	71.4
2 KOH Impregnated Plastic Coal	75.4	70.5	----	73.0
3 Pulverized Coal	94.3	91.3	90.3	92.0
4 Pulverized Extrudate	74.1	81.6	----	77.8

The gas samples taken were analyzed by mass spectroscopy by Analytical Research Laboratories, Inc., Monrovia, California. The gas analysis data are given in Table 7-3.

Table 7-3. Mass Spectroscopic Analysis of Gas Samples (Volume %)

	Plastic Coal		KOH Impregnated Plastic Coal		Pulverized Coal			Pulverized Extrudate	
Gas	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	Run 3	Run 1	Run 2
H_2	64.0	82.0	56.3	72.6	51.6	54.5	56.6	58.3	60.3
CH_4	0.4	0.2	0.3	0.3	0.1	0.01	0.1	0.2	0.1
CO	11.6	3.1	6.8	5.8	21.8	22.3	21.6	15.5	17.2
N_2	2.8	3.3	15.4	2.9	7.0	4.7	8.2	9.3	7.4
O_2	3.7	5.2	7.9	4.1	1.2	1.1	0.5	1.7	0.8
Ar	0.2	0.3	0.3	0.3	0.18	0.15	0.17	0.2	0.2
CO_2	17.2	5.3	13.0	13.9	18.1	17.2	12.8	14.8	13.4
CO/CO_2	0.67	0.52	0.52	0.42	1.2	1.3	1.69	1.04	1.28

Due to possible small amounts of excess hydrogen or oxygen present before the explosion and possible air infiltration during sampling and analysis, not much can be deduced from the H_2 or O_2 percentages. However, the CO/CO_2 ratio is an important parameter in gasification schemes. The CO/CO_2 ratios range from 0.42 to 0.67 for plasticized coals and from 1.04 to 1.69 for pulverized coal and extrudate runs. Higher ratio values are more favorable to gasification.

The experiments were performed under as similar conditions as possible. The amounts of hydrogen and oxygen in the chamber were very close to stoichiometric with H_2/O_2 values ranging between 1.96 to 2.04 for all experiments. Consequently, the excess hydrogen or oxygen in the reactor after ignition is less than 4% of the steam. The total pressures of the initial gas mixtures were chosen to result in identical pressures after ignition. The run data show that the final pressures range from 800 to 850 psia for all experiments reported above.

One basic difference in the experimental set-up between plasticized plastic coal, KOH impregnated plastic coal, non-plasticized pulverized coal, and pulverized extrudates coals was the thermal conditions of the reactor. For plasticized coals, the cylinder and the coal injector were heated to 800°F. To minimize the heat losses, the top plate of the batch reactor was kept at 600°F (see Figure 7-1). On the other hand, the pulverized coal and extrudate runs were made with room temperature hardware. Thus, from equilibrium thermodynamic calculations and pressure data, the temperature of the H_2-O_2 mixture before explosion is estimated to be around 500°F for plasticized coal runs. Therefore, the steam temperatures in this case are about 400°F higher than for non-plasticized coal. This should be taken into account in comparing reactivities.

The ash analyses were done at JPL in accordance with ASTM procedures. The initial ash values (A_1) are accurate within 0.5%. The accuracy of A_2 values are estimated to be within 3% because the amounts of sample were small (0.5 to 1 g). The inaccuracy in ash determination introduces ±2% uncertainty in the conversion values.

Taking into account the above factors, the most reactive of the coal samples for this ash reaction is the pulverized coal. The conversions calculated are between 90 and 94 percent. This reactivity is followed by that of pulverized extrudate. The conversions are 74 to 82 percent. The plasticized coals trail with conversions ranging from 70 to 75 percent.

One explanation for this behavior is that heating coal to its plastication temperature--17 minutes at 800°F--destroys the pore structure of coal, reducing its surface area. Another observation from these experiments is that the very fine coal spray observed in air or oxygen could not be achieved in the reactor. Coal, when extruded into the high temperature-pressure stagnant steam atmosphere, came out as a liquid jet about 0.05 to 0.1-inch diameter, drastically reducing the surface area exposed to steam. Thus, the plasticized coals showed a much lower reactivity than the pulverized coal. In the case of pulverized extrudate, the plastication that takes place is not extensive enough to destroy the pore structure. In addition, the degassing after extrusion results in a spongelike structure. Previous measurements have shown that the surface area of the extrudate is comparable to the area of raw coal. The slightly less reactivity of the pulverized extrudate compared to that of the coal might be attributed to a loss of lower hydrocarbons during the extrusion process.

The gas samples taken after the run show one basic difference between the plasticized and non-plasticized samples. For the former, the CO/CO_2 ratios are in the range from 0.42 to 0.67 whereas for the latter they range from 1.04 to 1.69. We have already mentioned that the steam temperatures are higher in case of plasticized coal. Equilibrium considerations show that CO rather than CO_2 should be favored at higher temperatures. The desired shift from CO_2 to CO does not take place in the sprayed coal as it does in the pulverized coal. We may deduce that the final gas is far from equilibrium, and its composition is determined by reaction kinetics of gasification and water shift reactions.

C. CONCLUSIONS

Experimental measurement of the extent of volatilization of pulverized raw coal and pulverized extrudate shows that the raw coal undergoes more extensive gasification and better yields in terms of a higher CO/CO_2 ratio.

Comparisons of the extent of reaction of hot sprayed plastic coal with pulverized raw coal were unreliable due to incomplete spray formation. The reactions of the spray coal were far less advanced than the reactions in the case of either pulverized raw coal or pulverized extrudate.

D. FUTURE PLANS

We recommend that the reactivity studies should be done in a steady state mode with a well-defined pressure, temperature, and residence time. The existing piston-die and reaction chamber apparatus can be incorporated into such a system. However, it is necessary to provide a steam generator that can supply high temperature, high pressure steam at steady flow rates.

It is known that a high pressure ratio across the die orifice is required to generate a fine spray, which is a condition violated with high pressure in the reaction chamber. Injector designs giving higher pressure drops should be studied in order to obtain a fine spray that will give the large surface area required.

SECTION VIII

APPLICATION OF THE PLASTICATING COAL PUMP TO COAL CONVERSION PROCESSES

A. SUMMARY

The plasticating coal pump developed by JPL may be applied to a number of coal gasification processes that require the continuous feed of coal into a high pressure reaction environment. The current configuration of the coal pump requires agglomerating coals for feed, which are found in commercially significant quantities in the high volatile bituminous coals of Pennsylvania, West Virginia, Ohio, Kentucky, and Illinois. Twin-screw extruders currently used in the thermoplastics industry may serve as prototype coal pumps. These extruders are currently available in sizes up to 18-tons per hour capacity.

The coal pump is proposed for use in high pressure gasifiers where coal is reacted directly with oxygen and steam to generate a medium Btu gas rich in CO and H_2. Synthetic gas may be generated with some shift in composition or hydrogen may be obtained with complete shifting of $CO + H_2O$ to $CO_2 + H_2$. Direct sprays of coal generated by the coal pump may be used in such processes as the Texaco, Shell-Koppers, Bell, Avco, and Bigas. Interface problems are believed to be solvable in these gasifiers. The main constraint is the demonstration of reliability in service of the coal pump relative to alternative feed methods such as the lock hopper and the slurry pump. If dilution by a slurry agent such as water cannot be tolerated, then the coal pump is a viable alternative.

Essentially the same configuration of high pressure coal spray into a reactor is proposed for the short residence time hydrogasification projects. Example processes that may use the coal pump-sprayer are the Cities Service/Rockwell and the Brookhaven process (if adapted to bituminous coal). The coal pump complements well the requirements for a coal feeder system in these processes.

The applicatiion of the coal pump to feed high pressure fluid bed processes such as the Hygas, the Exxon, or the Synthane processes requires more research into the mode of injection. The coal delivered by the coal pump is in a highly agglomerative state, hence it may cause problems of clump formation. Introduction into a fast moving hot, fluidized particle stream may be a solution since rapid devolatization would occur. The complex Hygas feed system includes a high pressure drying section. This section would be eliminated by use of dry feed from the coal pump.

The benefits of the coal pump used in the SRC-II process have been considered. Based on some preliminary cost estimates, there could be a 2% reduction in plant construction and operating costs if the coal pump were put in place of the more conventional slurry system.

B. ATTRIBUTES OF THE PLASTICATING COAL PUMP

1. Background

Coals that exhibit agglomerative properties may be pumped into pressurized reactors using the plasticating coal pump. Single- or twin-screw extruders accept the coal in a clean, dry, crushed state (typically -6 mesh/+40 mesh grind) and extrude the coal as a foamy fluid of high viscosity. Heating and shearing are adequate means of plasticating most eastern region high volatile bituminous coals without the need of additives or lubricants. Coal may be formed into pellets or sprayed directly in a finely atomized form into the reactor.

A feature of the plasticating coal pump is the high pressures obtainable at the discharge end. Pressures up to 2000 psi have been routinely obtained in the coal pumps operated to date.

The plastic state of coal obtained at the pump exit is a unique feature of the coal pump, compared to all other coal feed systems. The method of interfacing the coal pump with the coal conversion process is a subject of current research. We are developing a method to convert coal directly into a fine reactive spray suitable for use in entrained bed reactors.

The use of a plasticating coal pump in fluid beds is still untried. The agglomerating nature of the coal requires that the feed be introduced in a fast moving particle stream, much in the way coal is injected into the Westinghouse gasifier. It may be possible to introduce the coal pump extrudate as chopped pellets, thereby attaining a uniform controlled size.

Conventional thermoplastics extrusion devices with single screws have been successfully adapted to coal pumping both at JPL and at Ingersoll Rand, Inc. The 1.5-inch Centerline Machinery Company continuous extruder, the 1.5-inch Davis-Standard continuous extruder, and the Negri-Bossi 1.5-inch reciprocating extruder have demonstrated plastic state extrusion. Pumping rates from 40 to 200 pph have been reported. In the larger single-screw machines, feed screw instabilities occur due to the feedback of venting gases and condensing moisture. Control methods, such as venting the excess gases from the barrel, have been developed. In practical applications, venting gases would lose potentially valuable materials so that the twin-screw continuous extruder without vents is more desirable.

Plasticating extrusion has been demonstrated on the Werner and Pfleiderer ZSK-57 twin-screw extruder at rates up to 350 pph. The twin-corotating screw prevents build-up of oil, tar, and particulate material on the cooler parts of the screw. It has a positive feed action which overcomes the clogging problems of the single screw. Twin-screw extruders theoretically capable of delivering 18 tons per hour of coal have been built and are in use in the plastics industry.

2. Characteristics

The power requirements for plasticating screw extruders are determined by the amount of energy that can be imparted to the coal to raise its temperature and pressure. The net energy imparted to coal for a final temperature and pressure of 800°F and 1500 psig, respectively, is 212 hp-hr/ton. The heater and mechanical power capabilities of the extruder should be these values with additional power to overcome losses. Hence, the total power requirement of the extruder is estimated to be about 252 hp-hr/ton. Large size extruders operate in a region where the shaft power supplies 75 to 100% of the total energy. The remaining energy is supplied by heating coils surrounding the barrel of the coal pump.

Analytical scale-up studies to predict the performance of larger single-screw extruders are reported in Reference 3-1. Throughput as a function of extruder size was determined for the various functional zones (solids conveyance, plasticating, and pumping) of an extruder through the use of computer simulations and power law approximations developed by the plastics industry. The limiting factor in the scale-up is the plasticating capacity of the extruder which is roughly proportional to the shear work transfer area available; hence, the throughput of an extruder increases with the square of the diameter. The capacity of a single screw extruder vs. diameter is plotted in Figure 8-1. The shaded area represents the capacity of conventional extruders based on the scale-up of the 1.5- and 2.5-inch coal extruder data (References 3-1 and 3-2).

Twin-screw extruders scale-up correlation is based on experimental data on polymers. The dependence of throughput rate on the extruder size varies approximately as the diameter cubed for cases where most of the energy is imparted through shear work. The twin-screw extruder has much higher throughputs compared to the single screw of the same screw diameter. An estimate of the capacity for coal pumping of various size twin-screw extruder models currently in production at the Werner and Pfliederer Company has been furnished (Reference 3-2) and is presented in Figure 8-1 along with the single screw data. It is evident that the manufacturer's scaling estimate follows the cubic law and that a more compact machine will deliver comparable capacity.

3. Coals Extruded

A list of coals that have been tested for extrudability in the 1.5-inch Centerline coal pump is given in Table 8-1. A criterion of at least one hour at a steady state flow rate of 20 lb/hr was required for a coal to be deemed acceptably extrudable. The western subbituminous coals are notably not agglomerating, hence, not extrudable. A low volatility coal, Pocahontas No. 3, while not extrudable by itself, has been shown to be extrudable when mixed with a highly fluid coal like Pittsburgh No. 8. It is evident that coals that are considered marginally plastic, such as Kentucky No. 9, Illinois No. 6, and Elkhorn No. 1 which have maximum Gieseler fluidities of 16, 5.5, and 15.4 ddpm, respectively (ddpm is a relative measure of fluidity), compared to very fluid coals such as Pittsburgh No. 8 (Gieseler fluidity > 25,000 ddpm) can be extruded .

