DOE/PC/88886--T4

DE90 003036

TECHNICAL PROGRESS REPORT

FOR THE

FOURTH QUARTER

(July 1, 1989 - September 30, 1989)

DEVELOPMENT OF AN ADVANCED PROCESS FOR DRYING FINE COAL IN AN INCLINED FLUIDIZED BED

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Contract Number:

DE-AC22-88PC88886

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ABSTRACT

This research project is for the development of a technical and economical process for drying and stabilizing fine particles of high-moisture subbituminous coal. Project support is provided by the Pittsburgh Energy Technology Center (PETC) of the U.S. Department of Energy (DOE). The research is being conducted by the Western Research Institute (WRI) and AMAX Research and Development (AMAX R&D).

The project scope of work requires completion of five tasks: (1) project planning, (2) characterization of the two feed coals, (3) bench-scale IFB drying studies, (4) product characterization and testing, and (5) technical and economic process evaluation.

The two feed coals selected for this research are Eagle Butte coal from AMAX Coal Company's mine located in the Powder River Basin of Wyoming and Usibelli coal from Usibelli Coal Mine, Inc.'s mine located near Healey, Alaska. The feed coals are prepared by crushing to -590 μm (-28 mesh). The average particle diameter of the crushed Eagle Butte feed coal is 70 μm and the average particle diameter of the crushed Usibelli feed coal is 80 μm. These average particle diameters are based upon wet screening results. Both the feed coals are high-moisture subbituminous coals with "as received" moisture contents of 29% and 22% for the Eagle Butte and Usibelli coals, respectively. Coincidentally, both the Eagle Butte and Usibelli coals have a heating value of 8470 Btu/lb.

The minimum fluidization velocity (MFV) of the crushed Eagle Butte coal is approximately 1 ft/min (30.5 cm/min), and the MFV for crushed Usibelli coal is approximately 3 ft/min (91.4 cm/min).

Testing of the effects of IFB reactor slope and gas-to-solids ratio on the solids bed geometry and horizontal solids transport was also conducted using a cold-flow model. The results of these tests indicate that horizontal solids transport in the reactor occurs even at low reactor slopes and low gas-to-solids ratios. The average solids residence time correlates reasonably well to the Reynolds number depicting fluid flow in the lower portion of the reactor. The solids residence time decreases as the Reynolds number increases and the solids residence time also decreases as the IFB reactor slope increases. These effects were similar with both coals.

Results of thermogravimetric analysis (TGA) indicate that Usibelli and Eagle Butte coals show similar weight loss profiles at heating rates between 5 and 20°C/minute (9 and 36°F/minute). Both coals lose water rapidly below 100°C (212°F) and have lost at least 90% of the free water by 150°C (302°F). Each coal has a plateau of reduced weight loss between regions of water loss and pyrolysis product loss. This plateau is centered around 200°C (392°F) for heating rates used in this study. The onset of pyrolytic weight loss, mainly due to decarboxylation, occurs at about 250°C (482°F) for all heating rates studied.

A total of forty-one 4-hr (19 using Eagle Butte feed coal and 22 using Usibelli feed coal) and eight 12-hr (4 using each feed coal) bench-scale IFB drying tests were conducted using nominally a 10 lb/hr coal feed rate. IFB reactor slopes of 3, 6, 9, 12, and 15 degrees were investigated for each feed coal. The average IFB dryer temperature of these experiments ranged from approximately 350 to 750°F (177 to 399°C) and the carbon dioxide fluidizing gas velocity ranged from 1 to 6 scfm. The solids heating rate in the experiments varied from approximately 60 to 250°F/min (33 to 139°C/min) and solids residence times varied from 5 to 13 min. In all of these experiments the dried coal product contained less than 1.5 % moisture based upon proximate analysis. The heating values of the dried coals produced were increased from 8,470 Btu/lb to a range of 11,800 to 12,600 Btu/lb for Eagle Butte coal and to a range of 10,400 to 11,500 Btu/lb for Usibelli coal.

Solids entrainment from the IFB dryer was found to correlate to the Reynolds number depicting fluid flow in the disengagement zone in the dryer. Entrainment can easily be maintained below 15 wt % of the feed coal. Product composition and gas produced from the coal correlates to the average dryer temperature.

Product characterizations have demonstrated that the IFB drying process can produce dried coals with a significant reduction in moisture reabsorption. The equilibrium moisture of several of the dried coals is about one half that of the feed coals. The equilibrium moisture contents of these dried coals is significantly less than those produced from the same coals dried conventionally using lower temperatures and air as fluidizing gas. Further these dried coals contained very low fugitive dust compared to the feed coals. Spontaneous heating characteristics of the dried coals and feed coals are still being evaluated. Surface area analyses have also been conducted to determine the temperatures and residence times for which coal tars most effectively plug the dried coal pores.

The technical merits and economic potential of the IFB drying process will be evaluated in the next quarter of research. Thus far, it has been demonstrated that the explosion potential can be minimized by operation of the process at a slight positive pressure and by using carbon dioxide produced from decarboxylation of the coal which also occurs during drying. Fugitive dust emissions can be greatly reduced and moisture reabsorption can be significantly reduced. Further, preliminary studies indicate the IFB dryer should require less capital, operating, and maintenance costs than conventional fluidized bed dryers.

PROJECT OBJECTIVE

The main objective of this research is to develop a thermal process for drying fine coal that (1) reduces explosion potential, (2) uses a fluidized bed with minimum elutriation, (3) produces a stable dry coal by preventing moisture reabsorption and autogeneous heating, (4) reduces fugitive dust emissions, and (5) is technically and economically feasible.

PROJECT TASKS

The project scope of work requires completion of five tasks: (1) project planning, (2) characterization of the two feed coals, (3) bench-scale IFB drying studies, (4) product characterization and testing, and (5) technical and economic process evaluation. Table 1.1 and Figure 1.1 provide details regarding the project scope of work and schedule.

Task 1: Project Planning

This task was completed prior to the third quarter and has been reported previously.

Table 1.1 Project Scope of Work

TASK 1	Project Planning
TASK 2	Feed Coal Characterization
	2.1 Physical and Chemical Characterization
	2.2 Fundamental TGA Studies
	2.3 Optimizing TGA Studies
TASK 3	Bench-Scale IFB Drying Studies
	3.1 Minimum Fluidization Velocity
	3.2 IFB Drying Tests
TASK 4	Product Characterization and Testing
	4.1 Moisture Reabsorption
	4.2 Dust Formation
	4.3 Spontaneous Heating
	4.4 Surface Treating
TASK 5	Technical and Economic Evaluation

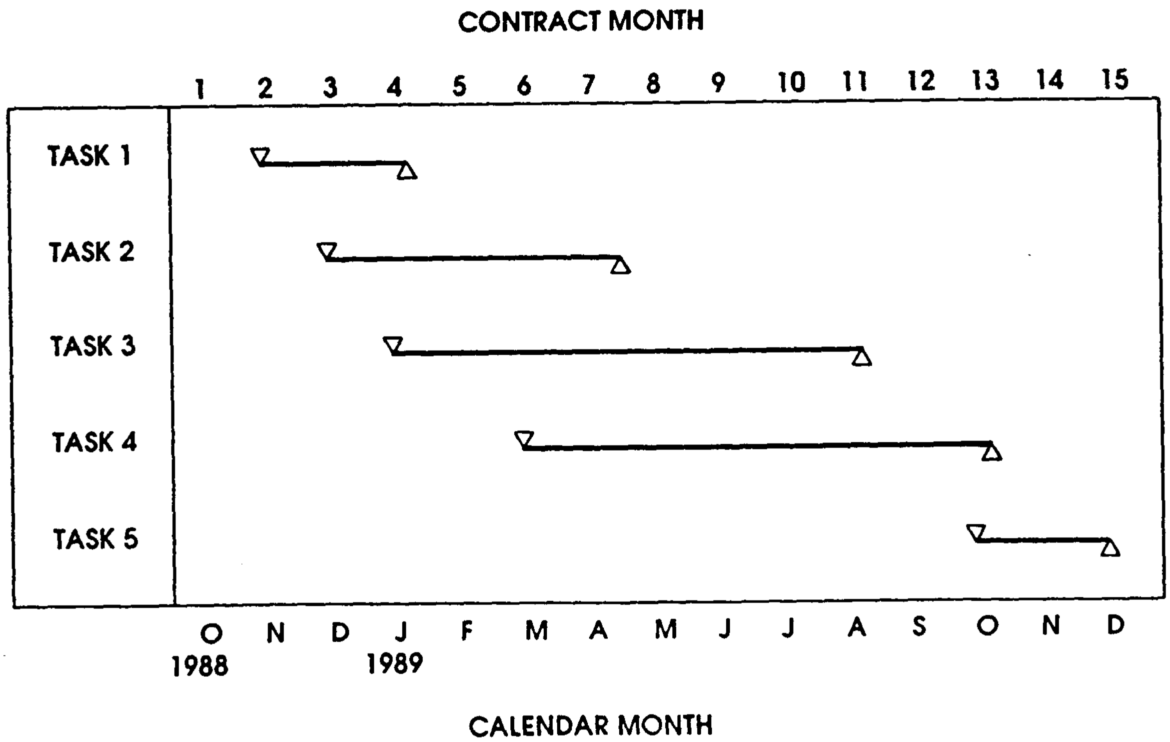

Figure 1.1 Project Schedule

Task 2: Feed Coal Characterization

Subtask 2.1: Physical and Chemical Characterization

This subtask was completed in the second quarter. Proximate, ultimate, and heating value analyses were performed on samples of Eagle Butte and Usibelli coals crushed to a -590 micron particle size. In addition, samples of each crushed feed coal were subjected to wet and dry screen analyses and solid density and void volume determinations. Both the chemical and physical analyses were performed in duplicate.

Results of the chemical analyses for proximate and ultimate composition and heating value analyses of both feed coals are presented in Table 2.1. All chemical analyses were performed using either ASTM procedures or standard methods for the automatic analyzers.

Screen analyses of the crushed feed coals were performed using standard screens. The fines content of the coals required that wet screening be performed to obtain an accurate analysis. Dry screening was also attempted but the dry screen data did not agree well with the wet screen analyses. Screen sizes used were 420, 297, 210, 149, 105, and 74 μm.

Table 2.1 Results of Chemical Analyses of Feed Coals

Analysis	Eagle Butte	Usibelli
Proximate (wt % as received)		
Volatile Matter	30.9	36.4
Fixed Carbon	35.2	33.3
Ash	4.7	8.3
Moisture	29.2	22.0
Ultimate (wt % on dry basis)		
Carbon	67.4	61.5
Hydrogen	5.1	5.2
Nitrogen	0.9	0.9
Sulfur	0.6	0.2
Oxygen	19.4	21.6
Ash	6.6	10.6
Heating Value, Btu/lb	8470	8470

Figures 2.1 and 2.2 are graphical representations of the results of wet screen analyses of the two crushed feed coals. The weight fraction retained on each screen is displayed in the bar chart for the crushed feed coal samples (Figure 2.1). The cumulative percent retained as a function of particle size is also presented for the crushed feed coal samples (Figure 2.2).

The wet screen analysis of the crushed feed coal samples indicate the average particle diameter for the crushed Eagle Butte coal is approximately 70 μm and the average particle diameter of the crushed Usibelli coal is approximately 80 μm. Figure 2.1 indicates that roughly one-third of the crushed Usibelli coal and one quarter of the crushed Eagle Butte coal is

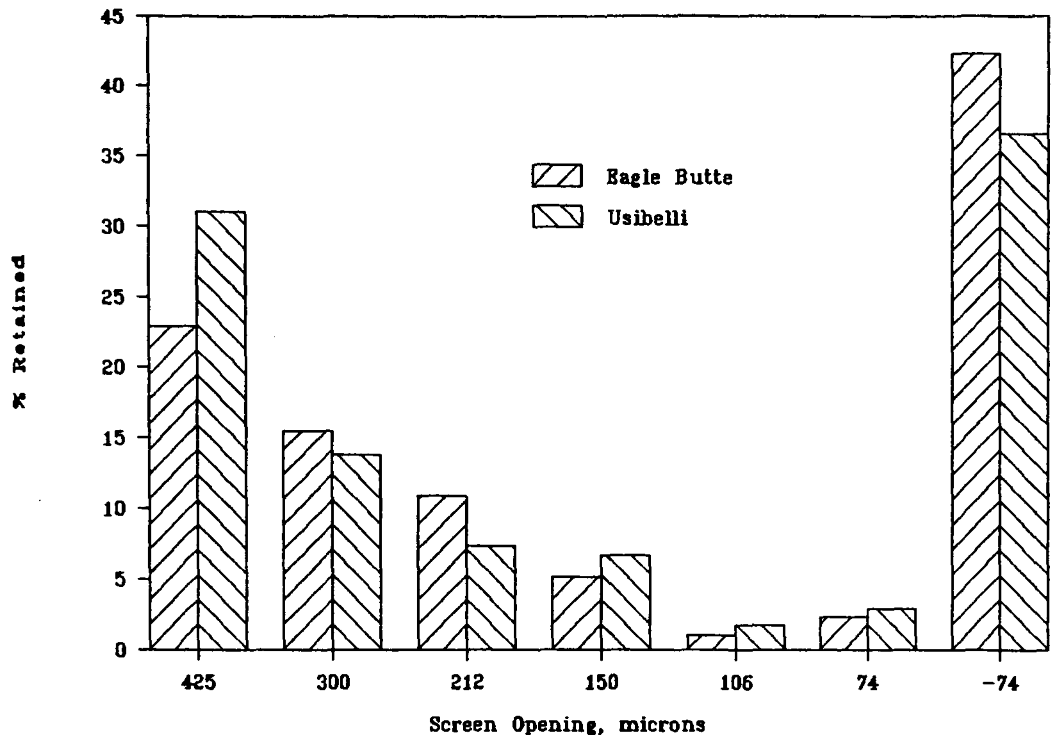

Figure 2.1 Particle Size Distribution of the Crushed Feed Coals

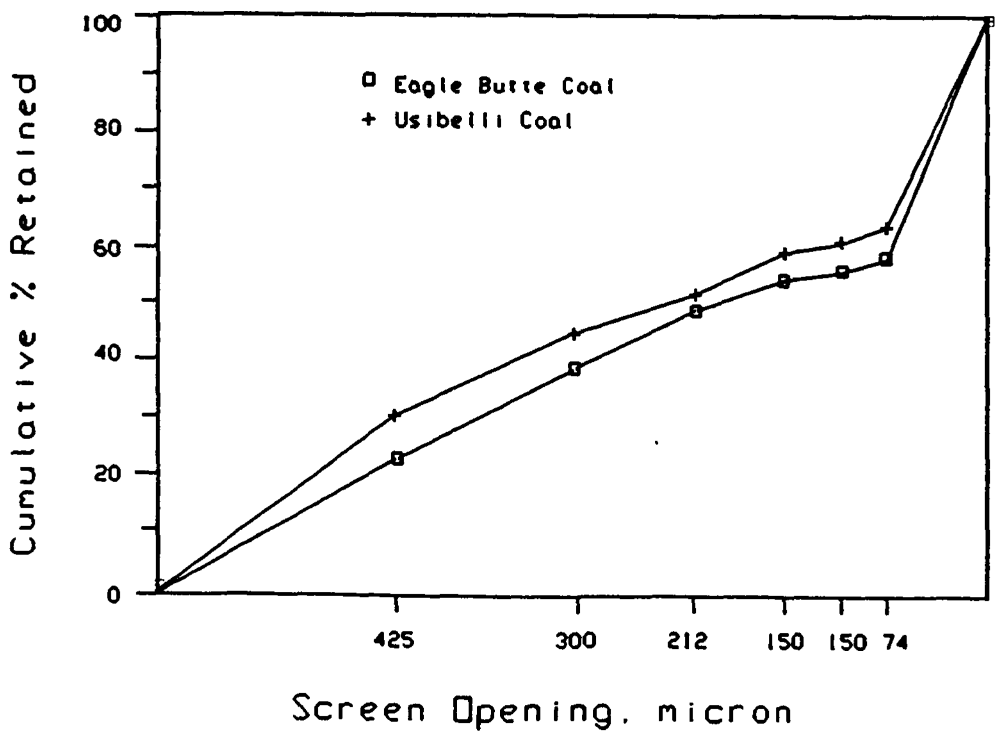

Figure 2.2 Cumulative Screen Analysis of the Crushed Feed Coals

+420 μm in size (Figure 2.2). Further comparison of the wet screen data (Figures 2.1 and 2.2) illustrates the smaller amount of fine particles in the Usibelli coal than in the Eagle Butte coal.

The tendency of the wet coal fines to form aggregates during dry screening can result in a size distribution that discriminates against the finer particles. For this reason, the wet screen analyses results of the crushed feed coals were used exclusively in experimental data analyses.

Subtask 2.2: Fundamental TGA Studies

This subtask was completed in the third quarter. Time and temperature dependence of volatile production from the coal samples were obtained using thermogravimetric analysis (TGA). The results of the Fundamental TGA Studies are presented in detail in the project report for the third quarter's activities.

Subtask 2.3: Optimizing TGA Studies

This subtask was completed in the third quarter. Optimum coal drying conditions have been estimated by examining the water, gas, and tar evolution profiles. The results of the Optimizing TGA Studies are presented in detail in the project report for the third quarter's activities.

Task 3: Bench-Scale IFB Drying Studies

Subtask 3.1: Minimum Fluidization Velocity

The minimum fluidization velocity (MFV) of the feed coals were experimentally determined in the second quarter and have been reported previously in the project report for the second quarter's activities. The MFV for -28-mesh Eagle Butte coal is approximately 1 ft/min and the MFV for -28-mesh Usibelli coal is approximately 3 ft/min. The pressure drop across the solids bed at the MFV is approximately 25 psf per foot of solids bed for the -28-mesh Eagle Butte feed coal and 31 psf per foot of solids bed for the -28-mesh Usibelli feed coal.

Testing of the effects of IFB reactor slope and gas-to-solids ratio on the solids bed geometry and horizontal solids transport was also conducted during the second and third quarters using the IFB cold flow reactor (Figure 3.1). The results of these tests indicate that horizontal solids transport in the reactor occurs even at low reactor slopes and low gas-to-solids ratios. However, IFB operation at these conditions results in the creation of a static bed in the feed end of the reactor, batch fluidization in the center of the reactor, and continuous fluidization at the discharge end of the reactor. Increase of the reactor slope under these operating conditions results in decreased sizes of the static bed and batch fluidization zones. If the IFB slope is increased sufficiently, an even fluidized bed through the entire length of the reactor results.

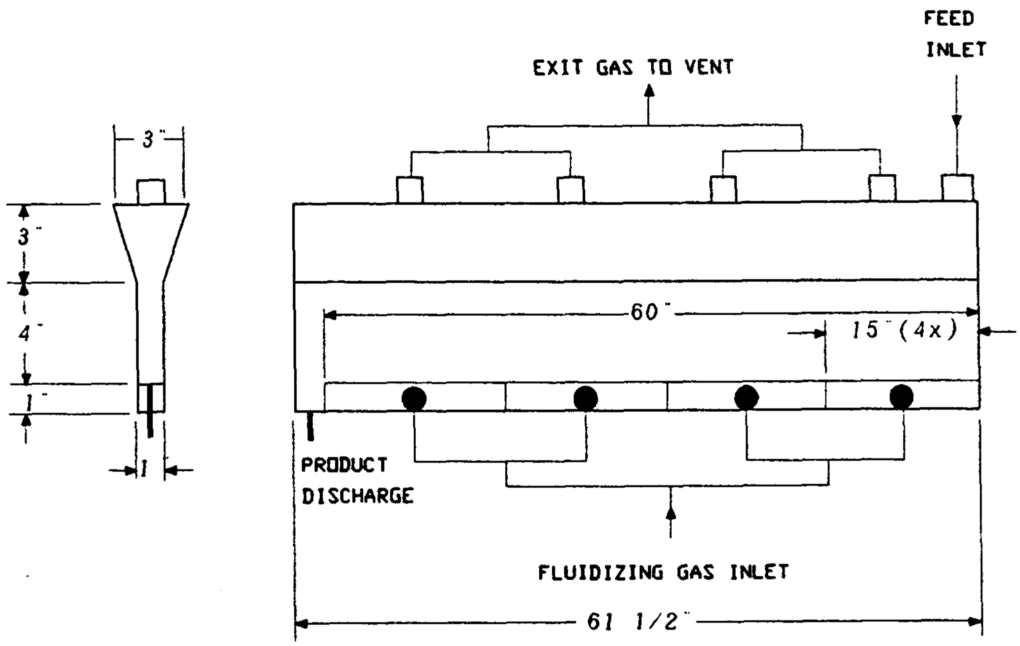

Figure 3.1 Inclined Fluidized Bed Cold Flow Model

As coal is fed into the IFB reactor, it tends to create a bed of solids near the solids inlet. In addition, the one fluidizing gas inlet to the fluidizing gas distributor in the bench-scale IFB is located near the solids inlet and feeds the entire length of the reactor. The variations in the depth of the solids bed through the length of the reactor and the fact that the fluidizing gas distributor has only one inlet facilitate an uneven vertical flow distribution with respect to the reactor length. Thus, at low gas-to-solids ratios and small reactor slopes, the fluidizing gas velocity increases through the length of the IFB reactor. The fluidizing gas velocity is the lowest near the reactor inlet and the greatest near the reactor outlet. Figure 3.2 relates the MFV data and the cold flow data.

This diagram is a graphical representation from the literature of the log of pressure drop across the solids bed versus the log of the superficial gas velocity (McCabe and Smith 1967).

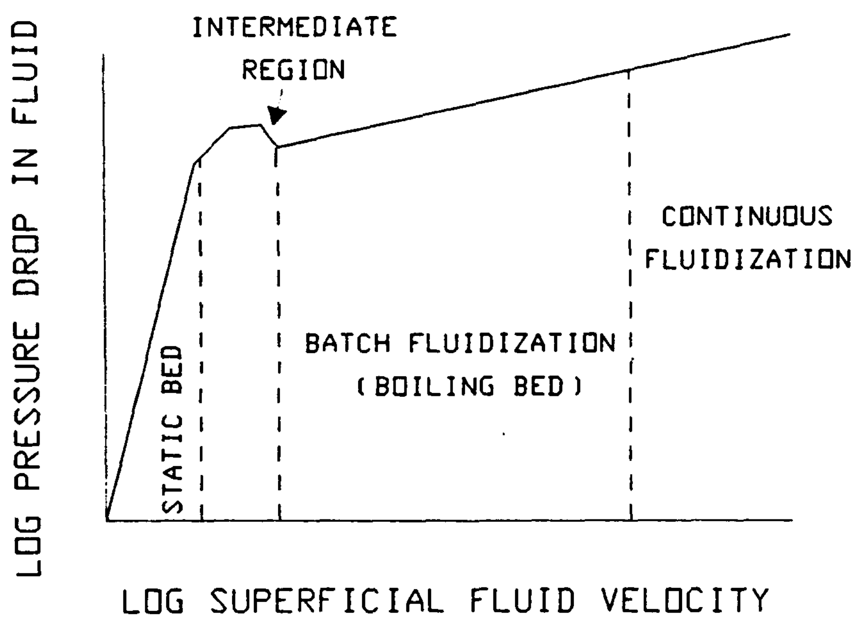

Figure 3.2 Pressure Drop in Fluidized Solids (from McCabe and Smith 1967)

Further understanding of the behavior of gases and solids flowing through the IFB is critical to understanding the behavior of the IFB drying process. Horizontal transport of solids not entrained and vertical transport of entrained solids occur simultaneously in the IFB. Horizontal solids transport occurs as a result of flow conditions in the lower portion of the reactor where the reactor cross-sectional area is minimum while vertical solids transport occurs as a result of flow conditions in the upper portion of the IFB where the reactor cross-section is maximum.

The gas velocity flowing through the solids bed is the maximum with respect to the vertical axis because the cross-sectional area of the IFB is smallest at the solids bed located in the bottom of the reactor. The gas velocity flowing through the disengagement zone near top of the reactor is the minimum with respect to the vertical axis because the IFB cross-sectional area is maximum at the disengagement zone.

The velocity of the gas flowing through the solids bed in the IFB will effect the horizontal transport of the solids. The solids will tend to move horizontally the quickest where the gas velocity flowing through the solids bed is the greatest. However, since the actual solids residence time is the sum of the solids residence times in each of the velocity regimes, the total solids residence time for horizontal solids transport through the entire reactor can be correlated with the average vertical velocity of gas flowing through the solids bed.

A gas velocity gradient near the top of the IFB would effect the transport of entrained solids. The outlet header is sized to provide equal flow restriction at each outlet. The amount of gas flowing out each outlet is dependent upon the pressure drop from the upper portion of the IFB to the gas outlet header and upon the restriction to flow of the outlet piping to the header. Since the flow restrictions of the piping from each outlet to the header are identical and there exist nothing in the upper portion of the reactor to restrict the horizontal cross-flow of gas, the gas flowing through the disengagement zone near the top of the reactor must have a near uniform velocity profile. Therefore, the vertical transport of entrained solids is related to the velocity of gases flowing through the disengagement zone.

Another series of IFB cold-flow experiments was performed during the third quarter to determine the relationship of the solids residence time to the gas-flow conditions in the IFB. This series of cold-flow experiments consisted of a total of 32 tests: sixteen using each feed coal. Each coal was tested using four different fluidizing gas flowrates and using four different IFB reactor slopes. In all cases, carbon dioxide fluidizing gas flowrates of nominally 1.5, 3.1, 5.4, and 7.8 scfm were tested for each reactor slope considered. IFB reactor slopes of 3, 6, 9, and 12 degrees were tested using crushed Eagle Butte feed coal and IFB reactor slopes of 6, 9, 12, and 15 degrees were tested using crushed Usibelli feed coal. The preliminary results of the 3 degree IFB slope using Eagle Butte feed coal indicated that cold fluidizing gas velocities of 5.4 scfm were required to prevent the cold flow reactor from plugging.

An IFB slope of 3 degrees was not tested using Usibelli feed coal. Instead, the 15 degree IFB slope tests using Usibelli feed coal replaced the 3 degree slope tests.

Data collection for this series of IFB cold-flow experiments was designed to provide sufficient data for the determination of the relationship of the solids residence time to the Reynolds number. The experimental procedure was as follows: The IFB reactor slope and fluidizing gas flowrate were fixed and recorded in the experimental logbook at the beginning of each experiment along with the tare weight of the empty IFB cold-flow reactor. A known mass of feed coal was introduced into the feed hopper and the feed was initiated. The mass of feed, feeder setting, and time when feed was initiated, were recorded. Observations regarding the development of the solids bed in the IFB were recorded also. When the solids bed was developed and stable, a dimensioned sketch of the bed geometry was recorded and included description of the sizes and locations of static, batch fluidization, continuous fluidization zones of the solids bed. Coal feed continued until the feeder emptied and was shut-off. Fluidizing gas flow was also shut-off immediately after the feeder emptied. The time when the feed was shut-off was recorded. The IFB reactor was then disassemble and weighed as was the product collection can. The IFB cold-flow reactor, feed system, and product collection can were then cleaned and made ready for another experiment.