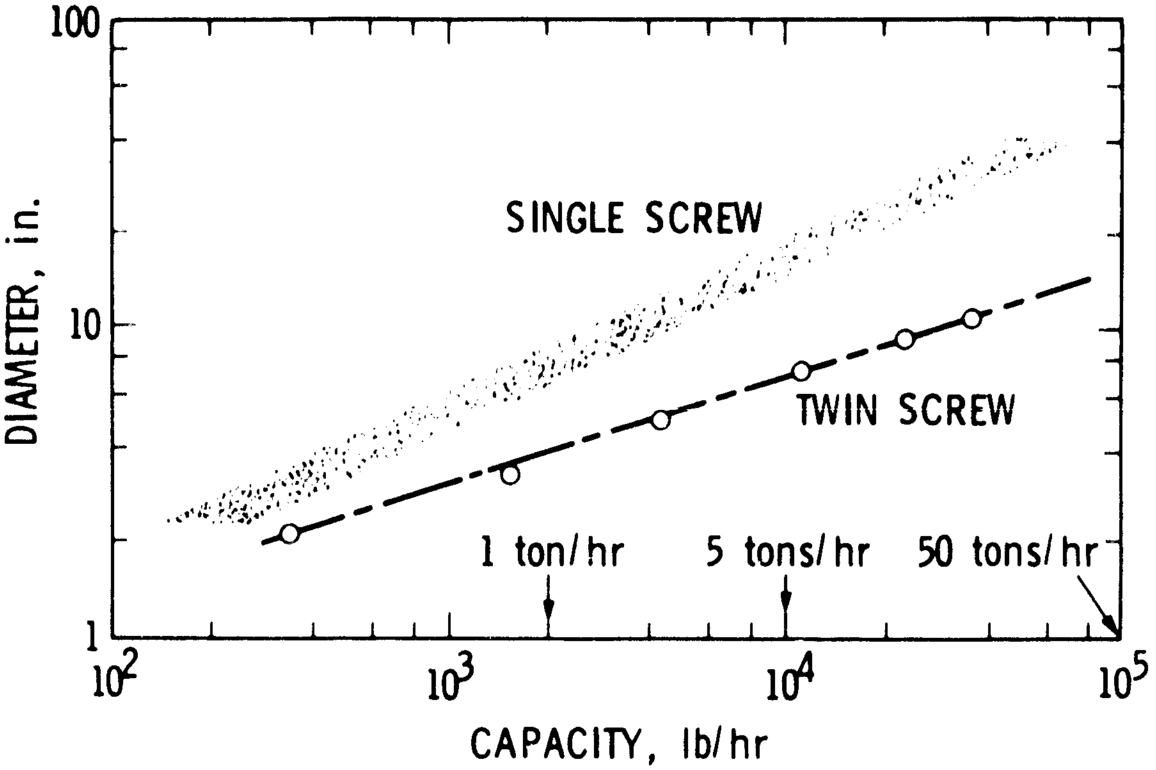

Figure 8-1. Size and Capacity of Thermoplastic Screw Extruders Adapted for Use as Coal Pumps. Shaded areas are estimated commercial single-screw extruders used as coal pumps. Twin-screw extruder performance estimate for coal pumping is given by Werner & Pfliederer, Inc.

Table 8-1. Coals Tested in the Plasticating Coal Pump for Extrudability

Coals	Maximum Fluidity Temperature °C	ddpm[a]	U.S. Reserve (10^6 tons)
Extrudable			
Pittsburgh No. 8	414-459	25000	16320
Kentucky No. 9	430	16	6590
Kentucky No. 11	435	6238	670
Ohio No. 9	435	114	1640
Illinois No. 6	425	5.5	29000
Elkhorn No. 1	450	15.4	850
Milburn	not available		
Lower Freeport	not available		
Elkhorn/Hazard (50/50)	not available		
Pittsburgh/Pocahontas (75/25)	not available		
Not Extrudable			
Pocahontas No. 3	480	1.8	
AMAX Wyodak	---	0.5	

[a] Dial divisions per minute as defined in the Gieseler test for coal plasticity (ASTM D 2639-74).

4. Advantageous Features

In order to examine the application to different coal conversion processes, the distinctive advantageous features of the plasticating coal pump compared to other feed systems are summarized:

- High discharge pressure can be obtained. The fluidity of coal is such that pressures of 1000 to 3000 psig at the coal pump discharge can be obtained routinely.
- No lubricants, additives, or slurrying agents need to be used to obtain smooth plastication.
- The discharge product is a plastic-like fluid.
- The fluid can be sprayed.
- The coal is hot (800 to 900°F).
- Crushed coal (-6 mesh) rather than pulverized coal (-20 mesh) is used as feed.

- The holdup of coal in the feed system is small relative to other feeder systems of comparable capacity.

- Commercially available thermoplastic extruders of standard design have been used successfully as prototype coal pumps.

- Numerous competitive designs are available for evaluation in seeking better operating characteristics.

- Commercial designs of extruders are available for up to 15 to 20 tons per hour capacity.

- Catalysts can be admixed efficiently even in very small amounts due to the thorough kneading action of the screw in the coal pump.

- With twin-screw extruders, there is positive feed in the screw.

- With non-agglomerating coals or chars, slurry pumping can be obtained using 10 to 20% addition of a slurrying agent, such as water. This is much less than other slurry pump methods.

- The coal pump may be used to simultaneously slurry and heat if a suitable waste fluid stream is available.

- Agglomerating coals need not be oxidatively pretreated with loss of valuable volatile matter.

- Most potentially reactive gases and volatile matter formed during the heating process inside the coal pump are contained and captured.

5. Potential Problem Areas

The plasticating coal pump must be integrated into the feed system and reactor process due to the unique form of coal at the pump outlet. This may be advantageous if integration results in process simplification, lower capital cost, and lower operating costs. It will, however, increase design uncertainty, and, hence increase the development risk. More information is needed on the coal pump at larger scales of operation in order to reduce those risks.

The treatment of the plastic coal to obtain a char-like solid, such as in fluid bed applications, needs to be developed. The control of the agglomerative properties once they have been exploited in the coal pump process is a subject of concern.

The attainment of spray either in a gas atomized form or with pressure atomization has been demonstrated. Sprays with mean particle sizes between 1.2 to 2.0 mm have been obtained with gas atomizers. Batch atomization into particles of less than 5-micron size has been demonstrated. Long duration spray capability into pressure needs to be demonstrated in order to show that injector wear and plugging can be adequately controlled.

The wearing of exposed surfaces in the plasticating coal pump has not been investigated. Current experience is limited to several hundred hours of operation on a small coal pump with several screws. Wear of one pump with a heat treated stainless steel screw was measured at 60 ppmp (pounds per million pounds throughput). It is expected that wear on the order of less than 1 ppmp can be achieved by using resistant alloy steels. Small scale demonstrations, however, are not good indicators of wear to be expected on large machines, so larger scale tests will be required to demonstrate the wear resistance of larger machines.

The long-term stability of operation when there are upsets due to wear in the screw, changes in coal properties, changes in operating conditions, malfunctions in the system, and other factors has to be demonstrated.

The reactivity of the coal after extrusion has been tested. These tests have been done on coal that has been pumped through a coal pump and then cooled. These recovered samples were then subjected to comparative test of conversion in liquefaction and gasification tests. Results have been reported in previous reports (References 3-1 and 3-2) and in Sections VI and VII of this report.

The coal pump heats coal to about 750° to 880°F for about 1 to 2 minutes. Some loss in volatile matter occurs (2.5 to 4.5 percent on a moisture and ash free basis) and the ash percentage increases. The fraction extractable by a dimethylformamide is increased somewhat, but essentially no change in the free swelling index results. Thermogravimetric analyses show the extrudate to volatilize slower (about 40% decrease in maximum rate) and to a lesser extent than the parent coal.

A small (about 2 to 5 percent) decrease in the extent of conversion is observed in uncatalyzed hydroliquefaction tests. Similar data were obtained in tests with CoMo catalysts.

It should be pointed out that any volatile matter lost during the coal pumping process would be recovered in practice, and, hence, be counted as part of the yield. The loss in reactivity may be more apparent than real since again in practice, one would not cool the extrudate to room temperature and to atmospheric conditions which causes the loss of some volatile matter.

C. COAL CONVERSION PROCESS STUDY

In a study of dry coal feeders for pressurized coal conversion processes, a preliminary judgment was made on the application of the JPL plasticating coal pump. The summary is tabulated in Table 8-2, where various coal conversion processes of recent vintage are listed. The coal feed requirements in terms of size, pressure, current feed system demonstrated. Long duration spray capability into pressure needs to be demonstrated in order to show that injector wear and plugging can be adequately controlled.

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	Grind	Feed	Meter	Dry	Pre Treat	
Gasification Process and Type	Coal Size Requirements	Reactor Operating Pressure Range psig	Conversion Reactor Feed Method	Reactor Feed Moisture Wt. Percent		
AI Molten Salt (Rockgas) Molten Salt Gasifier	Minus 1/4 inch x 0 (Coal is mixed with sodium carbonate)	150-280	Recycle Gas Injection with Sodium Carbonate	10 or less	No	Stea
AVCO High Thruput Gasification (Formerly Controlled Explosive) GRI	70% - 200M	150-900	Lockhopper + dense flow	2	No	Prod
Babcock & Wilcox Entrained Flow Slagging Gasifier	70-90% Minus 200M	ATM-300	Lockhoppers + tangential pneumatic injection into 8 nozzles	2	No	O_2 bl to g
BCR Low BTU Fluid Bed Gasifier	60% Plus 200M, 40% Minus 200M + 325M	Up to 235	Lockhopper + gravity	2	Yes	Stea
Bell High Mass Flux Gasifier	70% - 200M	450	LH + N_2 Dense Flow	Surface Dried	No	Air c
Bi-Gas BCR Entrained Flow Slagging Gasifier	70% Minus 200M 100% Minus 80M	500-1500	Slurry flash dried-dry coal injection w/steam thru eductors	2-4	No	O_2 bl throu
Catalytic Coal Conversion Fluid Bed TRW	70% - 200M	ATM-135	LH to reactor Dense phase to regenerator	2		Char
Catalytic Coal Gasification Fluid Bed Exxon	-8M + 100M	500	Coal + Catalyst + LH + Gravity	2	No	Feed reco
Clean Coke Process - U.S. Steel Fluidized Bed Carbonizer	10 x 100M Coal, Solvent + H_2	Carbonizer = 150 Hydrogenator = 4500	LH + Gravity slurry	2	No	Make No e
CS-R AI Hydrogasification	70% - 200M	500-2000	LH + Dense Flow w/N_2	Surface Dry	No	Exter from
Merc Stirred Bed Fluid Bed Gasifier	50% Less Than 1/2 inch	ATM-285	Lockhopper	ROM Moisture	No	Air b
Exxon Fluid Bed - Bottom Feed	-8M + 100M	500	LH + Recycle gas	2	No	Gasif
Exxon Donor Solvent Liquefaction Process	70% - 200M	250	Slurry + H_2	2	No	Exter
Fast Fluid Bed HRI	-20M x 0	150	LH + Gravity	2	?	2nd-- suppl
Fischer-Tropsch RMP Entrained Slagging Gasifier (Modified BI-Gas Type)	20M x 200M (20% - 200M OK)	468	4 Extruders to Stage 2 4 Extruders to Stage 1	2	No	Steam
Foster Wheeler Entrained Flow Slagging 2 Stage Gasifier	70% Minus 200M 100% Minus 80M	350	Lockhoppers and injected into stage 2	2	No	Air-b with
GE Gas GE Fixed Bed	-1/16 inch x 0	150-1100	Screw direct	ROM	No	Fines Deep
H-Coal HRI Ebullating Bed	-14M x 0	3000	Slurry w/solvent bottom fed	2	No	Testi Under
Hygas IGT Fluid Bed Hydro Gasifier	Minus 10M Plus 100M	1155-1165	Low Pressure Feeder (Feeds Coal Pretreatment Vessel) - Slurry to Gasifier	ROM	Yes	Hydro pretr for c
Koppers Totzek Entrained Flow Slagging Gasifier	70-90% Minus 200M	ATM 450	Lockhoppers + steam	1-8	No	O_2 bl type
Lurgi Slagging Conoco Fixed Bed Gasifier	1/8 inch x 1-1/2 inch	300-445	Lockhoppers	ROM	No	O_2 bl
M.H.D. AVCO Entrained - High Velocity	70% - 200M	150-300	Petrocarb L. H. System w/Air	2-5	No	Air b
Mountain Fuel Resources High Rate Entrained Flow	70% - 200M	150-200	LH + Recycle gas + coal to top of reactor	Surface Dry		O_2 =
Oil/Gas Complex RMP Entrained Bi-Gas Type	20M x 200K	1000	Screw to gasifier	2	No	1 Gas
Otto Rummel Entrained Flow Slag Bath Gasifier	Minus 16M x 0	ATM-360	Recycle Syn Gas + Lockhopper - High Velocity Injection	Surface Dry only req'd		O_2 bl injec
POGO RMP Entrained 2 Stage - New Type	70% - 200M	500	2 Screws to Pyrolyzer	2	No	Char 2 pyr
Riley Morgan Fixed Bed Gasification	2" x 1-1/4"	ATM + 1	Lockhopper	Surface Dry	No	Rotat
SRC-1 PM	70% - 200M	2000	Coal + Solvent + H_2 Slurry Pumped to Dissolver	2	No	Exter
SRC-2 PM	70% - 200M	2000	Slurry is Preheated	2	No	Exter
Synthane Lummus Fluid Bed Gasifier	Minus 20M + 325M	600-1000	Petrocarb Lockhopper System to Pre-treater - Gravity Disch. to Gasifier	2	Yes	O_2 bl requi bypas direc
Texaco Entrained Flow Slagging Gasifier	Pulverized	300-1200	Pressurized Water Slurry	2	No	O_2 bl (Dry
Westinghouse Fluid Bed Gasifier	Minus 6M + 100M	130-200	Pneumatic Injection w/Recycle Gas to Devolatilizer	Surface Dried	No	Air
Zinc Chl. Catalyst - Conoco Liquefaction	70% - 200M	1500-3500	Slurry w/Oil	2	No	Exter added

LH = Lockhopper
LPF = Linear Pocket Feeder
KE = Kinetic Extruder
C = Centrifugal
JPL = Extruder
IR = Screw + Ejector + Breaker
( ) = Number of gasifiers

Feed Moisture

[illegible] = [illegible]
LPF = Linear Pocket Feeder
KE = Kinetic Extruder
[illegible] = Centrifugal
[illegible] = Extruder
[illegible] = Screw + Ejector + Breaker
[illegible] = Number of gasifiers