The experimental solids residence time was determined using a method provided in the literature (Kunii and Levenspiel 1969). This method describes the solids residence time as:

$$\text{Average Solids Residence Time} = \frac{\text{Mass of reactor solids bed}}{\text{Feed rate - Entrainment rate}} \quad (1)$$

Only the mass of the active bed in the reactor was considered for these calculations. This was calculated by subtracting the estimated mass of the static bed in the reactor from the total mass of solids in the IFB cold-flow reactor at the time of shut-down. The volume of the static bed in the IFB was calculated from the description of the bed geometry provided for each test. The experimentally determined bulk density and porosity of the crushed feed coals were 67 lb/ft^3 and 35.5% for the crushed Eagle Butte feed coal and 68 lb/ft^3 and 33% for the crushed Usibelli feed coal. The mass of material in the static bed was then determined from the static bed volume by assuming the static bed to be a packed bed and using the bulk density and porosity.

The coal feed rate was determined as the amount of coal introduced into the reactor divided by the amount of time the feeder was in operation. The entrainment rate was determined as a percentage of the coal feed. The mass of material entrained was calculated as the mass of coal fed to the reactor minus the sum of the mass of product collected and the total mass in the reactor at shutdown.

The Reynolds number of the fluidized particles is defined by the following equation (Kunii and Levenspiel, 1969):

$$N_{Re} = \frac{D_s V_g \rho_s}{\mu_g} \qquad (2)$$

where:

N_{Re} = Reynolds number
V_g = gas velocity
D_p = average diameter of solid particles
ρ_s = solid particle density
μ_g = gas viscosity

The Reynolds number was determined for each fluidizing gas flowrate by using the average diameter of the feed coal, the average density of the solid particles and the carbon dioxide fluidizing gas velocity.

Table 3.1 provides a summary of cold-flow experiments using crushed Eagle Butte and Usibelli feed coals. Residence times reported in the previous quarter differ from data presented this quarterly report. These differences are a result of incorporation of the effect of the entrainment on the residence time, incorporation of the effect of the experimentally determined bulk density and porosity of each feed coal into the calculation, and the correction of numerical errors found in the experimental logbook.

Figure 3.3 illustrates the relationship of the average solids residence time to the Reynolds number for each of the four IFB slopes tested in the cold-flow experiments using Eagle Butte coal. Figure 3.4 illustrates the relationship of the average solids residence time to the Reynolds number for each of the four IFB slopes tested in the cold-flow experiments using Usibelli coal.

Table 3.1 Summary of IFB Cold-Flow Test Results

-28-mesh Coal Feed rate, g/min	IFB Reactor Slope, degrees	Solids Reynolds Number	Entrainment Rate, % of Feed	Total Solids in IFB, g	Estimated Static Bed, g	Solids Residence Time, min
			Eagle Butte Feed Coal:			
65	3	685	16.1	347	135	3.9
65	3	483	8.4	1056	425	7.2
	3	272	IFB Reactor Plugged			
	3	132	IFB Reactor Plugged			
65	6	685	19.4	195	0	3.8
65	6	483	7.7	720	394	5.5
65	6	272	0.3	882	338	8.5
	6	132	IFB Reactor Plugged			
65	9	685	13.7	206	0	3.7
65	9	483	9.9	354	127	5.5
65	9	272	1.4	843	338	8.5
	9	132	IFB Reactor Plugged			
65	12	685	14.9	156	0	2.8
65	12	483	10.2	309	113	3.4
65	12	271	2.4	463	84	6.0
	12	132	IFB Reactor Plugged			
			Usibelli Feed Coal:			
95	6	781	10.1	259	0	3.0
87	6	548	7.0	498	72	5.3
87	6	315	1.3	1209	539	7.8
	6	152	IFB Reactor Plugged			
90	9	781	8.7	204	0	2.5
95	9	548	8.0	278	0	3.2
88	9	315	4.0	512	148	4.3
89	9	152	1.0	755	241	5.8
93	12	781	9.4	152	0	1.8
85	12	548	7.8	217	0	2.7
86	12	315	4.2	352	34	3.9
89	12	152	0.7	717	311	4.6
95	15	781	8.9	146	0	1.7
95	15	548	6.8	225	0	2.5
95	15	315	3.2	453	135	3.5
100	15	152	1.3	647	269	3.8

As the fluidizing gas velocity approaches zero the solids cease to be transported horizontally and the solids residence time approaches infinity in a sharp asymptotic fashion. Similarly, as the Reynolds number approaches infinity and the solids residence time asymptotically approaches zero. Thus, the hyperbolic shape of these curves is defined. This analysis is subject to two constraints: 1) The slope of the IFB reactor must be less than the angle of repose of the solid material feed to the IFB or the material will flow without fluidizing gas; and 2), the fluidizing gas velocity must not be sufficiently large to entrain 100% of the solid material fed to the reactor. The general shapes of the curves shown in Figures 3.3 and 3.4 are hyperbolic as theory suggests. Further, the solids residence time decreases with the IFB reactor slope when other conditions are similar.

Since solid residence times are correlated by the Reynolds number (dimensionless), the relationships illustrated in Figures 3.3 and 3.4 should be similar for both coals. Figures 3.5, 3.6, and 3.7 provide the relationships of the average solids residence time versus the Reynolds number for each of the three IFB reactor slopes tested using both feed coals (6, 9, and 12 degrees). The agreement of these data is reasonable although there is a slight shift of the Eagle Butte data compared to the Usibelli data. The shift of the Eagle Butte data is probably due to the tendency of the Eagle Butte coal to stick together. Regardless of the explanation for the shift of the Eagle Butte data, the reasonable agreement of these data demonstrate that this non-dimensionalization technique will allow the estimate with reasonable accuracy the average solids residence time of another coal crushed similarly.

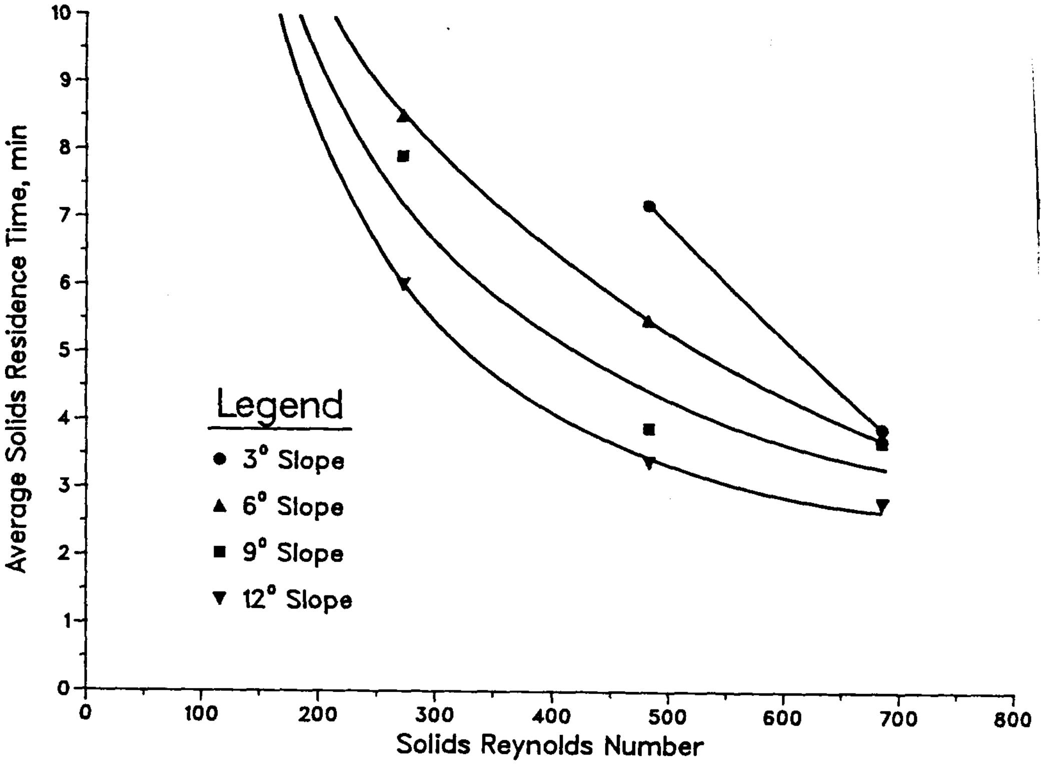

Figure 3.3 Average Solids Residence Time versus Solids Reynolds Number for Eagle Butte Coal

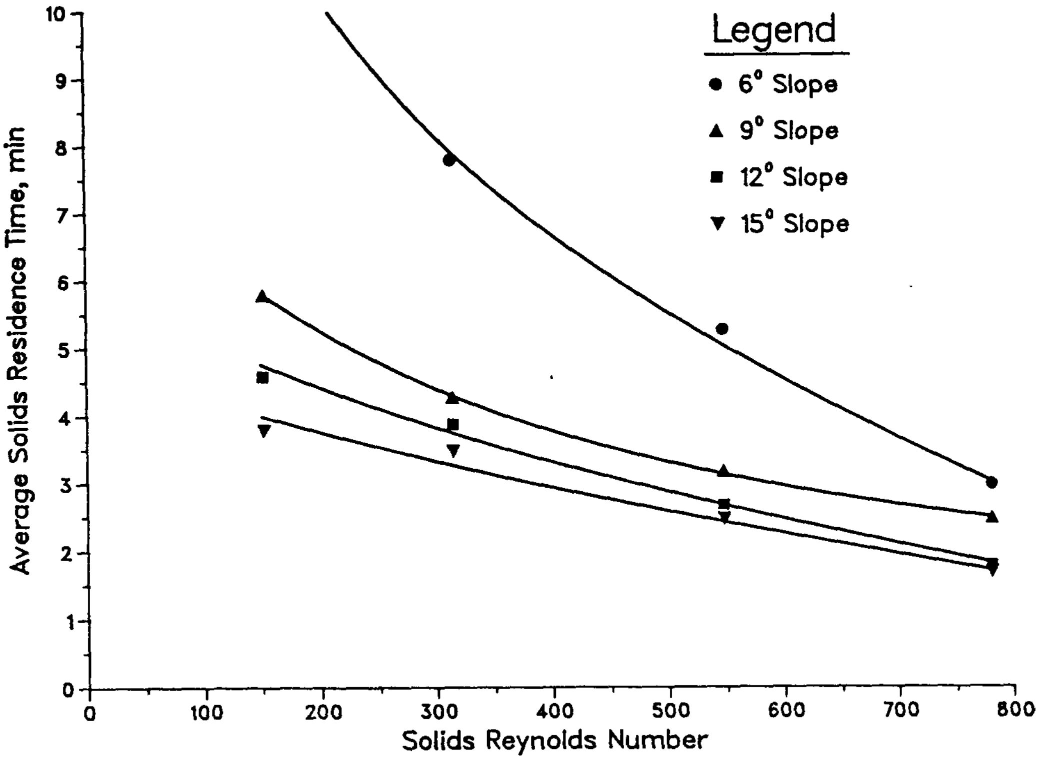

Figure 3.4 Average Solids Residence Time versus Solids Reynolds Numberfor Usibelli Coal

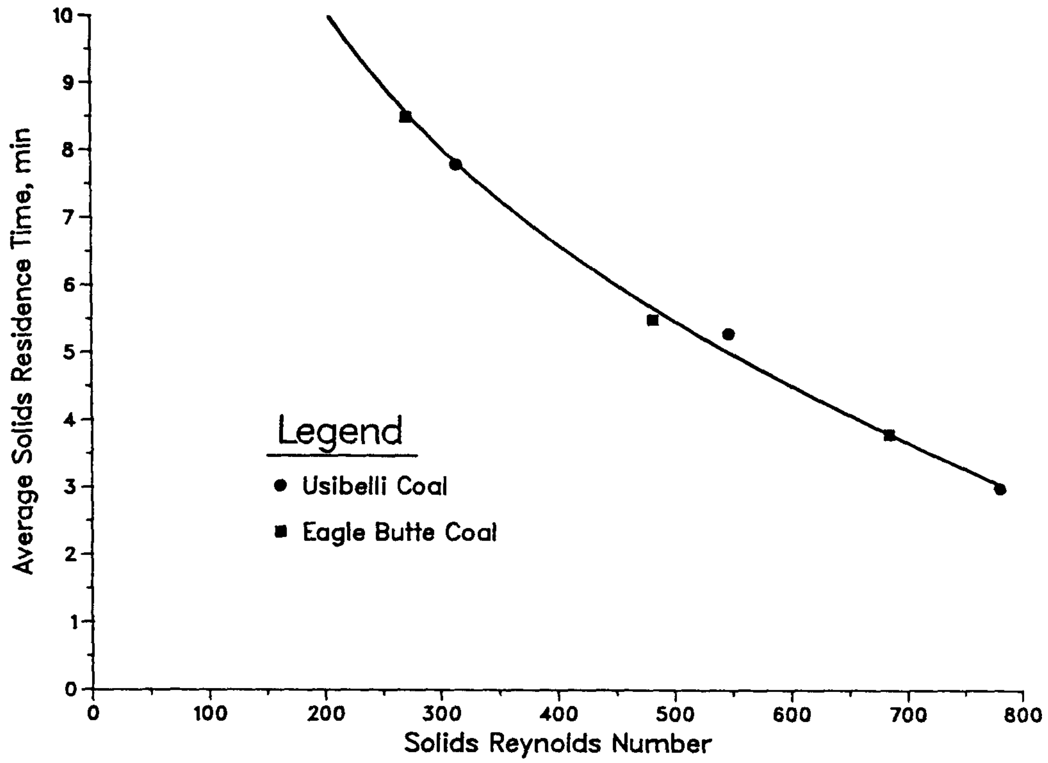

Figure 3.5 Average Solids Residence Time versus Reynolds Number for a 6 degree IFB Reactor Slope