FOLDOUT FRAME

Table 8-2. Process Summaries

ed Operating e Range sig.	Meter Conversion Reactor Feed Method	Dry Reactor **Feed Moisture** Wt. Percent	Pre Treat	Process Notes	Design Basis	(Coal) Capacity TPD	Feeder Application Potential
-280	Recycle Gas Injection with Sodium Carbonate	10 or less	No	Steam and Oxygen blown	PDU Pilot Comm. Concept	24 120 19,000	LPF IR Piston
-900	Lockhopper + dense flow	2	No	Products are $CO + H_2$	Bench	24	KE-C-JPL
-300	Lockhoppers + tangential pneumatic injection into 8 nozzles	2	No	O_2 blown operation. Char is recycled back to gasifier - pneumatically injected.	Pilot Plant Comm.	60 850 per unit (8 nozzles)	KE-C
o 235	Lockhopper + gravity	2	Yes	Steam Air Operation	PDU	1-1/4	KE-C-IR
50	LH + N_2 Dense Flow	Surface Dried	No	Air or Oxygen blown	[illegible] Facility by Bell	12	KE-C-JPL
-1500	Slurry flash dried-dry coal injection w/steam thru eductors	2-4	No	O_2 blown operation. Char fed with steam through eductors back to gasifier	Pilot Plant Commercial Planned	120 3750 (1) (2 nozzles)	JPL
-135	LH to reactor Dense phase to regenerator	2		Char feed to reactor and generator	Bench Comm.	1/10+ 4700	KE-C
00	Coal + Catalyst + LH + Gravity	2	No	Feed is to top of bed - catalyst is recovered. H_2 from cryogenic distillation	Pilot Plant	1/10	LPF-Piston IR
r = 150 tor = 4500	LH + Gravity slurry	2	No	Makes coke + feedstocks — Existing No external source of H_2 req'd — Planned Envisaged	5 PDUS Pilot Plant Comm.	1/4 ea. 100 17,000	LPF, Piston JPL
-2000	LH + Dense Flow w/N_2	Surface Dry	No	External Source hot H_2 required - char from process used in H_2 generator	Pilot Comm. (36 nozzles)	6 2592	JPL
-285	Lockhopper	ROM Moisture	No	Air blown operation	PDU	2	IR-Piston-LPF
00	LH + Recycle gas	2	No	Gasifier is fed from bottom	PDU Commercial Planned	1-1/4 3000	LPF-Piston-IR-JPL
50	Slurry + H_2	2	No	External Source of H_2 required — Tested Designed	Pilot Plant Pilot Plant	1 250	KE-C-IR-JPL
50	LH + Gravity	2	?	2nd--Slowbed gasifier used to supply char thru transfer leg.	PDU	7-1/4	LPF-Piston-IR
68	4 Extruders to Stage 2 4 Extruders to Stage 1	2	No	Steam is required for both coal and char	Commercial (Proposal)	13,256	LPF-IR-JPL
50	Lockhoppers and injected into stage 2	2	No	Air-blown operation. Char is injected with steam back to Stage 1	Pilot Plant	480	KE-C
-1100	Screw direct	ROM	No	Fines and Tar mixed w/Coal Deep Bed agitation.	PDU	15	IR-PISTON-JPL
00	Slurry w/solvent bottom fed	2	No	Testing completed in 1974 Under construction in Ky.	PDU Pilot Comm. (Envisaged)	3 600 18,600	JPL
-1165	Low Pressure Feeder (Feeds Coal Pretreatment Vessel) - Slurry to Gasifier	ROM	Yes	Hydro gasification process. Coal is pretreated in a low pressure fluidized bed for caking coals	Pilot Plant Demo Commercial	75 10,000 (1) 16,000 (2)	JPL
TM 50	Lockhoppers + steam	1-8	No	O_2 blown operation and steam pressure type under development	ATM-Commercial Hi-Pressure-Pilot	860 430	KE-C-JPL
-445	Lockhoppers	ROM	No	O_2 blown operation	Pilot Plant in Scotland	800+	LPF-Piston-IR
-300	Petrocarb L. H. System w/Air	2-5	No	Air blown - seed fed in slurry	Pilot Plant At Butte	144	KE-C
-200	LH + Recycle gas + coal to top of reactor	Surface Dry		O_2 + steam blown from top — Completed Designed Planned	Bench Testing Pilot Plant Commercial	1/2 30 600	KE-C
000	Screw to gasifier	2	No	1 Gasifier - 4 Feeders indicated	Commercial (Design)	10,000	JPL-IR
-360	Recycle Syn Gas + Lockhopper - High Velocity Injection	Surface Dry only req'd		O_2 blown operation. Coal, steam + O_2 injected thru 50 ml nozzles.	Commercial	850 (1) (4 nozzles)	LPF-Piston-IR
00	2 Screws to Pyrolyzer	2	No	Char is fed to gasifier pneumatically 2 pyrolyzers with 2 feeders each shown	Commercial (Proposal)	7000	KE-C-JPL
+ 1	Lockhopper	Surface Dry	No	Rotating grate	Commercial	2000	LPF-Piston-IR
00	Coal + Solvent + H_2 Slurry Pumped to Dissolver	2	No	External source H_2 required — Operating	Pilot Plant	50	JPL
00	Slurry is Preheated	2	No	External source of H_2 req'd — Operating Concept	Pilot Plant Commercial	50 33,000	JPL
1000	Petrocarb Lockhopper System to Pre-treater - Gravity Disch. to Gasifier	2	Yes	O_2 blown operation. Pretreatment is required for caking coals - Feed system bypasses pretreater and feeds gasifier directly for non-caking coals.	Pilot Plant Comm. Concept (3 units req'd)	75 16,000	IR-JPL
1200	Pressurized Water Slurry	2	No	O_2 blown operation (Dry feed type being evaluated)	Pilot Plant Comm.	145 *1000 (1)	JPL
-200	Pneumatic Injection w/Recycle Gas to Devolatilizer	Surface Dried	No	Air blown gasifier — Existing in Construction	Pilot Plant Commercial	120 8000	LPF-Piston-IR
-3500	Slurry w/Oil	2	No	External source of H_2 required - H_2 is added to slurry in hydrocracker.	PDU	1-1/2	JPL

FOLDOUT FRAME 2

Table 8-2. Process Summaries

Feed Moisture

FOLDOUT FRAME 2

pretreatment, and moisture are listed. In the last column, advanced concept continuous dry coal feeders which might be applicable to the process are named.

In judging applicability, the pressure of the system, the size of the coal feed, and the slurry agent, if any, were considered. The JPL plasticating coal pump is useful for high pressure reactors (above about 500 psig) or where a very fine spray of coal is required. The delivery of coarse dense particles required in the Lurgi fixed bed and the MERC stirred bed are considered outside the JPL coal pump capability. The judgments are somewhat arbitrary in that later considerations have indicated the possibility of applying the coal pump to fluid bed reactors.

A more detailed study was carried out on several of the more promising potential applications. The processes chosen are the Hygas, Bell, Exxon, Rockwell, Texaco, Shell-Koppers, Bigas, and SRC-II. In each, the basic process was reviewed and then a conceptual change from the originally diagramed feed system to a JPL coal pump was made. Preliminary assessment of the benefits of these changes were made on a subjective basis. The quantitative effects of changes were estimated crudely and, in most cases, with a fair element of optimism. All estimates of sizes and throughputs need to be subjected to more critical scrutiny, but for a preliminary study it was held to be more important to give some crude estimate than to withhold it pending verification.

1. Hygas Hydrogasifier with Steam-Oxygen Gasification

a. Description. Coal feed for this process is in the size range of 10 to 100 mesh. Bituminous coals are first pretreated by air oxidation in a fluidized bed at atmospheric pressure at 800°F. Pretreated coal is slurried with water and then fed to the hydrogasification reactor. (See Figure 8-2.)

The reactor consists of four stages: slurry drying, first stage hydrogasification, second stage hydrogasification, and steam-oxygen gasification. The slurry is pumped into the top of the reactor at 1200 psig, and it is dried in the top section. Dry coal flows by gravity through a dipleg into a lift pipe which serves as the first stage of hydrogasification. Here, a dilute phase contact occurs between the coal and the gases from the second stage.

As the dried coal is lifted by hydrogen-rich gas at 1700°F, it is heated to 1200° to 1300°F, and approximately 20% of coal is converted to methane. Twenty-five percent more coal is converted in the second stage to yield methane, hydrogen, and CO. This stage is a dense phase, fluidized bed reactor operating at 1700° to 1800°F. The hot gases rise to the first stage and then to the dryer.

The partially depleted char leaving the second stage is used to produce hydrogen in the steam-oxygen gasification section.

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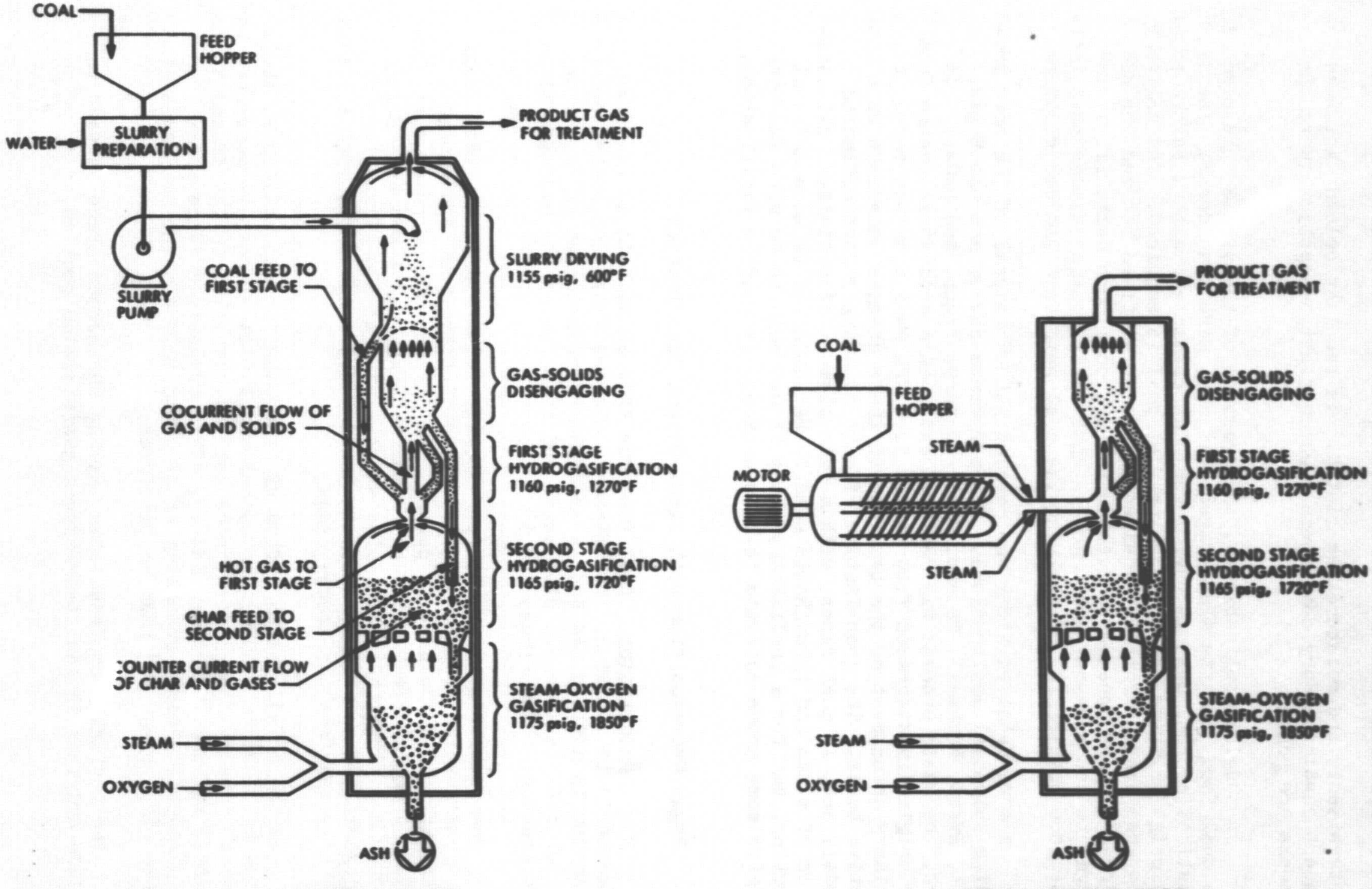
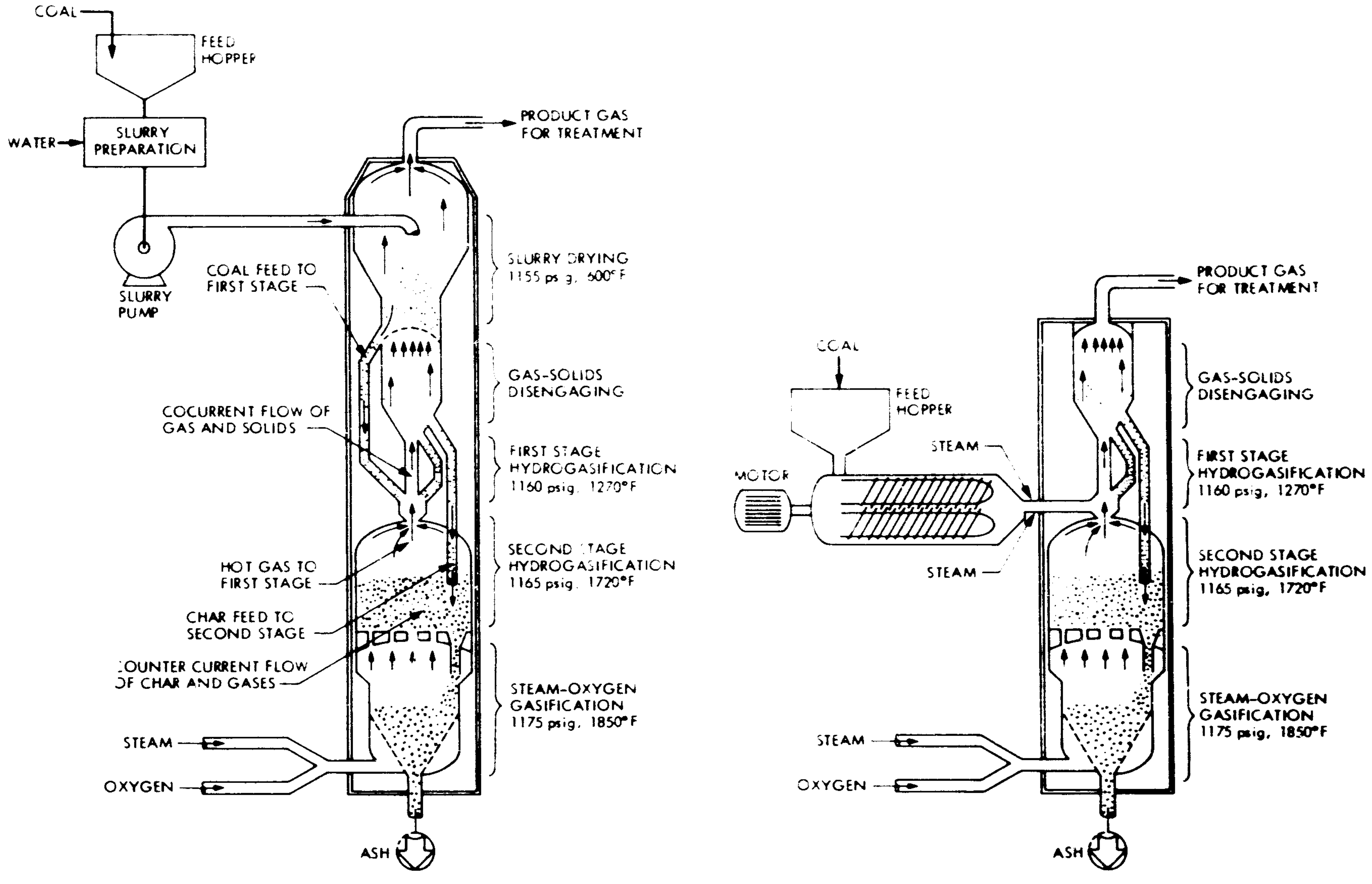