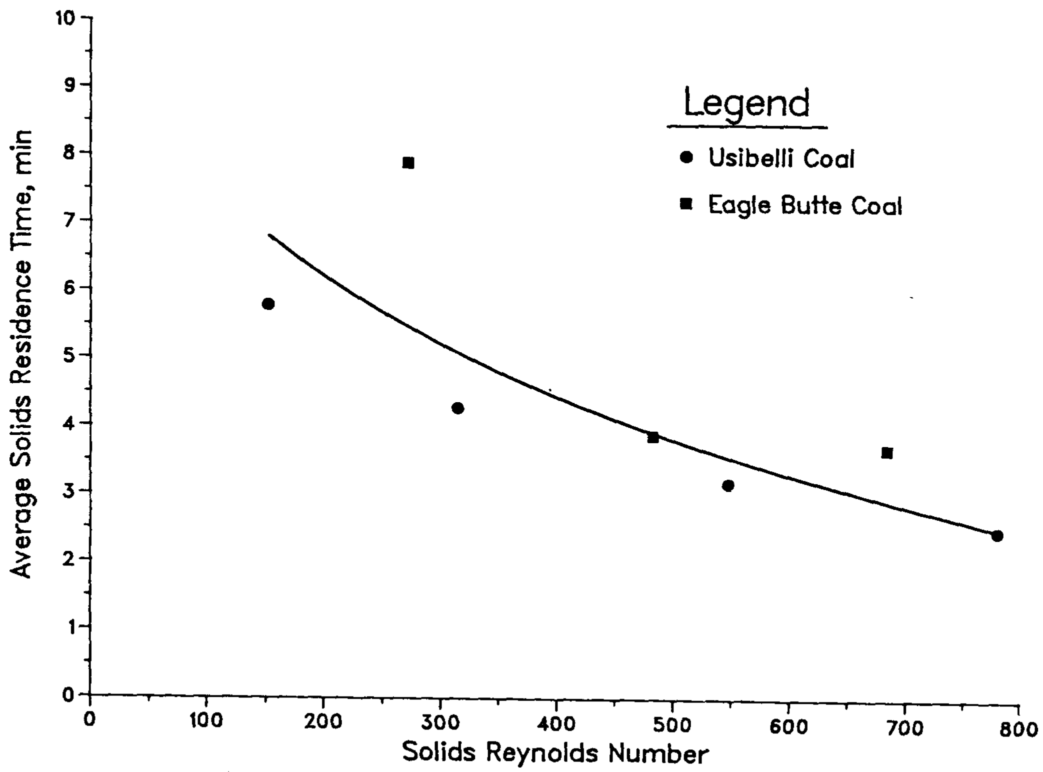

Figure 3.6 Average Solids Residence Time versus Reynolds Number for a 9 degree IFB Reactor Slope

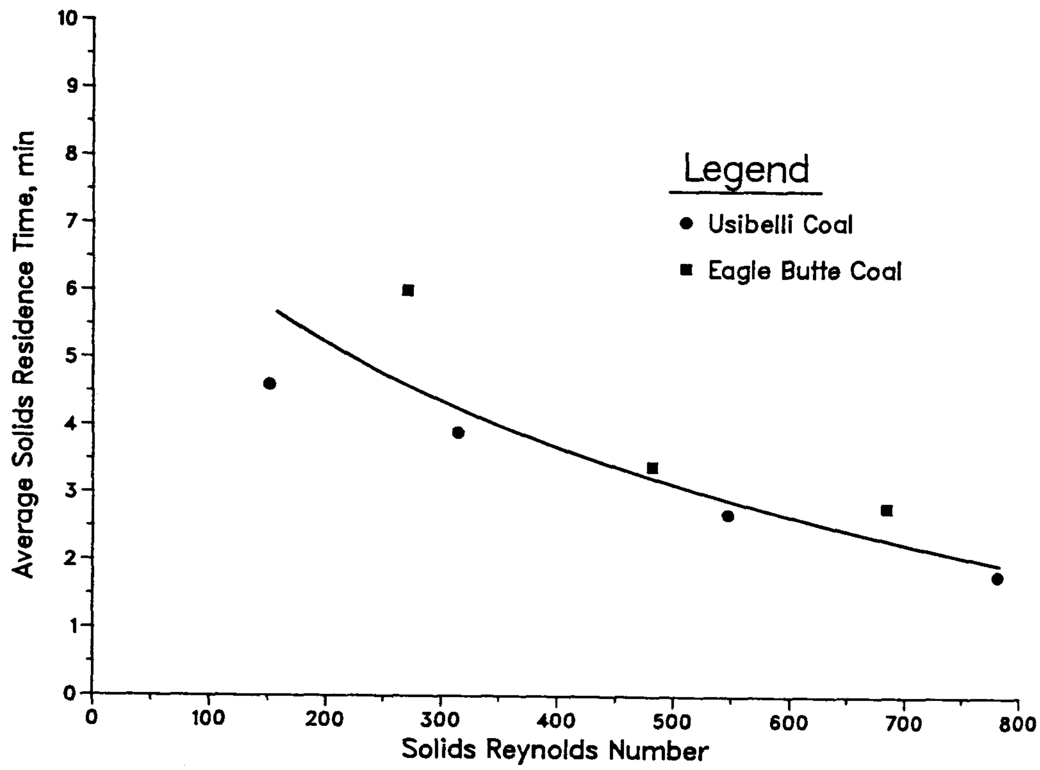

Figure 3.7 Average Solids Residence Time versus Reynolds Number for a 12 degree IFB Reactor Slope

Subtask 3.2: IFB Drying Tests

Drying tests using nominally a 10-lb/hr coal feed rate were completed in the fourth quarter. In these experiments the IFB reactor slope, fluidizing gas-to-solids ratio, and the average reactor temperature were varied to determine their effects upon drying behavior and particle entrainment. The experimental bench-scale IFB coal dryer process equipment consists of two 5-ft long IFB reactor in series separated by lockhopper valves that pneumatically isolate the two reactors while allowing for solids transfer from the first reactor to the second (Figure 3.8). Details regarding this equipment and its operation are provided in the project report for the third quarter.

A total of forty-one 4-hr (19 using Eagle Butte feed coal including 1 shakedown and 22 using Usibelli feed coal) and eight 12-hr (4 using each feed coal) bench-scale IFB drying tests have been conducted. IFB reactor slopes of 3, 6, 9, 12, and 15 degrees were investigated for each feed coal.

Experimental conditions, product proximate moisture content, and product heating values currently completed for the 4-hr and 12-hr tests using Eagle Butte coal are listed in Table 3.2. During the tests using Eagle Butte feed coal, gas-to-solids ratios ranging from approximately 0.7 to 9.7 lb/lb (kg/kg) and average IFB reactor temperatures ranging from approximately 370 to 730°F (188 to 378°C) were tested. In all of these experiments the dried coal product contained less than 1.5 % moisture based upon proximate analysis. The heating values of the products were elevated to a range of 11,800 to 12,600 Btu/lb from 8,470 Btu/lb.

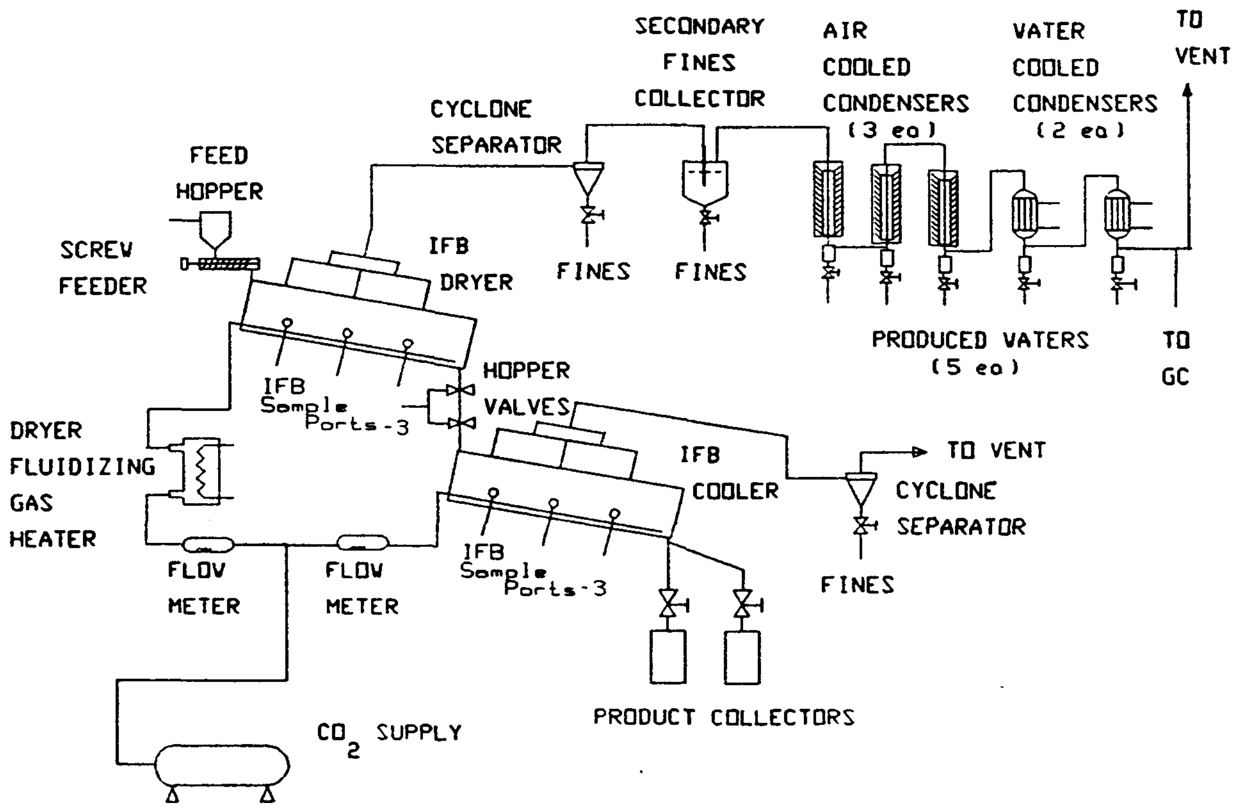

Figure 3.8 Experimental IFB Coal Dryer

Table 3.2 Summary of Experimental Conditions for IFB Bench-Scale Drying Tests using Eagle Butte Feed Coal

Reactor Slope, degrees	Gas to Solids, lb/lb	Average Dryer Temperature, °F	Product Moisture, %	Product HHV, Btu/lb
3	5.5	595	0.0	12,250
3	4.9	589	0.1	12,230
3	2.7	531	0.0	12,220
3[a]	3.9	695	0.0	12,440
6	2.7	595	0.2	12,250
6	4.0	599	0.1	12,320
6	4.1	623	0.0	12,320
6	2.5	666	0.0	12,040
6[a]	3.0	684	0.2	11,870
9	4.6	617	0.0	12,050
9	3.6	589	0.1	12,800
9	2.3	588	0.0	11,970
9	4.8	692	0.0	12,560
9	3.1	693	0.0	12,190
9[a]	1.5	611	0.0	11,940
12	1.4	603	---	------
12	1.3	649	1.3	------
12	2.3	682	0.0	------
15	1.4	645	0.1	------
15	1.4	377	0.2	------
15	0.7	589	---	------
15[a]	1.4	731	0.3	------

[a] Experiment of nominally 12-hr duration

Similarly, experimental conditions, product proximate moisture content, and product heating values for the 4-hr and 12-hr tests using Usibelli coal are listed in Table 3.3. During the tests using Usibelli feed coal, gas-to-solids ratios ranging from approximately 0.7 to 4.0 lb/lb (kg/kg) and average IFB reactor temperatures ranging from approximately 360 to 750°F (182 to 399°C) were tested. Once again, in all of these experiments the dried coal product contained less than 1.5 % moisture based upon proximate analysis. The heating values of these products were elevated to a range of 10,400 to 11,500 Btu/lb from 8,470 Btu/lb.

Material balances were performed for each bench-scale experiment. Total mass, fixed carbon, and ash balances were calculated from proximate analyses of the feed coal, product, and entrained solids. These balances were performed using the test data and proximate analyses of the feeds, products, and entrained solids. Proximate analyses were performed on composite samples of each experimental product and composite samples of solids entrained from each experiment. Proximate analyses of composite feed coal samples were performed for each 12-hour experiment but only proximate moisture analyses of composite feed samples were performed for each 4-hour experiment.

Table 3.3 Summary of Experimental Conditions for IFB Bench-Scale Drying Tests using Usibelli Feed Coal

Reactor Slope, degrees	Gas to Solids, lb/lb	Average Dryer Temperature, °F	Product Moisture, %	Product HHV, Btu/lb
3	2.6	494	1.2	10,450
3	3.4	705	0.0	11,380
3	3.7	690	0.4	------
3	3.4	605	0.1	------
3[a]	4.0	611	0.0	10,950
6	2.7	690	0.0	10,960
6	2.1	675	0.0	11,120
6	3.3	680	0.0	11,300
6	3.3	695	0.0	11,040
6	2.8	564	0.0	11,000
6[a]	2.6	664	0.3	10,560
9	2.6	637	0.0	11,520
9	2.8	678	0.0	11,170
9	2.7	595	0.1	11,110
9	2.7	571	0.2	11,130
9	1.8	653	0.0	11,050
9	1.9	603	0.1	10,830
9	3.8	707	0.0	10,850
9[a]	1.9	632	0.0	10,830
12	1.5	632	0.1	10,950
12	1.3	653	0.5	------
12	2.3	692	0.7	------
15	1.3	648	0.1	------
15	1.4	364	0.7	------
15	0.7	594	---	------
15[a]	1.3	752	0.1	------

[a] Experiment of nominally 12-hr duration

The method of material balance calculation is as follows: The mass of water removed from the coal is calculated as the difference between the moisture in the feed coal and the sum of the moisture in the product and moisture in the entrained solids collected. The mass of gas produced from heating the feed coal is calculated as the difference between the volatile matter in the feed coal and the sum of the volatile matter in the product and the volatile matter in the entrained solids. The total mass in is considered to be the mass of feed coal and the total mass out is considered to be the sum of the mass of product collected, mass of entrained solids collected, mass of gas produced, and the mass of water removed from the coal.

The experimental closures for total mass, fixed carbon, and ash balances are presented along with the IFB reactor slope and gas-to-solids ratio for the bench-scale IFB drying experiments conducted using Eagle Butte feed coal (Table 3.4). The two experiments with a fixed carbon balance closure less than 90% or greater than 110% are omitted from further analyses.

Similarly, the experimental closures for total mass, fixed carbon, and ash balances are presented along with the IFB reactor slope and gas-to-solids ratio for the bench-scale IFB drying experiments conducted using Usibelli feed coal (Table 3.5). The four experiments with a fixed carbon balance closure less than 90% or greater than 110% are omitted from further analyses.

Table 3.4 Summary of Experimental Balance Closures for IFB Bench-Scale Drying Tests using Eagle Butte Feed Coal

Reactor Slope, degrees	Gas to Solids, lb/lb	Average Dryer Temperature, °F	Balance Closures, % : Total Mass	Fixed Carbon	Ash
3	5.5	595	94.3	86.7	82.0
3	4.9	589	97.3	93.7	90.0
3	2.7	531	99.3	98.4	96.8
3[a]	3.9	695	97.8	95.2	88.5
6	2.7	595	102.2	105.6	100.4
6	4.0	599	98.8	97.9	92.6
6	4.1	623	102.1	105.4	100.7
6	2.5	666	97.4	94.3	89.4
6[a]	3.0	684	97.5	94.2	92.8
9	4.6	617	99.7	98.7	103.2
9	3.6	589	96.1	91.5	82.3
9	2.3	588	97.7	95.2	88.9
9	4.8	692	96.2	91.9	91.1
9	3.1	693	91.2	80.1	70.0
9[a]	1.5	611	102.4	107.5	100.5
12	1.4	603	----	----	----
12	1.3	649	95.8	90.3	85.9
12	2.3	682	97.6	94.8	89.4
15	1.4	645	97.5	93.9	93.5
15	1.4	377	98.5	96.5	96.9
15	0.7	589	----	----	----
15[a]	1.4	731	97.0	92.3	98.6

[a] Experiment of nominally 12-hr duration

Table 3.5 Summary of Experimental Balance Closures for IFB Bench-Scale Drying Tests using Usibelli Feed Coal

Reactor Slope, degrees	Gas to Solids, lb/lb	Average Dryer Temperature, °F	Balance Closures, % : Total Mass	Fixed Carbon	Ash
3	2.6	494	100.4	100.1	100.4
3	3.4	705	97.6	93.9	97.5
3	3.7	690	97.1	92.2	98.7
3	3.4	605	99.0	96.2	103.7
3[a]	4.0	611	98.2	97.3	91.1
6	2.7	690	98.1	93.7	104.2
6	2.1	675	96.1	90.6	92.0
6	3.3	680	105.7	113.3	114.0
6	3.3	695	96.6	93.1	87.6
6	2.8	564	97.6	94.7	93.5
6[a]	2.6	664	98.2	95.6	96.9
9	2.6	637	97.3	94.9	87.9
9	2.8	678	94.7	88.6	82.9
9	2.7	595	94.6	88.8	81.0
9	2.7	571	98.2	97.3	89.8
9	1.8	653	91.6	84.0	75.3
9	1.9	603	100.1	97.1	112.1
9	3.8	707	97.8	92.0	106.4
9[a]	1.9	632	99.1	100.3	90.7
12	1.5	632	100.4	98.9	109.5
12	1.3	653	99.3	97.7	101.0
12	2.3	692	96.3	91.8	90.9
15	1.3	648	100.9	101.1	106.4
15	1.4	364	97.8	92.7	103.6
15	0.7	594	----	----	----
15[a]	1.3	752	97.3	93.3	96.5

[a] Experiment of nominally 12-hr duration

The experimental yields determined from the proximate material balances are presented in Tables 3.6 and 3.7 for Eagle Butte and Usibelli coals, respectively. The yield of dry coal product, gas, entrained solids, and water expressed as a percent of the total feed coal are presented for each experiment. The difference between 100 and the sum of the yields shown is losses expressed as a percent of the total feed.

In addition, the relationships of the gas yield as a function of the average IFB dryer temperature are presented in Figures 3.9 and 3.10 for Eagle Butte and Usibelli feed coals, respectively. Similarly, the relationships of the product composition as a function of the average IFB dryer temperature are presented in Figures 3.11 and 3.12 for Eagle Butte and Usibelli feed coals, respectively. These diagrams illustrate the relationship of the volatile matter, fixed carbon, and ash contents of the dry coal produced to the average IFB dryer temperature for each experiment.

Reynolds numbers (Eq. 2) were calculated for each bench-scale experiment to non-dimensionalize the fluid flow through the disengagement zone and through the solids bed. The Reynolds numbers determined for the disengagement zone are correlated to the amount entrained solids for each experiment. The Reynolds numbers determined for the solids bed conditions were used to estimate the average solids residence time, actual solids heating time, and the solids heating rate in the bench-scale experiments.

Table 3.6 Summary of Experimental Yields for IFB Bench-Scale Drying Tests using Eagle Butte Feed Coal

Reactor Slope, degrees	Gas to Solids, lb/lb	Average Dryer Temperature, °F	Experimental Yield % : Product	Gas	Entrained Solids	Water
3	4.9	589	29.6	4.7	35.0	28.0
3	2.7	531	57.0	2.5	11.6	28.2
3[a]	3.9	695	36.7	8.8	28.4	28.9
6	2.7	595	34.0	2.2	38.5	27.2
6	4.0	599	38.3	3.3	35.3	21.9
6	4.1	623	58.0	2.7	20.5	20.9
6	2.5	666	50.7	7.5	12.3	26.9
6[a]	3.0	684	47.9	10.1	13.4	26.1
9	4.6	617	39.5	4.1	32.0	24.1
9	3.6	589	47.4	5.5	16.1	27.1
9	2.3	588	57.0	5.8	7.7	27.2
9	4.8	692	21.0	7.6	40.9	26.9
9[a]	1.5	611	52.6	3.7	11.1	35.0
12	1.4	603	----	---	----	----
12	1.3	649	55.9	7.1	6.7	26.1
12	2.3	682	45.5	9.2	15.1	27.8
15	1.4	645	55.8	4.8	9.3	27.6
15	1.4	377	63.6	0.9	10.1	23.9
15	0.7	589	----	---	----	----
15[a]	1.4	731	52.8	15.1	8.7	20.4

[a] Experiment of nominally 12-hr duration

Table 3.7 Summary of Experimental Yields for IFB Bench-Scale Drying Tests using Usibelli Feed Coal

Reactor Slope, degrees	Gas to Solids, lb/lb	Average Dryer Temperature, °F	Experimental Yield % : Product	Gas	Entrained Solids	Water
3	2.6	494	70.9	6.9	9.3	13.4
3	3.4	705	50.6	15.0	14.9	17.2
3	3.7	690	33.1	14.8	31.3	18.1
3	3.4	605	49.7	10.6	20.1	18.7
3[a]	4.0	611	54.2	8.3	15.3	20.5
6	2.7	690	53.9	13.3	13.6	17.3
6	2.1	675	52.8	17.2	6.2	20.0
6	3.3	695	56.0	14.0	7.0	19.6
6	2.8	564	64.9	5.9	8.0	18.8
6[a]	2.6	664	55.9	13.9	11.8	16.6
9	2.6	637	55.7	9.2	10.4	22.1
9	2.7	571	43.9	6.6	27.7	20.0
9	1.9	603	64.9	8.0	5.4	21.7
9	3.8	707	44.1	12.8	22.3	18.6
9[a]	1.9	632	60.9	10.2	10.2	17.8
12	1.5	632	66.0	7.4	8.6	18.4
12	1.3	653	63.7	7.7	10.0	17.9
12	2.3	692	58.5	12.1	9.9	15.8
15	1.3	648	66.6	7.2	7.1	20.0
15	1.4	364	69.3	3.7	5.5	19.3
15	0.7	594	----	---	---	----
15[a]	1.3	752	60.3	15.3	6.3	15.4

[a] Experiment of nominally 12-hr duration

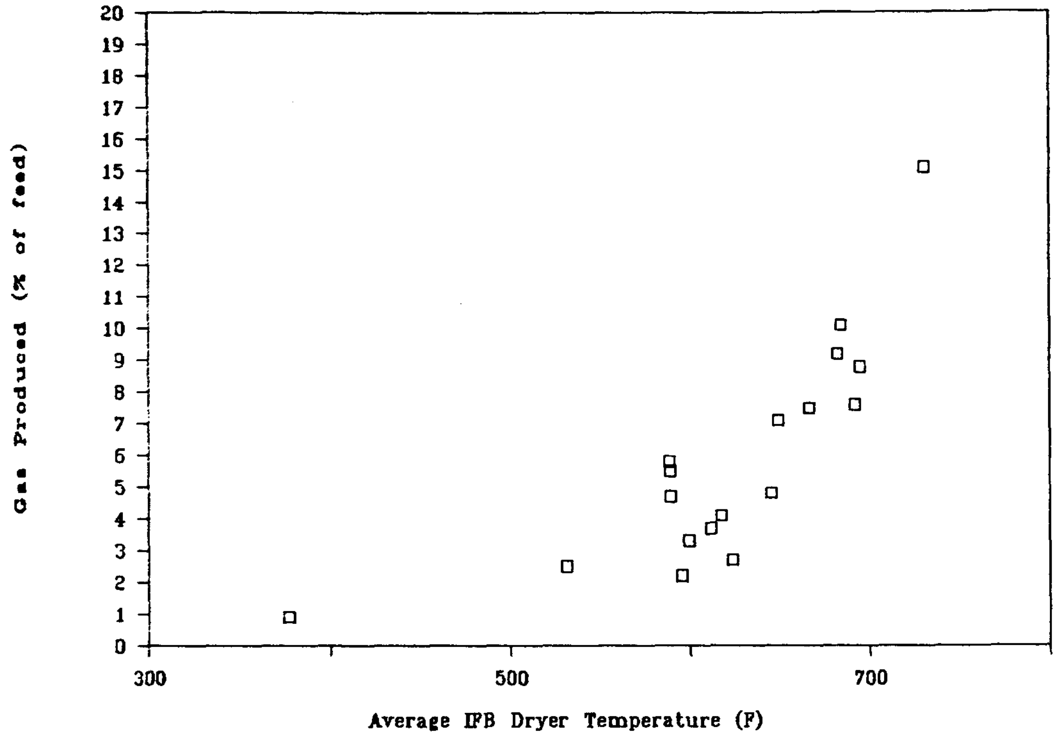

Figure 3.9 **Gas Yield versus Average IFB Dryer Temperature for Eagle Butte Coal**