SLURRY FEED

COAL PUMP FEED

Figure 8-2. Hygas Hydrogasifier With Steam-Oxygen Gasification



SLURRY FEED

COAL PUMP FEED

Figure 8-2. Hygas Hydrogasifier With Steam-Oxygen Gasification

b. **Research Program.**

1) **Testing Scale.**

- 35 feet high, 5.5 feet I.D. hydrogasification reactor with a capacity of 80 TPD of coal.

2) **Operating Conditions.**

	Pre-treater	Slurry Dryer	Hydrogasifier Stage First	Hydrogasifier Stage Second	Steam-Oxygen Gasifier
Temperature, °F	800	600	1270	1720	1850
Pressure, psig	15	1155	1160	1165	1175

3) **Mode of Operation.**

- Non-slagging fluidized bed.

4) **Experimental Results.**

- 15-day self-sustained test with Montana lignite.
- Up to 65% of the methane in the SNG product is formed in the gasifier.
- Steam-oxygen method of hydrogen generation is currently preferred, but steam-iron and electrothermal gasification processes have also been studied.

c. **Parameters.**

	Parameter	Slurry	Coal Pump Feed
(1)	Coal throughput required for a 250 billion Btu/day plant	13,650 TPD (dry) to gasifier 2,057 TPD (dry) for steam plant	12,413 TPD (dry) to gasifier 1,871 TPD (dry) to steam-plant.
(1a)	Water requirements (for slurry)	13,650 TPD	---
(2)	Hydrogen consumption	---	---

(3)	Oxygen consumption	0.216 lb/lb dry coal	0.216 lb/lb dry coal
(4)	Steam consumption	0.964 lb/lb dry coal	0.964 lb/lb dry coal
(5)	Injector design	3 nozzles, 8-inch schedule 80 pipe	
(6)	Particle size	10 to 100 mesh	70% - 60 mesh
(7)	Reactor capacity	4,550 TPD	4,550 TPD
(8)	Reactor size	184-ft tall, 24-ft I.D.	136-ft tall, 24-ft I.D.
(9)	Number of reactors required	3	3
(10)	Feeder capacity	4,550 TPD	864 TPD
(11)	Feeder size		60 ft x 10 ft x 10 ft
(12)	Number of feeders required	3	6 per train
(13)	Feeder power consumption	10,000 HP_E (7.5 MW_E)	108,000 HP_E (81 MW_E)

d. Application of Coal Pump--Potential Benefits.

- The need for slurry drying section in the reactor will be eliminated. This reduces the reactor volume.
- The energy loss due to evaporation of slurry is removed. Higher exit temperature allows more heat recovery.
- Higher exit temperature also reduces tar carried overhead.
- Direct coal input into the base of the riser portion is possible. This would considerably simplify the complicated arrangement of internal equipment.
- The pretreatment step is completely eliminated; thus, the loss of volatiles and the possible reduction of coal reactivity are avoided.
- The process is basically not self-sufficient in power and process steam requirements. The coal pump application may make it nearly self-sufficient.

e. Application of Coal Pump--Technical Uncertainties.

- Coal injector design is crucial to prevent agglomeration at the low operating temperature of the fluidized bed.
- A greater control over particle size distribution of feed coal is required.
- A redesign of the hydrogasification reactor may be required to take advantage of coal feed as a fine, hot spray.

f. Conclusions.

- The slurry feed system presently used is energy wasteful.
- Coal pump usage may reduce coal requirements by about 9%. The consumption of steam and oxygen will be reduced in proportion.
- Coal pump will make it possible to simplify the design of the hydrogasifier. A more efficient, smaller reactor is likely to result.
- Six coal pump units delivering coal at 36 TPH will be adequate to feed one reactor.

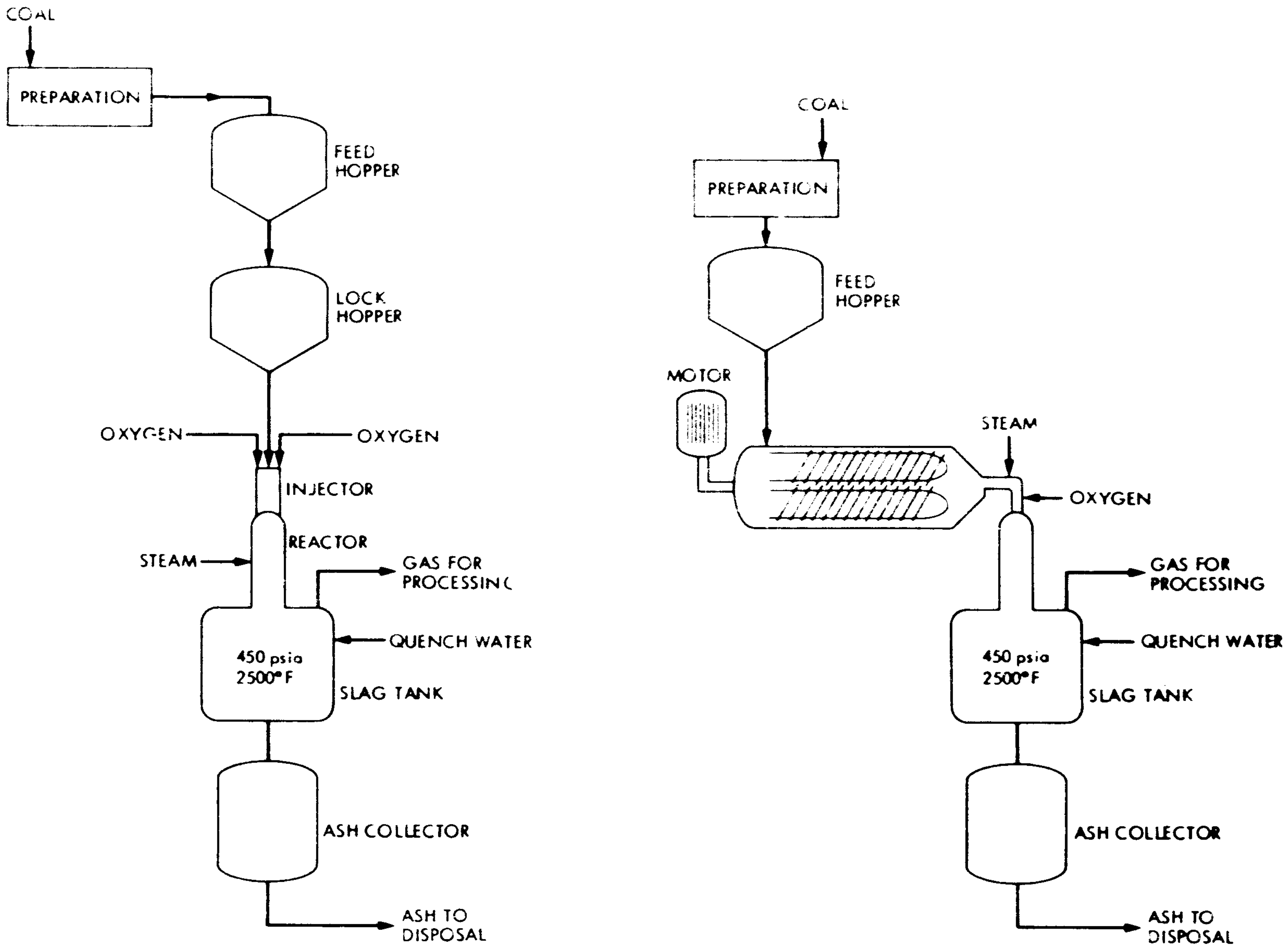
2. Bell High Mass Flux Gasification Process

a. Description. Dried, pulverized coal is fed via a dense-phase feed line into the gasifier through an axially located nozzle. Oxygen is fed in a coaxial nozzle; the coal and oxygen react to form a syngas consisting mostly of CO. Steam is injected downstream of the coal and oxygen; the entire mixture reacts to form a syngas consisting mostly of CO and H_2. Molten slag formed in the gasifier is resolidified to ash by a quench water spray. Most of the ash drops into a slag tank; the balance of the ash and any ungasified organic material, including ungasified carbon, is entrained with the syngas. Heat is recovered from the syngas and entrained solids. The bulk of the entrained solids are recovered in a cyclone from which they are sent to a steam plant to generate steam. The syngas is further cooled and particulates removed. The syngas is then sent to the downstream processing for eventual SNG synthesis. Units included in the downstream processing are shift, acid gas removal, and methanation. (See Figure 8-3.)

b. Research Program.

1) Testing Scale.

- 0.5 ton/hour capacity.



LOCK HOPPER FEED

COAL PUMP FEED

Figure 8-3. Bell High Mass Flux Gasification Process

2) Experimental Results.

- Carbon conversion efficiencies of up to 90% with lignite, Montana sub-bituminous coals, and Pittsburgh bituminous coals.
- Higher pressures are desirable for boosting the conversion of carbon.

c. Parameter.

	Parameters	Lock Hopper Feed	Coal Pump Feed
(1)	Coal throughput required for a 250 billion Btu/day plant	16,400 T/day	16,154 T/day
(2)	Oxygen consumption	0.709 lb/lb dry coal	0.670 lb/lb dry coal
(3)	Steam consumption	0.174 lb/lb dry coal	0.174 lb/lb dry coal
(4)	Injector design	Modified reverse flow, swirl type, and impinging sheet injectors	Modified injector to permit multipoint coal feed
(5)	Particle size	70% - 200 mesh	70% - 60 mesh
(6)	Feed coal temperature	60°F	900°F
(7)	Reactor capacity	3,300 TPD	3,300 TPD
(8)	Reactor size	2.25-feet I.D., 11-feet tall	2.25-feet I.D., 11-feet tall
(9)	Number of reactors required	5	5
(10)	Feeder capacity	3,300 TPD	864 TPD
(11)	Feeder size		60 ft x 10 ft x 10 ft
(12)	Number of feeders required	5	20
(13)	Feeder power consumption		120,000 HP_E (90 MW_E)

d. Application of Coal Pump--Potential Benefits.

- Coal pump can deliver hot (at 900°F) spray of fine particles of coal to the reactor and this coal can react with the oxygen and steam mixture in a short time.

- Delivery of hot coal will reduce oxygen consumption by the amount needed for coal preheat.

  - Expected savings in oxygen consumption = 0.0385 lb/lb coal.

  - Expected savings in coal consumption ÷ 0.0156 lb/lb coal.

- Coal pump has a lower cost than lock hoppers and can feed coal more reliably at high pressures than the dense feed method .

- Operation at high pressures which the coal pump may allow is expected to lead to higher carbon conversions for bituminous coals.

e. Application of Coal Pump--Technical Uncertainties.

- Each reactor is only 2.25 feet in diameter. Ten coal pump units with a capacity of 18 tons per hour will be required to deliver coal to this reactor. To achieve this a specialized design of the injector will be required.

- If such an injector cannot be designed, the reactor will have to be reduced in size so that the expected reactor throughput will not require more than four coal pump units.

f. Conclusions.

- The low carbon conversions obtained with bituminous coals may be improved by using higher pressures and better mixing is likely to result from the coal pump.

- The injector design will have to be specifically designed to create a uniform spray of fine particles from plastic coal.

- The reactor dimensions will have to be changed so that the throughput matches that given by two coal pump units. Another option is to inject coal at various points along the length of the reactor.

- Coal consumption is likely to be reduced by 1.5% and the oxygen consumption is likely to be reduced by 5.5% if the coal pump is used as a feeder.

3. Exxon Catalytic Gasification Process

a. Process Description. The feed coal is crushed to 8 mesh. A catalyst is added as an aqueous solution. The feed is dried and fed through lock hoppers to a fluid bed gasifier. The fluidizing gas is a mixture of steam and recycled CO and H_2. Unreacted steam is condensed from the reactor effluent gas, then CO_2 and H_2S are removed by conventional acid gas treating (physical solvent). The product methane is separated cryogenically from the recycled CO and H_2. The char, containing the catalyst, untreated carbon, and coal minerals, is removed continuously. About 90% of the catalyst is recovered by digestion with lime, followed by water washing and then is recycled.