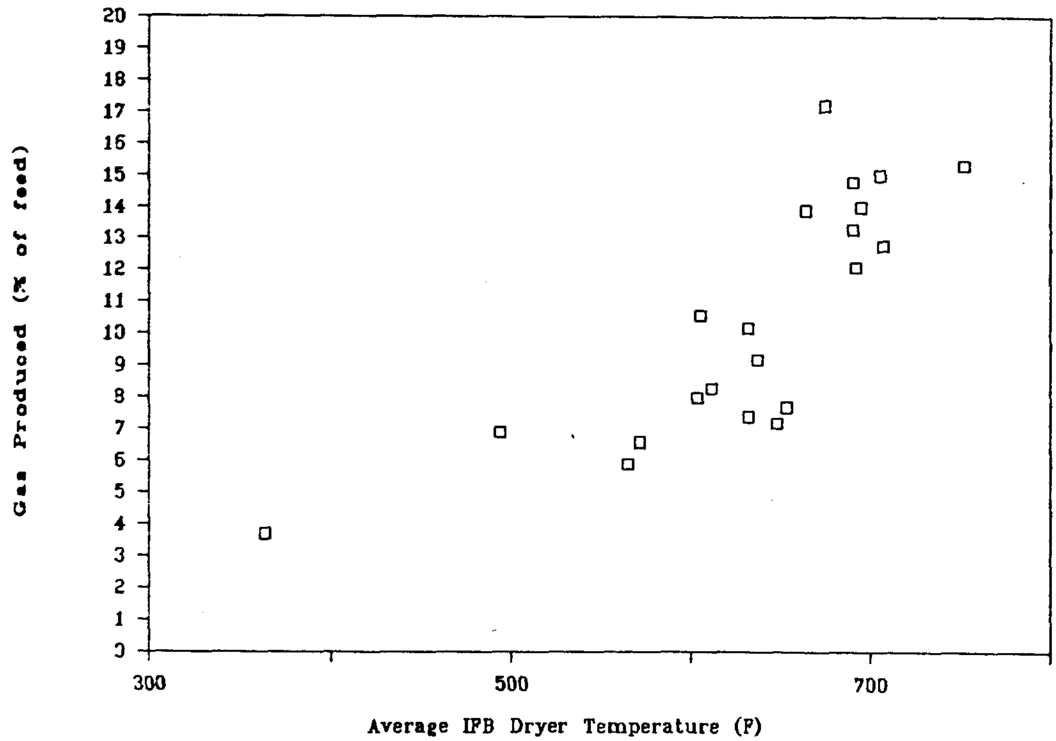

Figure 3.10 **Gas Yield versus Average IFB Dryer Temperature for Usibelli Coal**

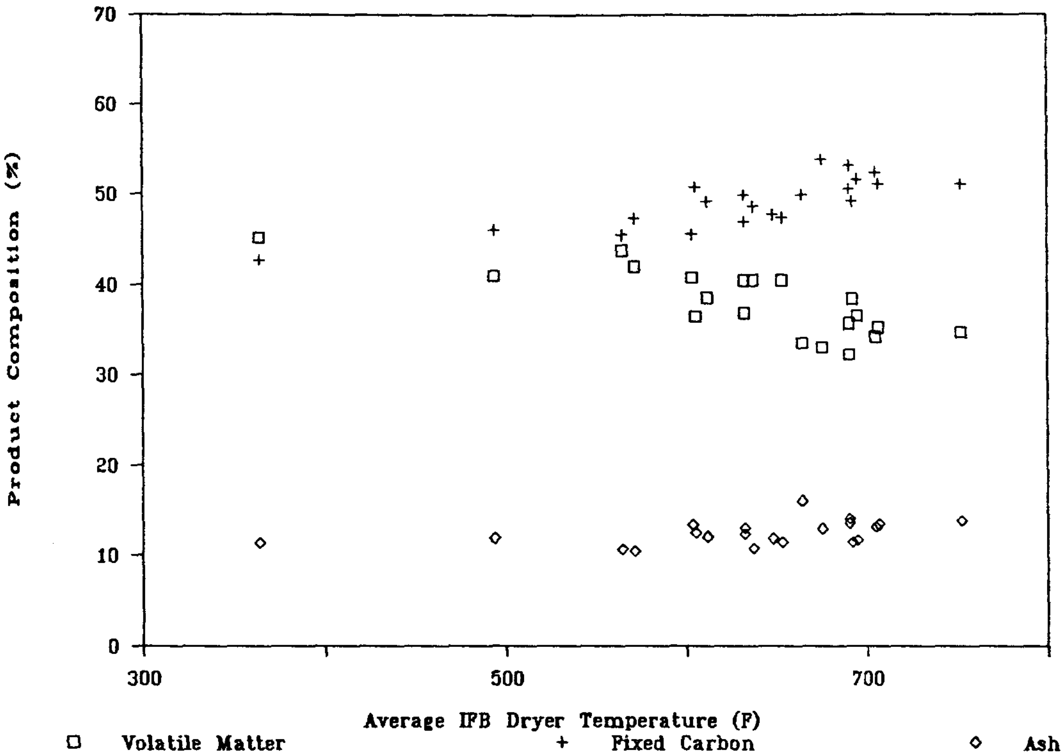

Figure 3.11 Product Composition versus Average IFB Dryer Temperature for Eagle Butte Coal

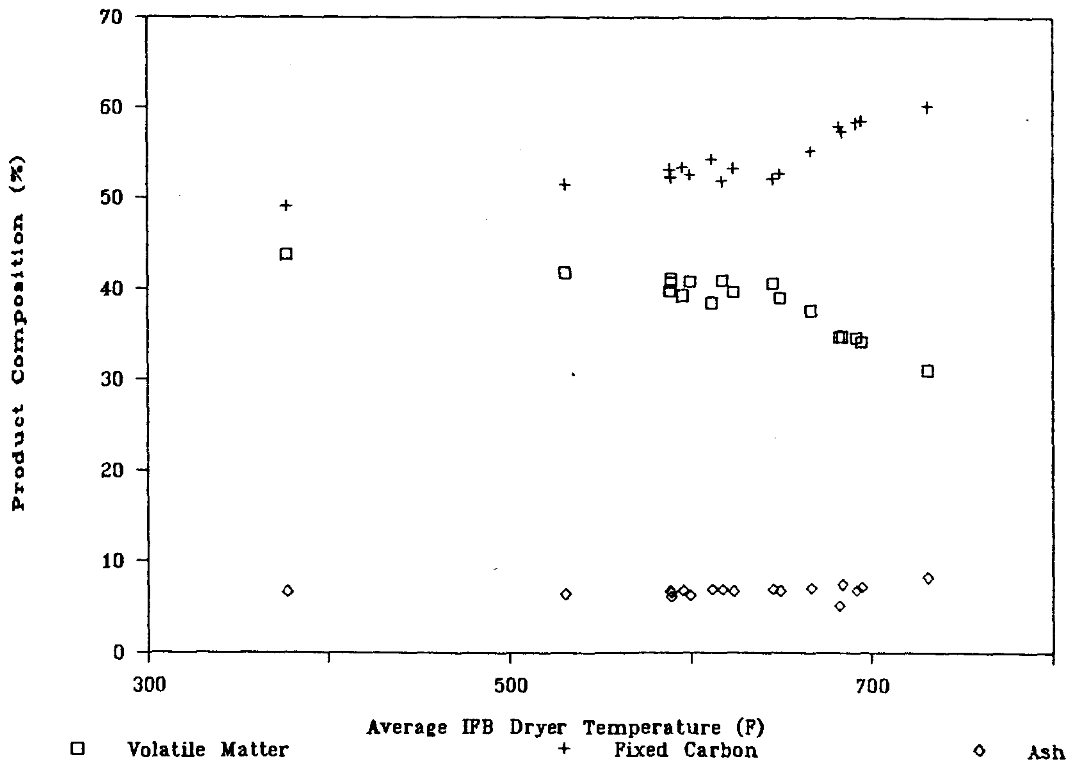

Figure 3.12 Product Composition versus Average IFB Dryer Temperature for Usibelli Coal

The exit gas flowrate through the disengagement zone is determined to be the sum of the fluidizing gas flowrate, the dryer nitrogen tracer flowrate (0.3 scfm in all experiments), the flowrate of the gas produced from heating the coal, and the flowrate of steam produced by removing the moisture from the coal. The exit gas velocity is determined using the exit gas flowrate and the surface area of the disengagement zone in the bench-scale IFB dryer (388 in^3). The ideal gas law is assumed to apply and the gas velocities calculated are corrected for temperature and pressure using the average IFB temperature and a 0.2 psig reactor pressure.

Similarly, the fluidizing gas velocity is determined using the fluidizing gas flowrate and the surface area immediately above the fluidizing gas distributor in the bench-scale IFB dryer (90 in^3). The ideal gas law is assumed to apply and the gas velocities calculated are corrected for temperature and pressure using the average IFB temperature and a 0.2 psig reactor pressure. In determination of the Reynolds numbers for both the disengagement zone and the solids bed at the bottom of the IFB dryer, the average solid particle diameters used are based upon wet screen analyses results of the feed coals and the solid particle densities used are based upon the experimentally determined values for the feed coals.

Herning and Zipperer (Katz, et al. 1959) proposed the following rule to calculate the viscosity of a mixture of gases:

$$\mu_m = \frac{\Sigma^i \mu_i x_i (M_i)^{1/2}}{\Sigma x_i (M_i)^{1/2}} \quad (3)$$

where μ_m = the viscosity of the gas mixture
μ_i = the viscosity of component i
x_i = the mole fraction of component i
M_i = the molecular weight of component i

The viscosity of the carbon dioxide fluidizing gas is calculated using the following equation (Bird et al., 1960):

$$\mu_g = (2.6693 \times 10^{-5}) \frac{(M\ T)^{1/2}}{\sigma^2\ \Omega} \quad (4)$$

where M = molecular weight of gas (44)
T = absolute temperature of gas
σ = collision diameter of the molecule (3.966 A)
Ω = k T/ϵ
k = Boltzman constant
ϵ = characteristic energy interaction between molecules (190)

The viscosity of other gas species and steam in the exit stream were found in the literature (McCabe and Smith, 1967) for each average IFB dryer temperature in the eight 12-hour bench-scale experiments conducted. The viscosity calculated (Eq. 3) for the mixture of non-condensable gases in the exit gas was found to be the same (within 3 decimal places) as the viscosity of pure carbon dioxide calculated from Eq. (4). This is probably due to the fact that the carbon dioxide concentration of the non-condensable portion of the exit gas from the bench-scale IFB drying experiments was always greater than 85%. For this reason the viscosity of the non-condensable exit gas fraction in the 4-hr experiments was assumed to be equal to the viscosity of pure carbon dioxide at the average IFB dryer temperatures considered. The viscosity of the total exit gas stream was calculated (Eq. 3) using the carbon dioxide viscosity and steam viscosity at the average IFB dryer temperature and the mole fractions of non-condensable gases and steam in the exit gas.

The IFB dryer slope, exit gas flowrate, exit gas velocity, average IFB dryer temperature, and the Reynolds number at the disengagement zone of the reactor resulting for each experiment are provided in Tables 3.8 and 3.9 for Eagle Butte and Usibelli coals, respectively. The Reynolds numbers determined based upon flow conditions in the disengagement zone of the IFB dryer are the minimum Reynolds number in the reactor.

The amount of entrained solids produced from the IFB dryer is of economic significance to plans for use of coal fines. The relationship of the solids entrainment to the Reynolds number in the disengagement zone of the IFB is illustrated in Figures 3.13 and 3.14 for the bench-scale IFB drying experiments using Eagle Butte and Usibelli coals, respectively. If the Reynolds number is maintained below 90, entrained solids from the dryer is less than 15% of the Eagle Butte coal and is less than 10% of the Usibelli coal.

The IFB dryer slope, fluidizing gas flowrate, fluidizing gas velocity, average IFB dryer temperature, and the Reynolds number at the bottom of the reactor resulting for each experiment are provided in Tables 3.10 and 3.11 for Eagle Butte and Usibelli coals, respectively. The Reynolds numbers determined based upon flow conditions at the bottom of the IFB dryer are the maximum in the reactor.

Table 3.8 Minimum Reynolds Numbers for IFB Bench-Scale Drying Tests using Eagle Butte Feed Coal

Reactor Slope, degrees	Exit Gas Flowrate, scfm	Exit Gas Velocity, ft/min	Average Dryer Temperature, °F	Minimum Reynolds Number in IFB
3	7.8	7.7	589	128
3	6.1	5.7	531	103
3[a]	7.1	7.6	695	119
6	7.7	7.6	595	130
6	6.2	6.2	599	102
6	6.0	6.1	623	100
6	4.3	4.6	666	74
6[a]	5.4	5.8	684	92
9	5.8	5.8	617	95
9	4.8	4.7	589	80
9	4.1	4.0	588	70
9	7.4	7.9	692	123
9[a]	3.8	3.8	611	67
12	---	---	603	---
12	3.5	3.7	649	61
12	5.1	5.5	682	88
15	3.5	3.6	645	61
15	3.3	2.6	377	55
15	---	---	589	---
15[a]	3.3	3.7	731	58

[a] Experiment of nominally 12-hr duration

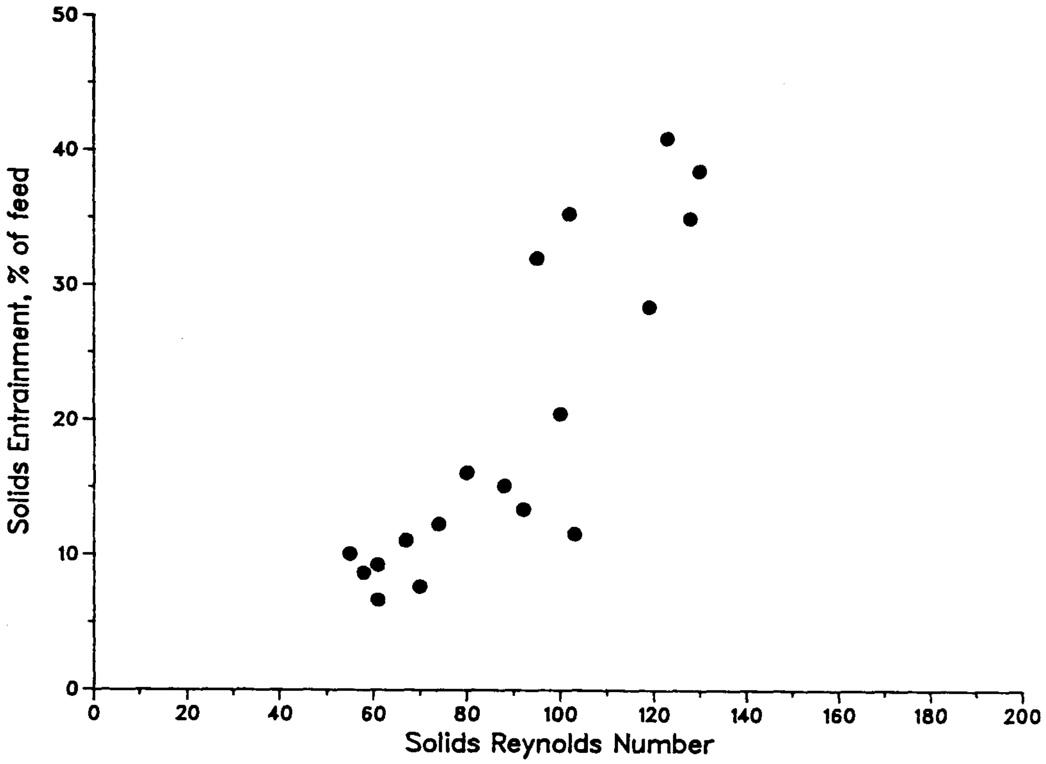

Figure 3.13 Solids Entrainment versus Reynolds Number for Eagle Butte Coal

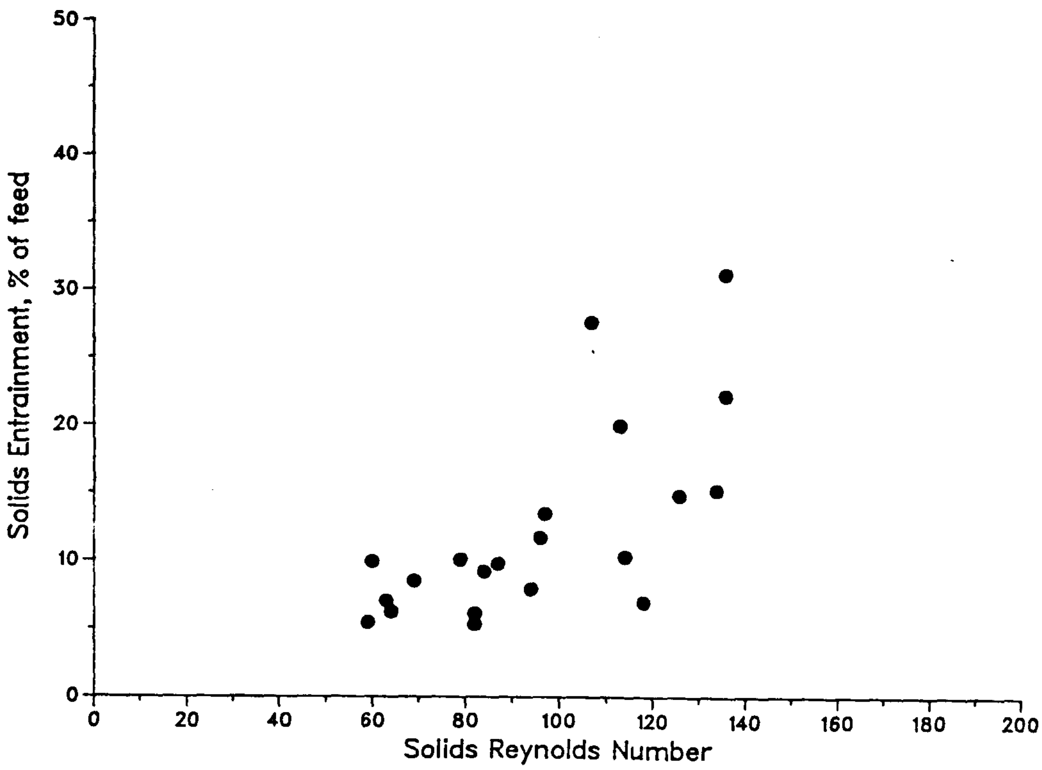

Figure 3.14 Solids Entrainment versus Reynolds Number for Usibelli Coal

Table 3.9 Minimum Reynolds Numbers for IFB Bench-Scale Drying Tests using Usibelli Feed Coal

Reactor Slope, degrees	Exit Gas Flowrate, scfm	Exit Gas Velocity, ft/min	Average Dryer Temperature, °F	Minimum Reynolds Number in IFB
3	4.7	4.2	494	84
3	6.8	7.4	705	126
3	7.4	7.9	690	136
3	6.2	6.2	605	113
3[a]	7.4	7.4	611	134
6	5.2	5.6	690	97
6	4.4	4.7	675	82
6	6.4	6.9	695	118
6	5.1	4.9	564	94
6[a]	5.2	5.5	664	96
9	6.1	6.3	637	114
9	5.8	5.6	571	107
9	4.4	4.4	603	82
9	7.3	8.0	707	136
9[a]	4.3	4.4	632	79
12	3.6	3.7	632	69
12	3.1	3.3	653	60
12	4.7	5.0	692	87
15	3.3	3.4	648	63
15	3.2	2.5	364	59
15	---	---	594	---
15[a]	3.3	3.8	752	64

[a] Experiment of nominally 12-hr duration

Table 3.10 Maximum Reynolds Numbers for IFB Bench-Scale Drying Tests using Eagle Butte Feed Coal

Reactor Slope, degrees	Fluidizing Gas Flowrate, scfm	Maximum Fluidizing Gas Velocity, ft/min	Average Dryer Temperature, °F	Maximum Reynolds Number in IFB
3	6.4	16.0	589	248
3	4.5	10.6	531	172
3[a]	5.5	15.2	695	219
6	5.7	14.3	595	222
6	5.1	12.9	599	198
6	5.0	12.9	623	195
6	3.0	8.1	666	118
6[a]	4.0	10.9	684	159
9	5.0	12.8	617	195
9	3.9	9.8	589	151
9	3.0	7.5	588	116
9	6.0	16.5	692	238
9[a]	2.1	5.4	611	82
12	2.1	5.3	603	82
12	2.0	5.3	649	79
12	3.5	9.5	682	139
15	2.0	5.3	645	79
15	2.0	4.0	377	74
15	1.1	2.8	589	43
15[a]	2.0	5.7	731	80

[a] Experiment of nominally 12-hr duration

Table 3.11 Maximum Reynolds Number for IFB Bench-Scale Drying Tests using Usibelli Feed Coal

Reactor Slope, degrees	Fluidizing Gas Flowrate, scfm	Maximum Fluidizing Gas Velocity, ft/min	Average Dryer Temperature, °F	Maximum Reynolds Number in IFB
3	3.8	8.7	494	166
3	5.5	15.3	705	253
3	6.0	16.5	690	275
3	5.0	12.7	605	225
3[a]	6.1	15.6	611	275
6	4.0	11.0	690	183
6	3.0	8.1	675	137
6	5.0	13.8	695	229
6	4.0	9.8	564	178
6[a]	4.0	10.7	664	182
9	4.5	11.8	637	204
9	4.5	11.1	571	201
9	3.0	7.6	603	135
9	6.0	16.7	707	276
9[a]	3.0	7.8	632	136
12	2.4	6.3	632	109
12	2.0	5.3	653	91
12	3.5	9.6	692	161
15	2.0	5.3	648	91
15	2.0	3.9	364	85
15	1.0	2.5	594	45
15[a]	2.1	6.1	752	98

[a] Experiment of nominally 12-hr duration

Average solids residence times were estimated for each bench-scale experiment by using the maximum Reynolds number and the relationships for the residence time as a function of Reynolds number developed from the cold-flow experiments discussed previously.

The heating rate of the solid particles in the IFB bench-scale experiments was determined from the maximum zone temperature in the IFB dryer, and the amount of time the solid particles were heated. The maximum average zone temperature in the IFB dryer was determined from the experimental data. The location of this zone and the average solids residence time for the experiment were then used to determine the amount of time the solid particles were heated. In all experiments the maximum zone temperature occurred between 30 and 45 inches from the feed end of the reactor. In all cases the solid particles were cooled in the last quarter of the reactor. Solid heating rates for each experiment were estimated using the maximum zone temperature and the amount of time the solid particles were heated.

The average solids residence times, solids heating times, and the heating rates are summarized in Tables 3.12 and 3.13 for Eagle Butte and Usibelli coals, respectively. The average solid residence times ranged from approximately 5 to 13 minutes for all the experiments; the actual heating time of the solid particles ranged from approximately 3 to 9 minutes for all the experiments; and, the heating rates ranged from approximately 50 to 200°F/min in experiments using Eagle Butte feed coal and from approximately 70 to 250°F/min in experiments using Usibelli coal.

Table 3.12 Solids Residence Times and Heating Rates for IFB Bench-Scale Drying Tests using Eagle Butte Feed Coal

Reactor Slope, degrees	Average Dryer Temperature, °F	Maximum Reynolds Number in IFB	Average Solids Residence Time, min	Solids Heating Time Required, min	Solids Heating Rate, °F/min
3	589	248	11	6	100
3	531	172	12	9	60
3[a]	695	219	11	9	80
6	595	222	10	5	120
6	599	198	10	5	120
6	623	195	10	5	120
6	666	118	12	9	70
6[a]	684	159	11	6	120
9	617	195	6	3	180
9	589	151	7	3	170
9	588	116	7	4	160
9	692	238	6	4	160
9[a]	611	82	8	6	100
12	603	82	7	5	120
12	649	79	7	5	130
12	682	139	6	4	160
15	645	79	5	4	180
15	377	74	5	4	90
15	589	43	5	4	150
15[a]	731	80	5	4	200

[a] Experiment of nominally 12-hr duration

Table 3.13 Solids Residence Times and Heating Rates for IFB Bench-Scale Drying Tests using Usibelli Feed Coal

Reactor Slope, degrees	Average Dryer Temperature, °F	Maximum Reynolds Number in IFB	Average Solids Residence Time, min	Solids Heating Time Required, min	Solids Heating Rate, °F/min
3	494	166	13	6	80
3	705	253	11	8	80
3	690	275	10	5	130
3	605	225	11	8	70
3[a]	611	275	10	8	80
6	690	183	10	5	130
6	675	137	12	6	110
6	695	229	9	5	140
6	564	178	10	8	70
6[a]	664	182	10	5	130
9	637	204	6	5	130
9	571	201	6	3	180
9	603	135	7	5	110
9	707	276	5	3	250
9[a]	632	136	7	5	120
12	632	109	6	5	140
12	653	91	7	5	130
12	692	161	6	4	170
15	648	91	5	4	170
15	364	85	5	4	90
15	594	45	5	4	150
15[a]	752	98	5	4	220

[a] Experiment of nominally 12-hr duration

Task 4: <u>Product Characterization and Testing</u>

Feeds and selected test products were characterized during the quarter for moisture reabsorption, dustiness, and spontaneous heating tendencies. Surface area and particle size analyses are also being conducted using some of the feed and dried coal products. Selected samples representing the range of test conditions were examined. Work centered on examination on the longer-duration (12-hour) drying tests. Other samples were examined to determine effects of process conditions on dried coal properties. Characterization of the feeds was also conducted. The following sections describe the characterization results.

Subtask 4.1 Moisture Reabsorption

Moisture reabsorption was determined from tests conducted using a controlled temperature/humidity chamber. Conditions similar to those used for equilibrium moisture determinations (30°C and about 95% relative humidity) were utilized for most tests. Additional tests were conducted using lower levels of relative humidity (RH) which are more typical of the conditions encountered during storage and transportation of the dried coal.

Eagle Butte coal feeds and selected test products were subjected to moisture reabsorption tests as shown by the results in Table 4.1 and 4.2. As observed during earlier work, a significant reduction in equilibrium moisture occurred following inclined fluidized-bed drying. The moisture reabsorption is a function of the drying temperature as evidenced by greater equilibrium moisture values for samples dried at the lower test temperatures. For example, Eagle Butte and Usibelli coals which were dried at relatively low temperatures (samples D-49 and D-48) exhibited the greatest values of moisture reabsorption and equilibrium moisture. Figure 4.1 shows equilibrium moisture content as a function of the average drying temperature for both the Eagle Butte and Usibelli coals.

Table 4.1 Reabsorption of Moisture by Eagle Butte Coal

Sample	Average Dryer Temp, °F	Moisture Content, Wt %		
		As Received	Moisture Reabsorption[1]	Equilibrium Moisture[2]
EB Feed	---	28.1	27.3	26.9
D-39 Feed	---	19.7	21.7	26.1
D-45 Feed	---	26.8	26.5	28.2
D-53 Feed	---	16.2	19.4	23.5
D-2	586	2.6	13.8	12.8
D-30	531	1.9	16.8	16.0
D-31	695	0.6	13.9	13.2
D-37	684	0.9	14.4	12.5
D-39	611	0.8	14.6	13.4
D-41	603	0.7	14.9	15.9
D-45	682	1.0	13.9	13.4
D-47	645	0.7	14.2	14.2
D-49	375	0.4	18.6	19.9
D-51	589	1.0	15.6	14.1
D-53	731	0.6	14.0	12.2

1 reabsorption of moisture upon exposure of the as-is sample to conditions of 95% relative humidity/30°C for 5 days.

2 reabsorption of moisture in samples which were first immersed in deionized water and then exposed to conditions of 95% relative humidity/30°C for 5 days.