The process is unique in conducting the gasification, shift, and methanation reactions in the same reactor. Potassium catalyzes the gasification reaction allowing operation at temperatures around 1,300°F. The potassium-char catalyzes the shift and methanation reactions with the result that gas phase equilibrium is attained. The lower reactor operating temperature shifts the equilibrium in favor of methane. Since the only products removed from the reactor are methane, CO_2, H_2S, and NH_3 (CO and H_2 are totally recycled), and since the exothermic heat of the shift and methanation reactions essentially balance the endothermic heat of the gasification reaction, the gasifier requires no oxygen or air for heat input. Preheating the steam and CO plus H_2 recycle gas to about 1,550°F is sufficient to balance heat losses from the reactor. The catalyst destroys the caking tendency of bituminous coals and renders pretreatment unnecessary. (See Figure 8-4.)

b. Research Program.

1) Testing Scale.

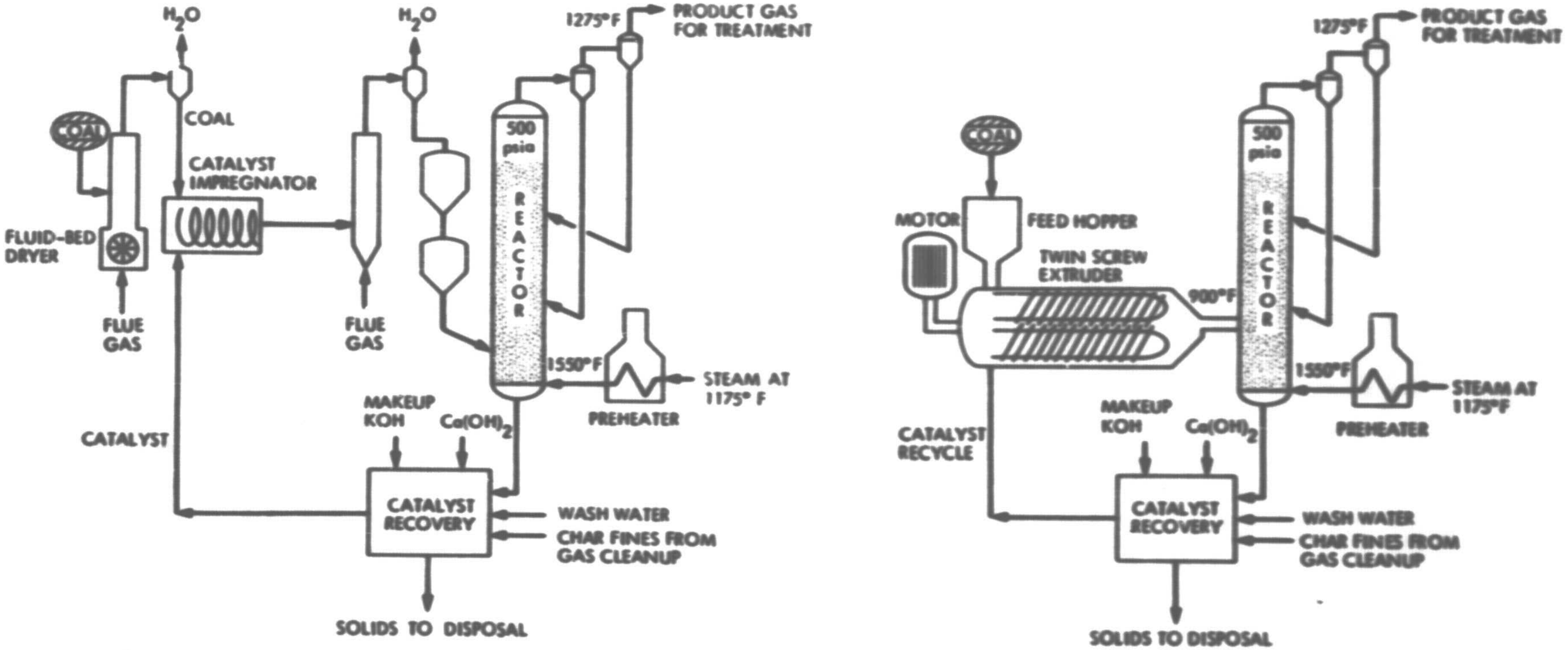
- 6-inch diameter x 40-feet tall fluid bed gasifier.
- 1 T/day process development unit.

2) Operating Conditions.

- 15% by weight catalyst (as K_2CO_3) on dry feed coal.
- Operating temperature 1,275°F.
- Operating pressure 500 psia.

3) Experimental Results.

- Carbon conversion 80 to 90%.
- Steam conversion 40 to 60%.



LOCK HOPPER FEED WITH A SEPARATE CATALYST IMPREGNATOR

COAL PUMP FEED

Figure 8-4. Exxon Catalytic Gasification Process

c. Parameters.

Parameter	Lock Hopper Feed	Coal Pump Feed
(1) Coal throughput required for a 250 billion Btu/day plant	14,500 T/day	14,500 T/day
(2) Hydrogen consumption	---	---
(3) Oxygen consumption	---	---
(4) Steam consumption	1.6 lb/lb dry coal	1.4 lb/lb dry coal
(4a) Catalyst consumption	190 T/day	Less than 190 T/day
(5) Injector design	Multiple coal injector points at the bottom of the gasifier	Multipoint coal injection
(6) Particle size	8 mesh	8 mesh
(7) Feed coal temperature	300°F	900°F
(8) Reactor capacity	3,600 T/day	3,600 T/day
(9) Reactor size	22-feet I.D., 97-feet high	22-feet I.D., 97-feet high
(10) Number of reactors required	4	4
(11) Feeder capacity	3,600 T/day	864 T/day
(12) Feeder size		60 ft x 10 ft x 10 ft
(13) Number of feeders required	4	16
(14) Feeder power consumption		96,000 HP_e or 72 MW_e

d. Application of Coal Pump--Potential Benefits.

- The extruder will simplify mixing coal with the catalyst. Mixing the catalyst with plastic state coal is likely to result in the same coal conversion.

- The catalyst has a tendency to gradually destroy the caking tendency of coal. The advantage of this property may be taken to design the extruder so that a non-agglomerating extrudate can be produced.
- Use of the coal pump may lead to reductions in the costs for coal preparation and handling, catalyst impregnation, and steam preheat furnace.

e. Application of the Coal Pump--Technical Uncertainties.

- Catalyst addition is likely to complicate the design of the extruder.
- The gasifier operates at a low temperature of 1,300°F. There could be operating problems if the extrudate has any residual caking tendency.

f. Conclusions.

- A commercial plant will use 12% less steam. At 1.6 lb/lb dry coal, steam usage is a big cost item in the current design.
- The coal pump system will reduce the cost of the catalyst addition system.
- Further savings are likely from reduced catalyst usage and smaller reactor volume if this results in more efficient mixing between the coal and the catalyst.
- Because of limitations imposed by catalyst addition a more complex design of the coal pump may be required.

4. Rockwell Flash Hydropyrolysis Process

a. Description. This gasification process consists of two major subsystems--a direct hydrogasification system to produce SNG and a steam/oxygen gasification system to produce hydrogen.

This process attempts direct hydrogenation of the carbon in coal to methane in a single stage reactor. The hydrogenation reaction is carried out during entrained flow of pulverized coal particles. Coal is injected into the reactor at low temperatures to prevent caking and then heated convectively by rapid mixing with injected hot hydrogen.

Excess hydrogen is supplied to the reactor to promote methane synthesis and to supply the coal-heating function. The hot product gases from the reactor are used in a heat exchanger to preheat the incoming hydrogen to about 1,500°F. Final heating of this hydrogen to 2,500°F is provided by partial combustion with oxygen.

C-2

Rocket engine injector design criteria are applied to the hydrogasifier to achieve rapid and thorough mixing of the pulverized coal and hot hydrogen. (See Figure 8-5.)

b. **Research Program**.

1) **Testing Scale**.

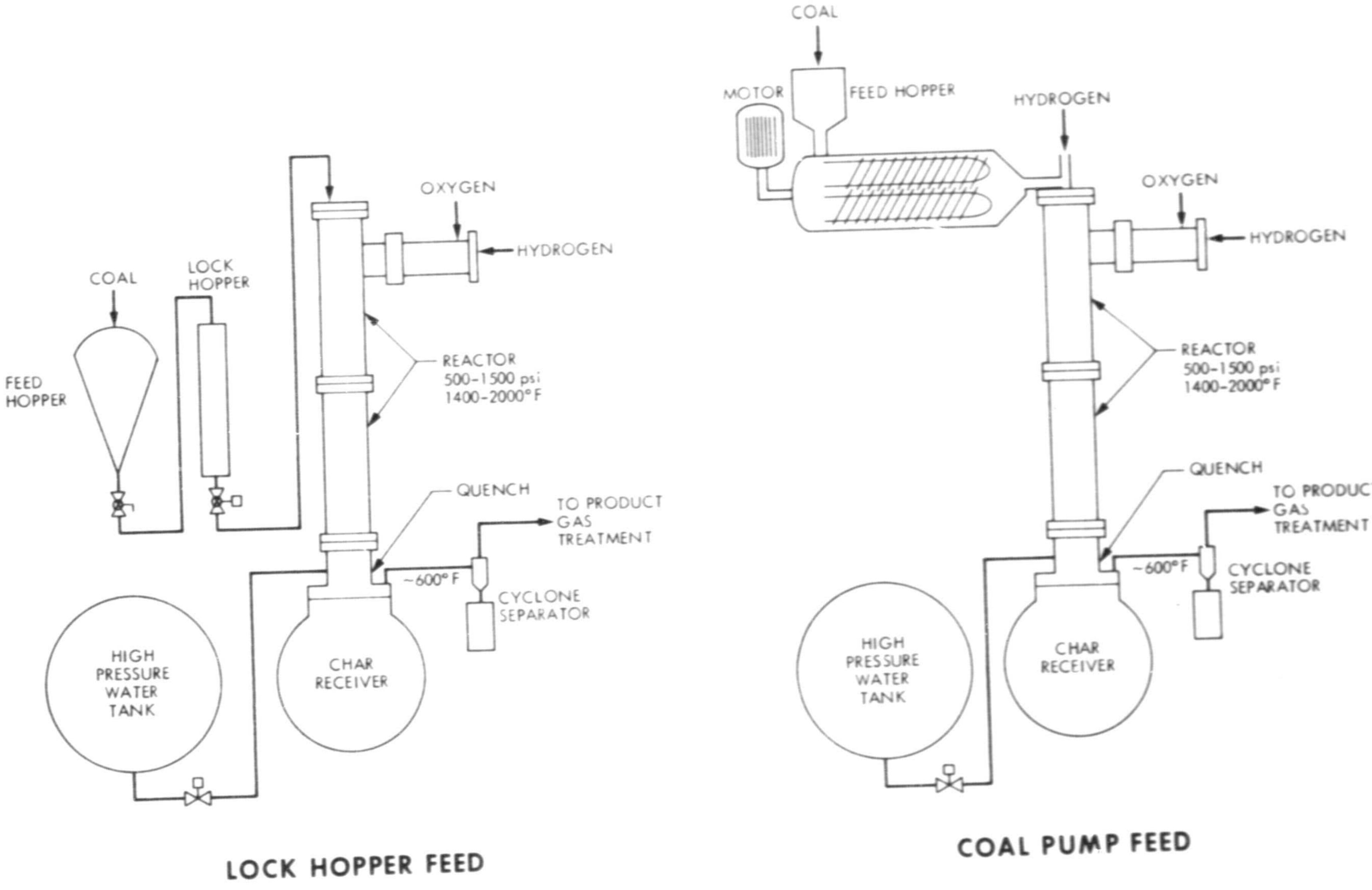
- Test data collected on 1/4 TPH unit. Presently a 3/4 TPH engineering scale testing unit is being operated. Also a 3/4 TPH integrated process development unit is being designed.
- 2.5 to 8.3-inch I.D., 15-feet tall reactor tubes.

2) **Experimental Results**.

- Overall conversion not sensitive to reactor residence time over the range from 30 to 640 milliseconds, but the carbon conversion to liquids diminishes with increasing reactor residence time.
- Overall carbon conversion increases with temperature, reaching almost 70% at 1,900°F and 640 milliseconds residence time.

c. **Parameters**.

	Parameter	Lock Hopper Feed	Coal Pump Feed
(1)	Coal throughput required for a 250 billion Btu/day commercial plant	10,817 TPD for hydrogasifier 2,545 TPD for char gasification 2,836 TPD for utilities	10,817 TPD for hydro gasifier 2,445 TPD for char gasification 2,836 TPD for utilities
(2)	Hydrogen consumption	0.08 lb/lb coal	0.0769 lb/lb coal
(3)	Oxygen consumption	0.052 lb/lb coal for hydrogasification 2.164 lb/lb coal for char gasification	0.0270 lb/lb coal for hydrogasification 2.164 lb/lb coal for char gasification
(4)	Injector design	Rocket engine type	Modified rocket engine type (hydrogen to be introduced to help in forming a spray)



LOCK HOPPER FEED

COAL PUMP FEED

Figure 8-5. Rockwell Flash Hydropyrolysis Process

(5)	Particle size	70% - 200 mesh	70% - 60 mesh
(6)	Feed temperature	60°F	900°F
(7)	Reactor capacity	4 TPH/element	4 TPH/element
(8)	Reactor size	6-inch diameter, 20-ft tall	6-inch diameter, 20-ft tall
(9)	Number of reactors required	36 elements/train, 3 trains/plant	36 elements/train, 3 trains/plant
(10)	Feeder capacity	3,500 TPD	864 TPD
(11)	Feeder size		60 ft x 10 ft x 10 ft
(12)	Number of feeders required	3	4/train, 3 trains/plant
(13)	Feeder power consumption		72,000 HP_E or 54 MW_E

d. Application of the Coal Pump--Potential Benefits.

- Delivery of hot coal (at 900°F) to the reactor will cut down on use of expensive hydrogen and oxygen needed to preheat the coal.

- Hydrogen consumption will be reduced by 0.00313 lb/lb coal and oxygen consumption will be reduced by 0.0250 lb/lb. Extra energy consumption to drive the coal pump will be 280 Btu_E/lb coal or 373 Btu_T/lb of coal.

- Introduction of a high speed spray of fine coal particles is essential to the high throughput, short residence time reactor used in this process. The coal pump can generate such a spray.

- The rocket engine type injector used in this process for intimate mixing of coal and hydrogen is entirely compatible with coal pump.

e. Application of the Coal Pump--Technical Uncertainties.

- The coal reactivity is important in this process because of short residence time. If extrudate reactivity is not comparable to the reactivity of feed coal, the product gas yield may be adversely affected. The present design of the hydrogasifier envisions a single reactor train to contain 36 reactor elements, each with its separate injector. Coal will have to be fed separately to each individual injector.

- The current injector design is based on cold operation. It will have to be modified to deal with 900°F feed coal.

f. Conclusions.

- Considerable savings are possible in consumption of coal, oxygen, and hydrogen.
  - Coal (for char gasification) 4%
  - Oxygen (for hydrogasification) 48%
  - Hydrogen 4%
- To deliver coal to each 4 TPH reactor element may require complicated piping and injector designs.
- Because of the short residence time in the reactor, the coal particle size will be an important parameter. Coal spray consisting of smaller than 60 mesh particles will probably be required.

5. Texaco Process

a. Description. The Texaco pilot gasifier is a vertical, cylindrical pressure vessel with a carbon steel shell. Coal reacts with steam and oxygen under slagging conditions in a refractory lined partial oxidation chamber in the upper portion of the gasifier. The resulting gases and molten slag particles flow downward through a water spray chamber and a slag quench bath. Quenching reduces the gas temperature in this zone to a low enough level so that processing in unlined steel equipment is possible.

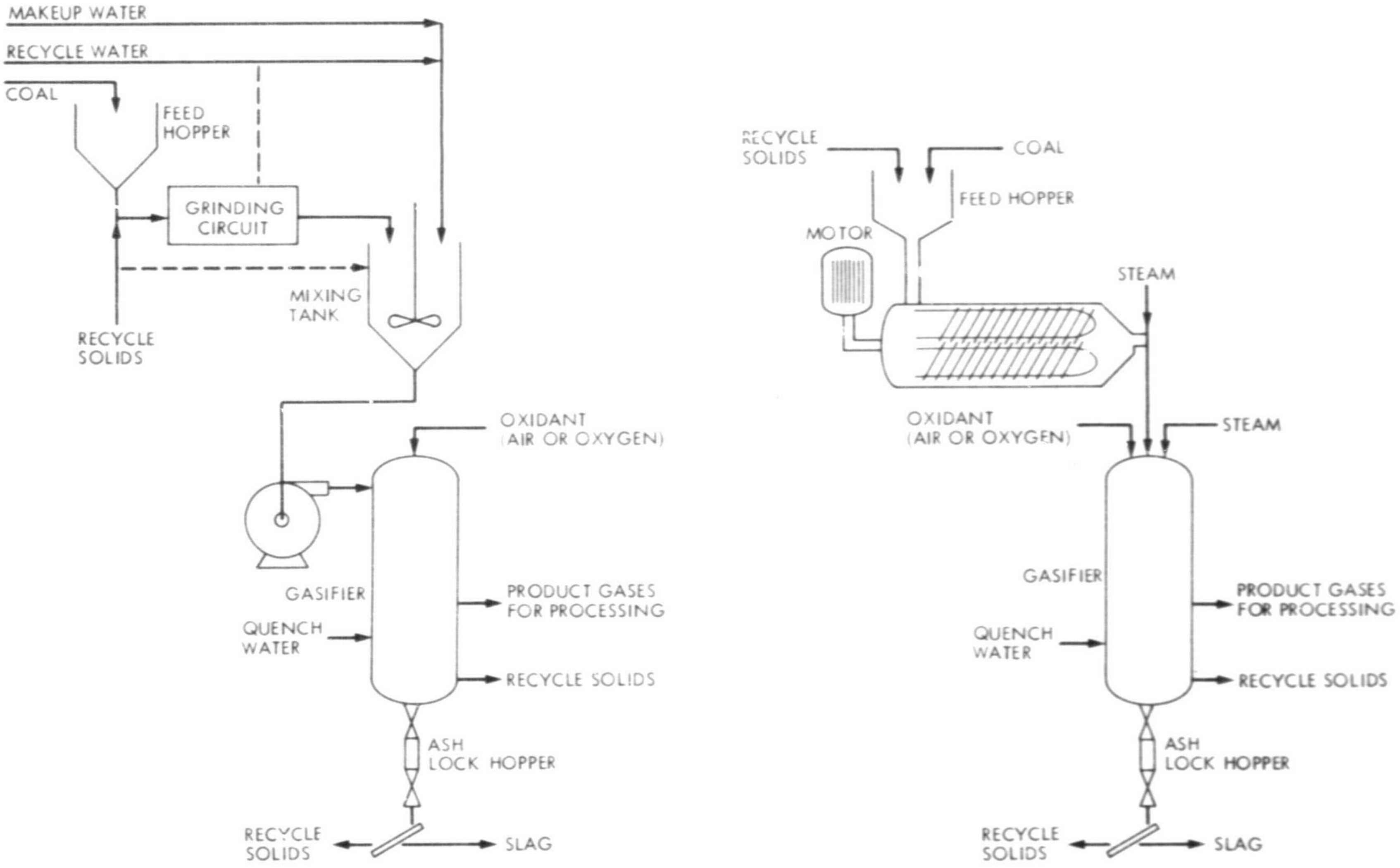
Steam and oxygen gasify the pulverized coal in the partial oxidation chamber, and the gas formed flows downward. Water is sprayed just beneath the partial oxidation chamber to cool the gas; and, as a result, a large quantity of high pressure steam is generated. The gas is further cooled as it leaves the gasifier through the water in the slag quench bath.

Entrained slag is separated from the gas in the slag quench bath and discharged through the slag pot. Product gas leaving the gasifier is further cleaned in a water scrubber to remove residual slag particles. The resulting gas is a medium-Btu synthesis gas. The slag-water mixture from the slag pot and the water scrubber is collected and separated. Slag is sent to disposal, while water is recycled either to the slag pot or the water scrubber. (See Figure 8-6.)

b. Research Program.

1) Testing Scale.

- 15 TPD pilot plant in Montebello, California.



SLURRY FEED **COAL PUMP FEED**

Figure 8-6. Texaco Process

- Two 150-TPD demonstration plants planned at Ruhrchemie Chemical Plant in West Germany, and TVA's ammonia plant in Muscle Shoals, Alabama.

- One 1000-TPD demonstration plant to be built near Barstow, California.

2) Experimental Results.

- Not published.

c. Parameters.

	Parameter	Slurry Feed	Coal Pump Feed
(1)	Coal throughput required for a 250 billion BTU/day plant	19,000 TPD	17,570 TPD
(2)	Oxygen consumption	0.858 lb/lb dry coal	0.768 lb/lb dry coal
(3)	Steam Consumption	---	0.610 lb/lb dry coal
(4)	Water consumption	0.503 lb/lb dry coal	---
(5)	Injector design	Slurry and oxygen introduced coaxially into reactor	Modified for spray formation
(6)	Particle size	70% - 200 mesh	70% - 60 mesh
(7)	Reactor capacity	3,800 TPD	3,800 TPD
(8)	Reactor size	12-ft I.D., 15-ft high	12-ft I.D., 15-ft high
(9)	Number of reactors required	5	5
(10)	Feeder capacity	4,000 TPD	864 TPD
(11)	Feeder size		60 ft x 10 ft x 10 ft
(12)	Number of feeders required	5	20
(13)	Feeder power consumption	16,000 HP_E (12 MW_E)	120,000 HP_E (90 MW_E)

d. Application of Coal Pump--Potential Benefits.

- Higher energy efficiency is possible because the energy loss due to the evaporation of water used for slurry feed is eliminated.
- Oxygen consumption can be reduced because coal is delivered hot (at 900°F) and also the heat sink, due to water in coal slurry, is removed.
- Higher gas yields can be obtained.
- Slurry feed would require fine grinding of coal to a reasonably uniform size distribution. The coal pump can tolerate coarser feed and the size distribution can be mixed, within limits.

e. Application of Coal Pump--Technical Uncertainties.

- Water-slurry feed is an integral part of the present version of Texaco process. Whether steam added externally will give the same conversion of coal compared with steam produced in place from slurry water is not known.

f. Conclusions.

- Significant savings in consumption of coal and oxygen are likely.

- Coal	7.5%
- Oxygen	10.5%

- Delivery of hot coal (at 900°F) to the reactor and the elimination of the heat duty due to the water content of the slurry lead to these savings.
- Additional burden on the utility system will be caused by the large power consumption required to run the coal pumps. This will be partially offset by the elimination of the slurry pumping system.
- Coal or other utility fuel requirements are likely to increase due to increased steam consumption.
- Whether switching from water to steam as a carrier fluid will change the process yield is not known.

6. Shell-Koppers Process

a. Description. Pulverized dried coal is fed into a reaction chamber through diametrically opposed diffuser guns and reacts with blast jets of oxygen or air and steam, in a flame-like reaction. Flame temperatures can be as high as 1,800° to 2,000°C, but the reactor outlet temperatures will not normally exceed 1,400° to 1,500°C. A typical operating pressure is 35 atmospheres. The reactor is a hollow pressure vessel.

Coal is normally crushed and ground to size (90% <90 microns) and dried. The bulk of the molten ash is collected in the water-filled bottom compartment of the reactor. Some ash, however, is entrained with the synthesis gas. This ash is recycled to the reactor together with the unconverted carbon (normally less than 2% of the coal intake). It is a strict requirement to solidify these entrained ash droplets before they enter the waste heat boiler. To this end, a quench section is provided at the reactor outlet.

An integral part of the process is the removal of particulate matter from the raw gas. This is mainly based on a proprietary system consisting of cyclones and scrubbers. Apart from its relatively low cost and temperature independence, its main advantage is the elimination of solids-containing waste water, thus omitting the need for filtration. After the gas has passed the last scrubber, its solids content is less than 1 mg/m^3. (See Figure 8-7.)

b. Research Program.

1) Testing Scale.

- 6 T/day pilot plant operated since December 1976.
- 150 T/day gasifier operated since November 1978.

2) Mode of Operation.

- Entrained bed slagging type.

3) Operating Conditions.

- Temperature 2,700°F.
- Pressure 500 psia.

4) Experimental Results.

- Principally medium-Btu gas is produced. Raw gas contains 93 to 98% by volume hydrogen and carbon monoxide.
- Coals with up to 50% ash and up to 8% sulfur by weight have been gasified.

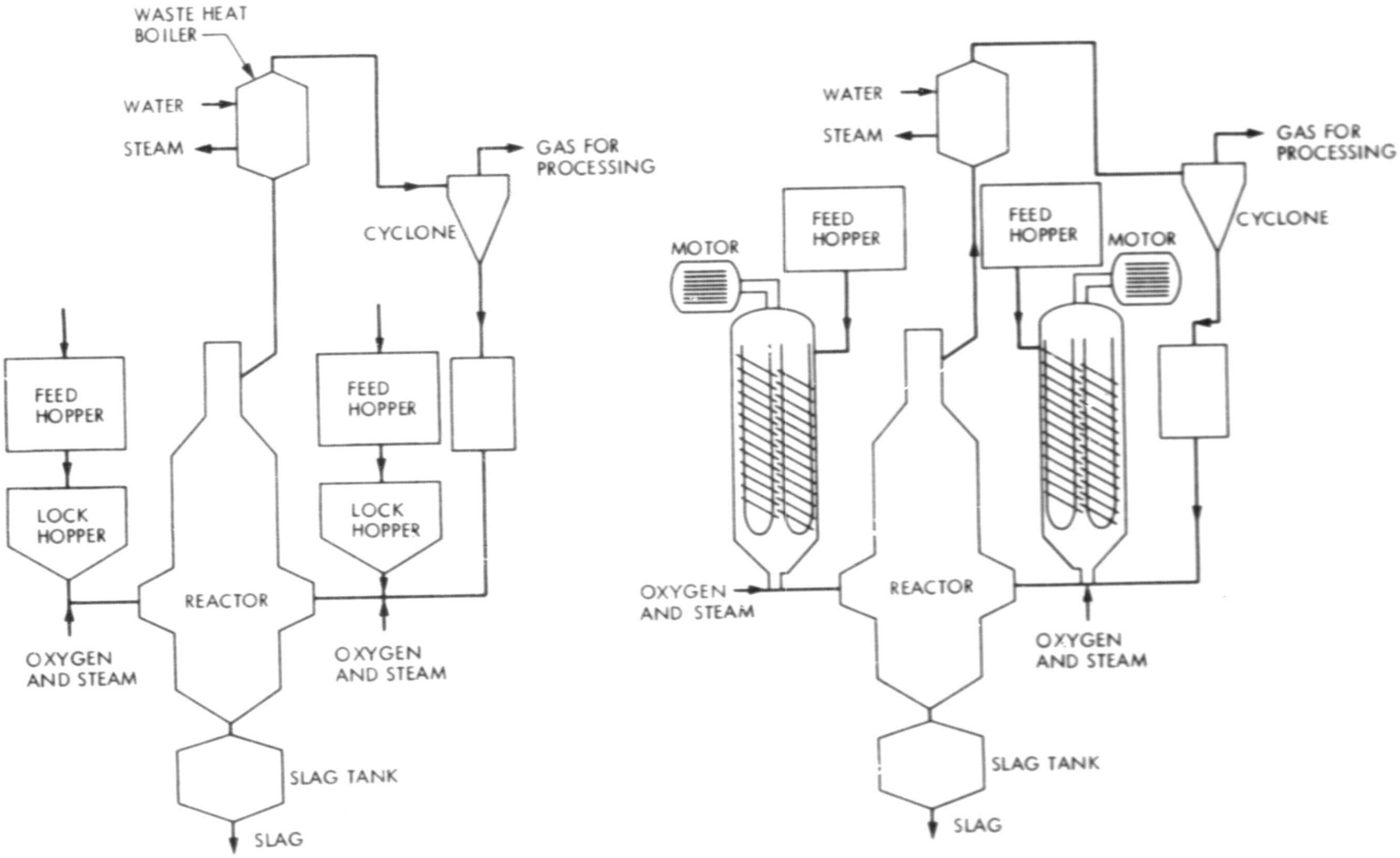


Figure 8-7. Shell-Koppers Process

- Coal has to be dried to between 1 to 8% water content.

- No byproducts produced.

- Extremely fine material may also be gasified.

- Gasification thermal efficiency = 82%.

c. Parameters

	Parameter	Lock Hopper Feed	Coal Pump Feed
(1)	Coal throughput for a 250 billion Btu/day plant	11,799 T/day	11,615 T/day
(2)	Oxygen consumption	1.0 lb/lb MAF coal	0.962 lb/lb MAF coal
(3)	Steam consumption	0.08 lb/lb MAF coal	0.080 lb/lb MAF coal
(4)	Injector design	Two diametrically opposed burners	Three burners
(5)	Particle size	70% - 200 mesh	70% - 60 mesh
(6)	Feed coal temperature	60°F	900°F
(7)	Reactor capacity	2,400 T/day	2,400 T/day
(8)	Reactor size	10-feet I.D., 15-feet high	10-feet I.D., 15-feet high
(9)	Number of reactors required	5	5
(10)	Feeder capacity	2,400 T/day	864 T/day
(11)	Feeder size		60 ft x 10 ft x 10 ft
(12)	Number of feeders required	5	15
(13)	Feeder power consumption		90,000 HP_E (67 MW_E)

d. Applications of Coal Pump--Potential Benefits.

- Delivery of hot coal at 900°F will cut consumption of coal by 1.56% and of oxygen by 3.85%.

- By using the coal pump, the mass flux through the reactor can be significantly improved, thereby leading to smaller reactors.

e. Applications of Coal Pump--Technical Uncertainties.

- The quality of coal feed achieved by the coal pump will affect gasification efficiency.

f. Conclusions.

- Coal pump is compatible with this entrained bed process.
- Savings of 1.5% in coal use and 4% in oxygen consumption are likely because hot coal at 900°F is delivered to the reactor by the coal pump.
- Successful adaptation of coal pump will depend upon its ability to deliver small (preferably smaller than 60 mesh) uniform coal particles.

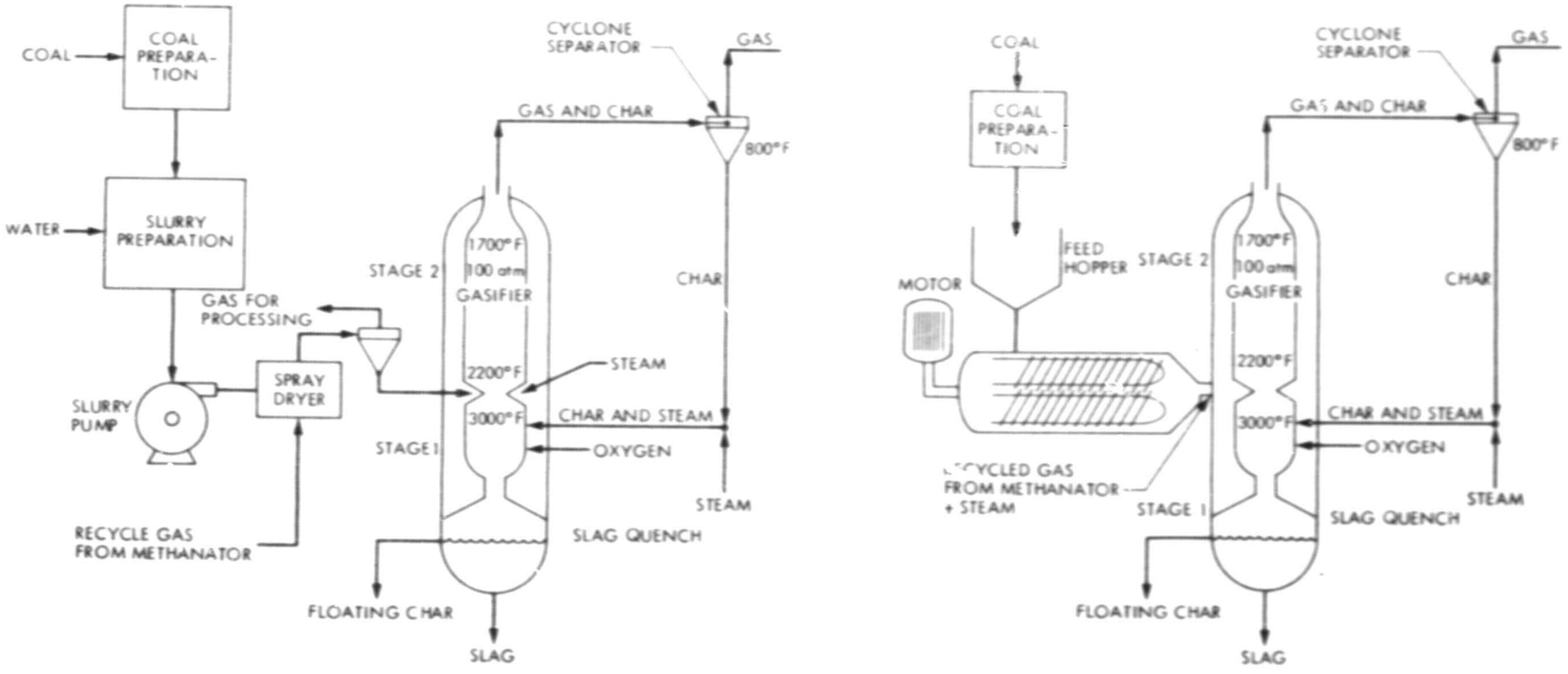
7. Bigas Process

a. Description. Pulverized coal and steam are fed into the upper station (Stage 2) of the gasifier and oxygen and steam are fed with char into the lower portion (Stage 1). The volatile portion of the coal introduced with steam into Stage 2 is converted into a methane-rich gas by reaction with the hot synthesis gas coming up from Stage 1. The gasifier operates at 1,000 and 1,500 psi, and 3,000° and 1,700°F in Stages 1 and 2, respectively. Hot synthesis gas results from the gasification of char with oxygen and steam. Ash from the coal flows down the walls of the gasifier and is withdrawn at the bottom as a slag.

Raw product gas is withdrawn from the top of the gasifier and passed through a cyclone which separates the char for return to the gasifier. The remaining gas, still uncleaned, moves downstream for processing. Char is recycled to the gasifier and helps to make the process continuous.

Hydrogen is produced in the shift converter by the reaction of carbon monoxide with steam and is used in the methanation step. The combined hydrogen, carbon monoxide, and methane are cleaned in the scrubber for removal of acid gases for potential production of sulfur and ammonia.

Clean gas is methanated to convert carbon monoxide and hydrogen to methane thus increasing the heating value of the gas and making it acceptable for natural gas streams. The final product has a heating value of over 900 Btu/cu ft. (See Figure 8-8.)



WITH SLURRY FEED

WITH COAL PUMP FEED

Figure 8-8. Bigas Process

b. Research Program.

1) Testing Scale.

- 120 T/day fully integrated pilot plant (with a 2-ft I.D., 32-ft tall reactor).
- 120 lb/day externally heated reactor.
- 1.2 T/day process and equipment development unit.

2) Method of Operation.

- Entrained bed gasifier.
- Water-slurry feed.

3) Operating Conditions.

- Temperature 2,800°F in Stage 1, 1,700°F in Stage 2.
- Pressure 1,220 psig.

4) Experimental Results.

- Methane yields are sensitive to coal rank, temperature, and hydrogen partial pressure.
- No liquid byproducts.

c. Parameters.

	Parameter	Slurry Feed	Coal Pump Feed
(1)	Coal required for a 250 billion Btu/day plant	13,870 TPD	13,870 TPD
(2)	Water consumption for slurry preparation	21,700 TPD	---
(3)	Oxygen consumption	0.425 lb/lb coal	0.409 lb/lb coal
(4)	Steam consumption	1.052 lb/lb coal	1.052 lb/lb coal
(5)	Injector design	Two 14-inch nozzles	Modified to permit spray formation

(6)	Particle size	70% - 200 mesh	70% - 60 mesh
(7)	Feed temperature	550°F	900°F
(8)	Reactor capacity	7,000 TPD	7,000 TPD
(9)	Reactor size	5.25-ft I.D., 135-ft high (Stage 2) 6.33-ft I.D., 50-ft high (Stage 1)	5.25-ft I.D., 135-ft high (Stage 2) 6.33-ft I.D., 50-ft high (Stage 1)
(10)	Number of reactors required	2	2
(11)	Feeder capacity	7,000 TPD	864 TPD
(12)	Feeder size		60 ft x 10 ft x 10 ft
(13)	Number of feeders required	2	16
(14)	Feeder power	Approximately 10,000 HP_E (7.5 MW_E)	96,000 HP_E (72 MW_E)

d. Application of Coal Pump--Potential Benefits.

- A slurry pump system is not very efficient because large volumes of the slurry medium, usually water, have to be vaporized in the reactor. A coal pump system will operate much more efficiently.

- The entrained bed mode of operation is perfectly compatible with a coal pump feeder.

- Coal pump can feed the reactor at fairly high mass flux rates. A design which incorporates this feature may lead to reduced reactor volumes.

e. Application of Coal Pump--Technical Uncertainties.

- One process reactor will require coal feed from several coal pump units. Therefore, the injector design will become more complicated.

- The gas yield may depend on the quality of coal feed achieved by the coal pump.

f. Conclusions.

- Application of the coal pump will significantly improve the energy efficiency of this process. This process presently uses a dilute water slurry for feeding coal. The heat load for evaporation is currently equivalent to 11.7% of coal fed to the process.

- Eight coal pump units will be required to supply coal to one reactor. To facilitate reactor design, the feed will have to be injected at multiple points in the reactor.
- Because of the high-temperature entrained bed mode of operation, no agglomeration near the coal injectors is expected.
- The extra power required for coal extrusion will be significantly greater than the savings from elimination of the power usage for the slurry feed method.

8. SRC-II Liquefaction Process

a. Process Description. Raw coal is pulverized and dried in the coal preparation area, then mixed with hot recycle slurry solvent. The coal recycle slurry is made up in a mixing tank, pumped, mixed with hydrogen, and then heated to reaction temperature in a fired preheater. The temperature at the preheater outlet is 700° to 750°F, hence some coal has already dissolved in the preheater. The hydrogenation and hydrocracking reactions are exothermic and occur in the dissolver section. The mixture is quenched by adding hydrogen. The reactor effluent goes through a hot, high pressure separator, whereupon a vapor stream, light liquid stream, and bottom stream are taken off. Part of the bottom stream is taken for the recycle solvent and the remainder is sent to a vacuum tower. The overhead from the vacuum tower is the major heavy fuel oil product. The bottoms are sent to a gasifier for generating the synthesis gas which comprise one source of makeup hydrogen. The non-condensible gases are sent through purification stages to remove acid gases. Cryogenic separation of hydrogen and methane is effected. Methane is sold as pipeline gas and the hydrogen is recycled. (See Figures 8-9 and 8-10.)

b. Basic Features.

- Feed to Process = 20,000 T/D of Kentucky No. 9 Coal (as received)
- Distillate Solvent Rate = 20,000 T/D
- Slurry Solvent = 40,000 T/D
- Operating Pressure = 1900 psig
- Operating Temperature = 860°F
- Dissolver Retention Time = 15 minutes
- Internal Diameter of Dissolver = 12 ft 6 in.

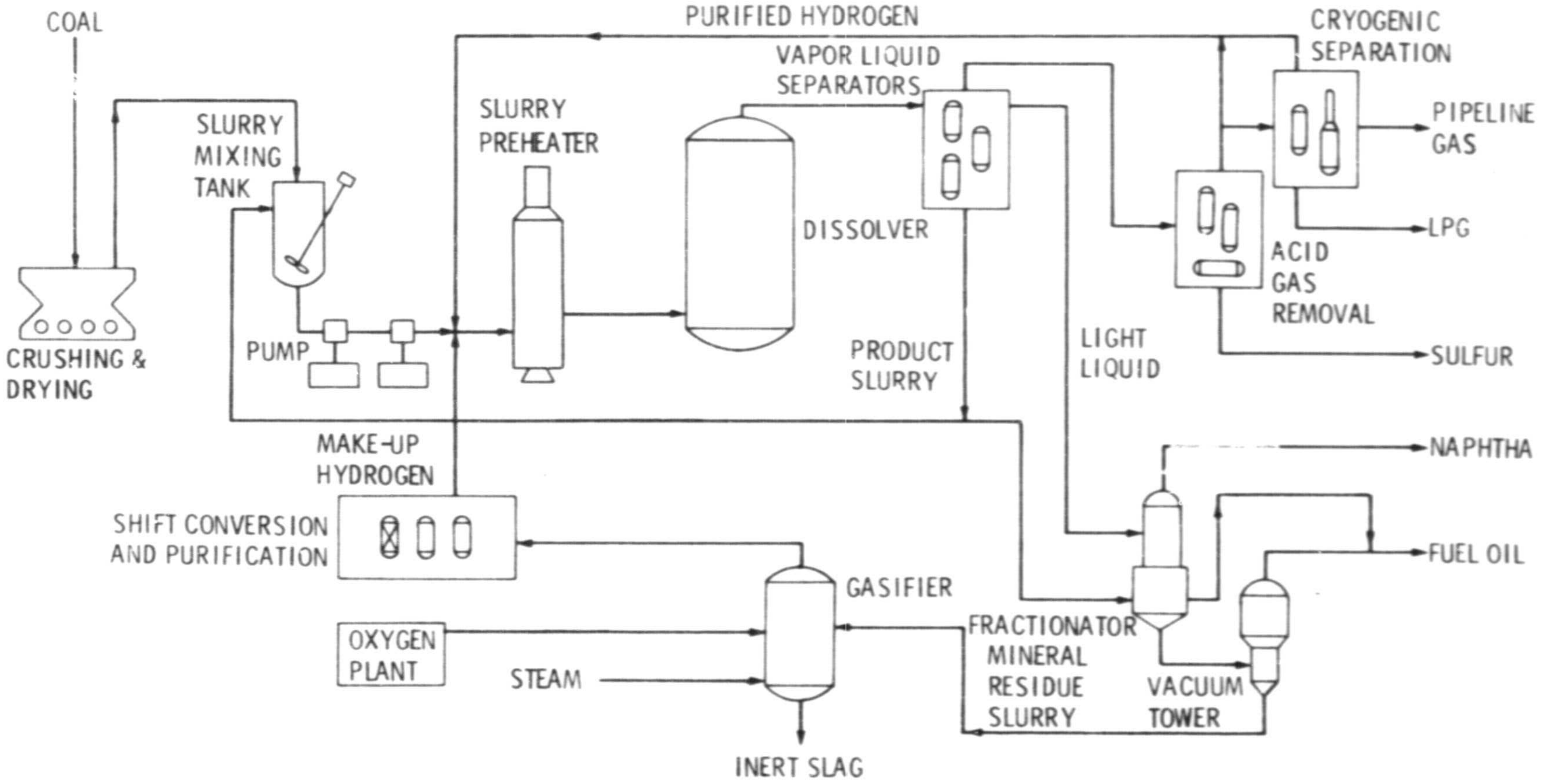


Figure 8-9. SRC-II Process Slurry Pump Feed

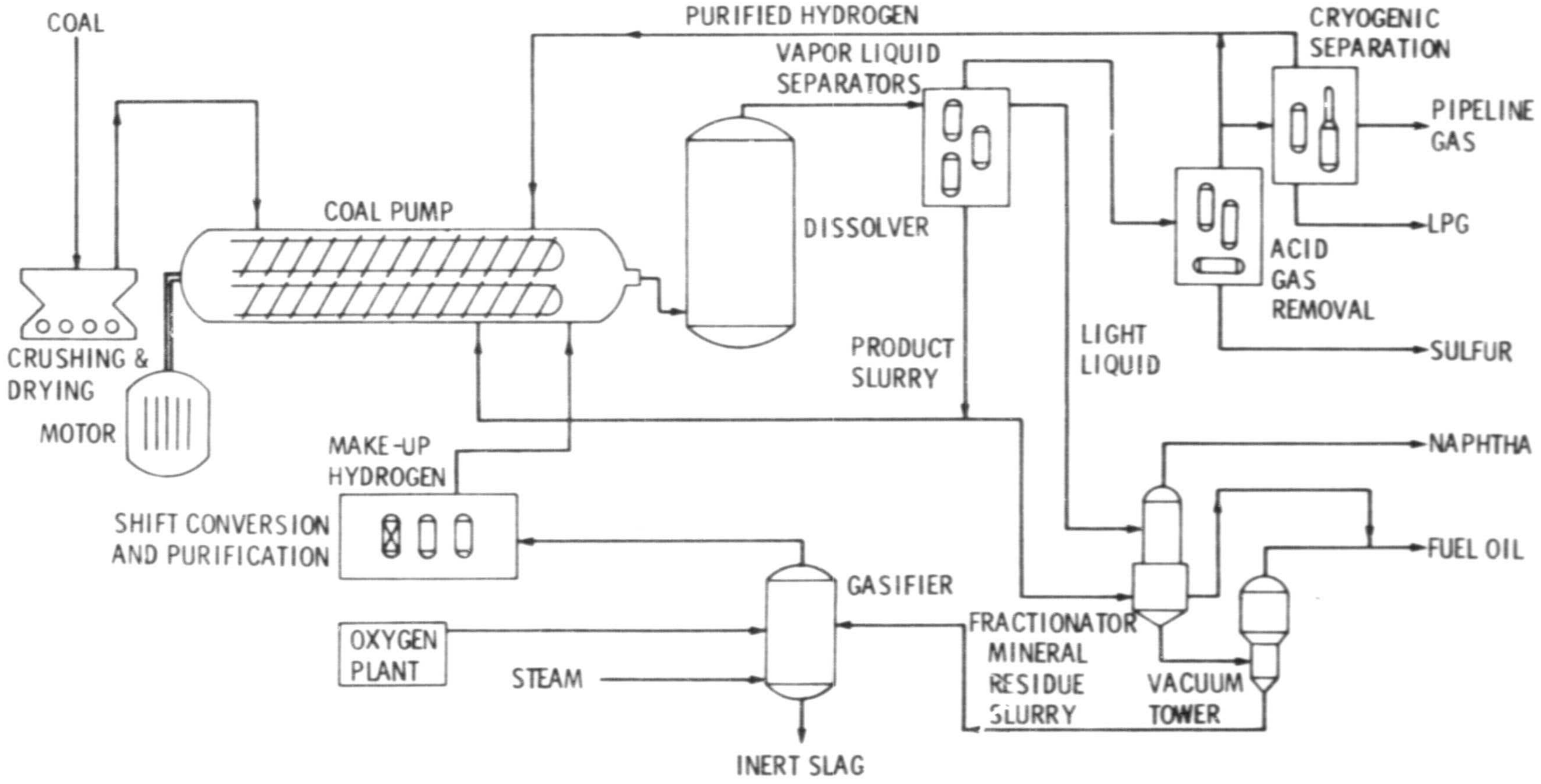


Figure 8-10. SRC-11 Process Coal Pump Feed

- Wall Thickness of Dissolver = 12.75 in.
- Number of Trains = 3
- Overall Conversion, % MAF = 93.40
- Dissolver Space Rate, lb/hr-ft^3 = 22

c. Application of the Coal Pump--Basic Assumptions.

- 10% reduction in coal storage, grinding, and drying unit cost.
- 50% reduction in costs of pumps and their drivers caused by elimination of the slurry pumps.
- 33% decrease in the size of the reactor because of extra residence time provided by the coal pump.
- Furnaces, heaters, agitators, mixers, and blenders eliminated.
- Savings in utility consumption:
    - 66.4 MW for slurry preheating or 730 mm Btu/hr at 11,000 kWh/Btu.
    - 1.4 MW due to 10% reduction in coal handling system.
    - 35 MW due to elimination of feeders (1000 hp), agitators (100 hp), and slurry pumps (30,000 hp).
- Coal pump power consumption of 5000 hp/unit or a total of 90 MW for 24 coal pumps.
- Cost of a 36 TPH coal pump = 1.5 $MM, including the cost of drivers.
- Power consumption for a 20,000 TPD SRC-II Plant:

  Slurry feed = 272 MW.

  Coal pump feed = 259 MW.

d. Application of Coal Pump--Potential Benefits.

- Coal pump can serve the functions of the coal/solvent mixer, slurry pump, and slurry preheater.
- It can also provide additional residence time for coal dissolution. This will cut down the size and the cost of the dissolver.
- A coal pump is potentially more reliable than a slurry pump.

- When the power/energy consumption for slurry pump, mixing, and pre-heating are combined, the total usage is likely to exceed that due to coal pump.

- The net product cost for a coal pump system is likely to be lower by about $0.10/MM Btu.

- The particle size required for liquefaction is usually not smaller than 8 mesh. It has already been established that coal pump can produce coal feed of this size.

e. Application of Coal Pump--Technical Uncertainties.

- The biggest coal pump commercially available today has a capacity of 18 TPH. It is assumed that it will be feasible to construct a 36 TPH unit.

- How much residence time will be contributed by the coal pump to the liquefaction process is not known. It is assumed that it will provide an equivalent of 5 minutes of residence time.

- Whether the coal extrusion process will change its reactivity remains to be established.

- It is assumed that injection of hydrogen and solvent into the coal pump will not impede the extrusion process. Experimental verification of this hypothesis is required.

f. Capital Investment ($MM).

Basis: Coal Feed = 20,000 TPD (as received)

	Slurry Feed		Coal Pump Feed
	Mid-1977	March 1980	March 1980
Coal Preparation	44	55	51
Slurrying and Dissolving	236	301	277
Fractionation	14	19	19
Hydrogen Generation, Air Separation, Gas Cleanup, Sulfur Recovery	424	538	538
Hydrogen Recovery	34	44	44
Off-Sites	113	144	144
	865	1101	1073

g. Major Equipment Costs--$MM.

Process Element		Slurry Feed March 1980		Coal Pump Feed March 1980
Coal Preparation Unit		35.7		35.7
Coal Storage, Grinding, Drying		29.7		26.7
SRC Dissolving		113.2		102.0
Process Feeders	28.1		42.0	
Heat Exchangers	20.9		20.9	
Furnaces and Heaters	5.1		---	
Pumps and Drivers	6.7		3.3	
Compressors and Blowers	7.1		7.1	
Material Handling	0.2		0.2	
Agitators, Mixers, and Blenders	2.5		---	
Reactors	42.3		28.2	
Other Minor Equipment	0.3		0.3	
		178.6		164.4

h. Operating Costs, $MM per Year.

Basis: 20,000 TPD Facility, 330 Operating Days Per Year (March 1980).

	Slurry Feed	Coal Pump Feed
Feedstock		
Coal at 1.75/mm Btu	292.8	292.8
Direct Costs		
Water at 0.51/m-gal	2.9	2.9
Chems and Lubes	6.4	6.4
Power at 4.0¢/kWh	85.3	81.2
Labor Related	16.8	16.8

Maintenance at 4%[1]	44.0	42.5
Subtotal	155.4	149.8
Capital Costs at 16%[1]	176.2	170.1
Total Required Revenues, $M/year	624.4	612.7
Net Fuel Production, Quad/year	121.3	121.3
Required Selling Price, $/mm Btu	5.15	5.05

i. Conclusions.

Based on cost data referenced to March 1980, there would be a savings in equipment cost of 28 million dollars out of a plant cost of 1,101 million dollars. Operating costs per year would decrease 11.7 million dollars from 624.4 million dollars per year. There is not expected to be any significant change in product quality due to a change to a coal pump feed system.

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[1] Not included is the appropriate contribution from contingency, interest during construction, startup, and working capital costs.

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DEFINITION OF ABBREVIATIONS

A	ash
AFC	amount of fixed carbon
Al	aluminum
ASTM	American Society for Testing and Materials
ATM	atmosphere
A_1, A_2	ash percentage before, 1, and after, 2, gasification
A_1, A_4	total flow areas in central and impinging jets
BCR	Bituminous Coal Research
Btu	British thermal unit (also BTU)
Btu_E	Btu electrical
Btu_T	Btu thermal
C	centigrade (Celsius)
cc	cubic centimeter
CL	center line
CO	carbon monoxide
Comm	commercial
Co/Mo	cobalt and molybdenum
Conoco	Continental Oil Company
D	distance, diameter
ddpm	dial division per minute
demo	demonstration
DOE	Department of Energy, U.S.
FC	fixed carbon
fps	feet per second
FSI	free swelling index

G	net volumetric flow rate per unit grove length
g	gram
GE	General Electric Company
GN_2	gaseous nitrogen
Hi	high
HP	horsepower (also hp)
HP_E	HP electrical
hp-hr	horsepower hour
HV	heating value
H_2	hydrogen
I.D.	inside diameter (also i.d.)
IGT	Institute of Gas Technology
IMMR	Institute of Mining and Minerals Research, University of Kentucky
IR	screw + ejector + breaker
JPL	Jet Propulsion Laboratory, Caltech
K	thousand
KE	kinetic extruder
kW	kilowatt
kWh	kilowatt hour
lb	pound
lb_f	pound force
lbm	pound mass
lb/hr	throughput pound per hour
LH	lock hopper
LN_2	liquid nitrogen
LPF	linear pocket feeder

LPG	liquid petroleum gas
LTA	low temperature ash
M	micron
M	molar
maf	moisture and ash free (also MAF)
MERC	Morgantown Energy Research Center, DOE
mg/m^3	milligram per cubic meter
MM	million (also mm)
$MM	million dollars
MHD	magnetohydrodynamic
MW	megawatt
MW_E	megawatt electrical
μ	fluid with constant viscosity
μ_ℓ	liquid viscosity
NASA	National Aeronautics and Space Administration, U.S.
N_2	nitrogen
O_2	oxygen
P	poise
P_B	barrel pressure
PDU	preliminary design unit
PFC	percentage of fixed carbon
PIO	public information office
POGO	power-oil-gas-operation
PPH	pound per hour (also pph)
ppmp	pound per million pound throughput
psi	pound per square inch
psia	psi atmosphere

PSIG	psi gauge
Q_a	gas volumetric flow rate
Q_ℓ	liquid volumetric flow rate
RMP	Ralph M. Parsons Co.
ROM	run of mine
rpm	revolution per minute (also RPM)
ρ	pressure
p	density of fluid
ρ_k	liquid density
ℓ_1, ℓ_4	density of central, impinging fluids
SA	surface area
S_{MD}	Sauter mean diameter (volume number mean)
SRC	solvent refined coal
SRT	short residence time
SNG	substitute natural gas
τ	surface tension
TC	thermocouple
TPD	ton per day (also T/day)
TPH	ton per hour
T/hr	ton per hour
TRW	Thompson Ramo Woolridge, Inc.
Θ	angle between impingement and center jet
u	longitutional flow velocity
v	barrel surface velocity
VM	volatile matter
v_r	relative velocity
W/	with

W_1, W_4	total mass flow in central, impinging jets
Xp	impingement penetration distance
δ_m	mean slot height
μ_A, μ_B	viscosity of fluids in slots A, B