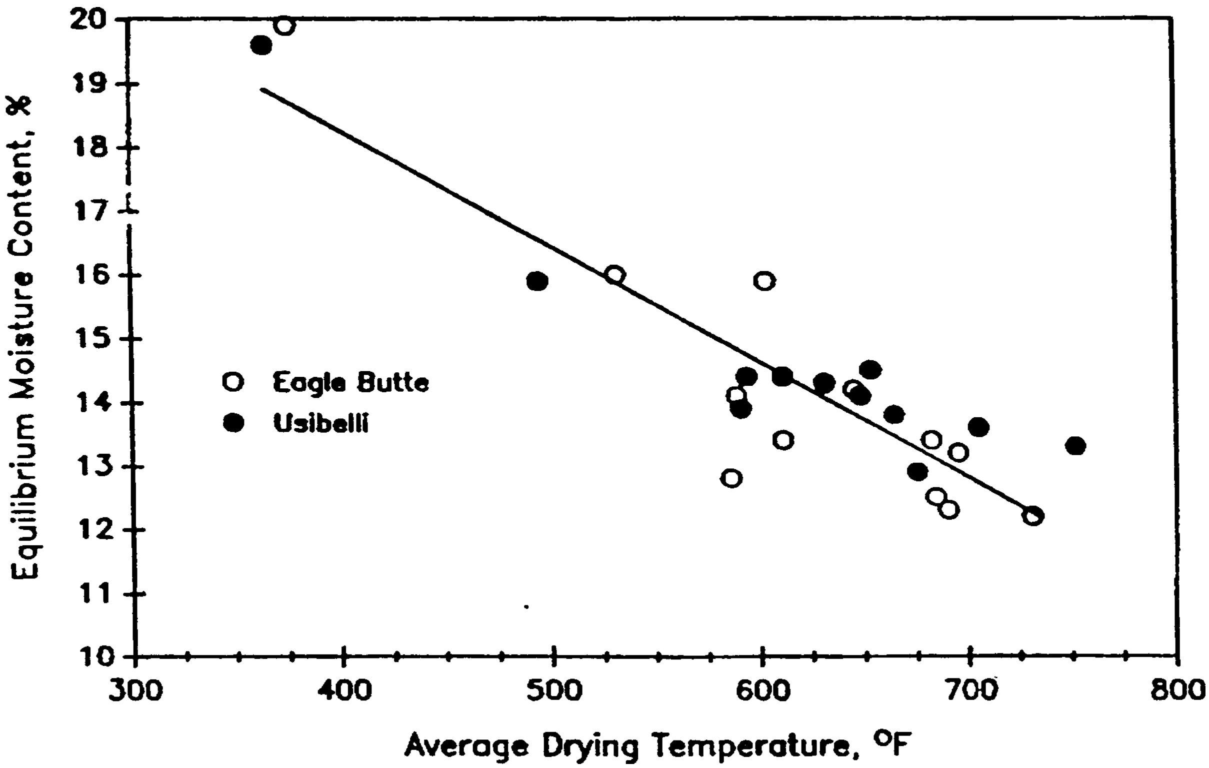

Figure 4.1 Equilibrium Moisture as a Function of Drying Temperature

Table 4.2 Reabsorption of Moisture by Usibelli Coal

Sample	Average Dryer Temp, °F	Moisture Content, Wt %		
		As Received	Moisture Reabsorption[1]	Equilibrium Moisture[2]
USI Feed	---	20.3	21.1	21.4
D-38 Feed	---	14.3	17.7	20.4
D-44 Feed	---	15.9	19.1	21.4
D-52 Feed	---	12.8	16.1	20.4
D-29	494	1.1	14.7	15.9
D-32	705	0.3	14.6	13.6
D-35	611	0.7	15.3	14.4
D-36	664	0.8	13.7	13.8
D-38	631	0.9	15.0	14.3
D-43	653	0.4	14.8	14.5
D-46	648	0.5	14.5	14.1
D-48	364	0.3	18.8	19.6
D-50	594	0.6	15.9	14.4
D-52	752	0.6	15.0	13.3

1 reabsorption of moisture upon exposure of the as-is sample to conditions of 95% relative humidity/30°C for 5 days.

2 reabsorption of moisture in samples which were first immersed in deionized water and then exposed to conditions of 95% relative humidity/30°C for 5 days.

The dried coals reabsorbed roughly the same amount of moisture regardless of whether they were first immersed in deionized water to saturate the coal pores. As shown in Figure 4.1, the level of moisture reabsorption into the dried coal does not appear to be a function of coal type. Even though the Usibelli coal feed contained a lower level of equilibrium moisture than the Eagle Butte coal feed, the dried Usibelli and Eagle Butte coals exhibited similar moisture reabsorption characteristics when dried under similar conditions.

Additional moisture reabsorption tests were conducted using conditions of lower relative humidity more representative of environments which would be encountered during storage and transportation. Average values near 50 percent relative humidity are typical for areas such as Colorado and Utah. Average values near 80 percent relative humidity are typical for areas along the western coast of the United States such as San Francisco and Seattle. Many other areas of the United States experience average relative humidities between these values. Average temperatures, however, are typically lower than the 30°C used for he moisture reabsorption tests. For these additional tests, conditions of 30°C and 80 percent relative humidity were utilized. The temperature was fixed at 30°C in order to allow comparison of the effect of relative humidity only.

Tests conducted at the lower-humidity conditions were completed. As shown in Table 4.3, significantly lower levels of moisture reabsorption were obtained using the lower-humidity conditions. For example, the dried Eagle Butte coal samples subjected to the 50% relative humidity environment exhibited moisture reabsorption and equilibrium moisture values between about 7 and 9 percent. These compare to values of 12 to 15 percent under 95% humidity conditions. Similarly, the dried Usibelli coals exhibited moisture reabsorption and equilibrium moisture values between about 8 and 11 percent at 50% relative humidity compared to values between 13 and 15 percent at 95% relative humidity. Even lower levels of moisture reabsorption would be expected at the more typical average temperature conditions (between about 10 and 20°C) in the regions of the United States discussed above.

Table 4.3 Reabsorption of Moisture by Eagle Butte and Usibelli Coals

Sample	Avg Dryer Temp, °F	As Received	Moisture Reabsorption	Equilibrium Moisture
			30°C/~50% RH	
Eagle Butte:				
D-53 Feed	--	16.2	11.3	14.5
D-39	611	0.8	7.3	9.0
D-53	731	0.6	7.0	8.0
			30°C/~80% RH	
Eagle Butte:				
D-53 Feed	--	16.2	17.7	18.8
D-39	611	0.8	11.8	10.8
D-53	731	0.6	11.1	9.6
			30°C/~95% RH	
Eagle Butte:				
D-53 Feed	--	16.2	19.4	23.5
D-39	611	0.8	14.6	13.4
D-53	731	0.6	14.0	12.2
			30°C/~50% RH	
Usibelli:				
D-52 Feed	--	12.8	7.9	13.8
D-38	631	0.9	7.6	9.1
D-52	752	0.6	7.9	11.2
			30°C/~80% RH	
Usibelli:				
D-52 Feed	--	12.8	13.4	16.8
D-38	631	0.9	12.0	10.5
D-52	752	0.6	1.9	10.1
			30°C/~95% RH	
Usibelli:				
D-52 Feed	--	12.8	16.1	20.4
D-38	631	0.9	15.0	14.3
D-52	752	0.6	15.0	13.3

Notes: Moisture reabsorption was determined following exposure of the as-is sample to the indicated temperature and humidity conditions for 5 days.

Equilibrium moisture was determined from samples which were first immersed in deionized water and then exposed to the indicated temperature conditions for 5 days.

Moisture reabsorption tests were also performed on the Eagle Butte and Usibelli feed coals following conventional oven drying at about 100°C (about 16%) were slightly greater than those exhibited by the IFB-dried coal products shown in Table 4.1 and 4.2 (typically 14-15%). However, equilibrium moisture values of the coals dried at 100°C were significantly greater (20-22%) than those of the IFB-dried coals shown in Table 4.1 and 4.2 (13-16%). These results show that the inclined fluidized bed drying conditions contribute to more stable product characteristics in terms of equilibrium moisture.

Table 4.4 Moisture Reabsorption Characteristics of Oven-Dried Eagle Butte and Usibelli Coals.

	Moisture Content, Wt %		
Sample	Oven Dried	Moisture Reabsorption	Equilibrium Moisture
Eagle Butte	<1.0	16.4	21.9
Usibelli	0.6	16.4	20.3

Additional moisture reabsorption tests were performed on compressed pellets prepared at WRI from dried Eagle Butte and Usibelli coals. Table 4.5 summarizes the results. Due to limited sample availability, a single pellet (about 1.5-inches diameter) of each coal type was broken to perform both the moisture reabsorption and equilibrium moisture determinations.

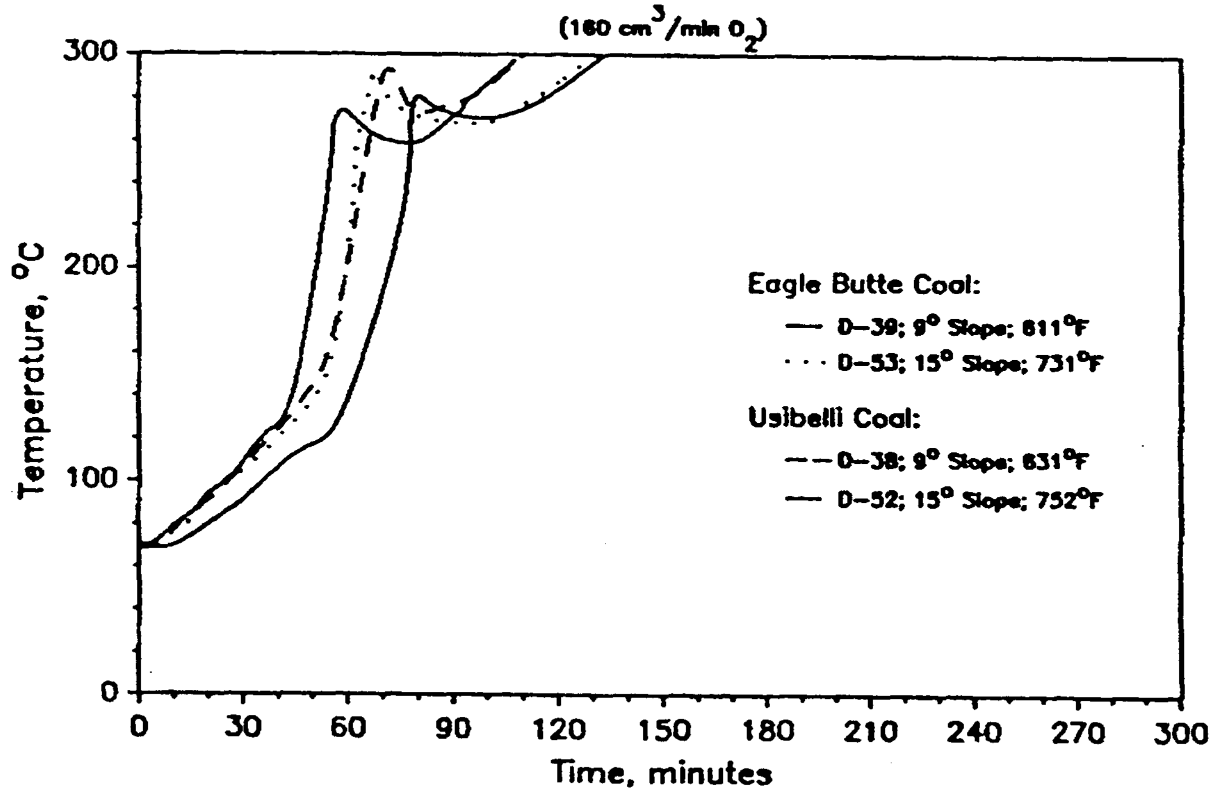

Figure 4.2 Effect of Drying Conditions on Self-Heating Characteristics

Although an attempt was made to prepare two large segments from each pellet, some additional breakage occurred. As a result, additional surface area was created. The compressed pellets exhibited reduced moisture reabsorption compared to the powdered, dried coals shown in Table 1 and 2. Even lower levels of moisture reabsorption would be expected when testing unbroken large pellets.

Table 4.5 Moisture Reabsorption Characteristics of Compressed Eagle Butte and Usibelli Coal Pellets

	Moisture Content, Wt %		
Sample	Oven Dried	Moisture Reabsorption	Equilibrium Moisture
Eagle Butte	<1.3	12.1	10.9
Usibelli	0.8	12.0	10.1

4.2: Dust Formation

Dust tests were conducted on selected samples corresponding to those used for moisture reabsorption and spontaneous heating evaluations and on all 12-hour drying test products. Table 4.6 and 4.7 summarize these results. The test results are compared by noting the level of light transmission in an opacity meter at elapsed times of 15 and 60 seconds. This provides a relative indication of the level of dustiness for each sample. (Greater light transmission indicates lower dust levels.) New samples of the two feed coals were also evaluated.

Table 4.6 Opacity Meter Measurements of Eagle Butte Coal Feeds and Dried Products

Sample	% Moisture	Light Transmission, % at t = 0.25 minute	1.0 minute
Eagle Butte Feed	27.7	16	28
D-39 Feed	19.7	6	11
D-45 Feed	26.9	26	41
D-53 Feed	16.2	5	8
D-2	2.6	99	100
D-8	0.1	96	100
D-14	0.5	95	98
D-30	0.6	100	100
D-31	0.3	98	99
D-37	0.9	95	98
D-39	0.8	75	85
D-41	0.7	75	86
D-45	1.0	92	95
D-47	0.7	74	86
D-49	0.4	95	97
D-51	1.0	65	81
D-53	0.6	76	88

Table 4.7 Opacity Meter Measurements of Usibelli Coal Feeds and Dried Products

Sample	% Moisture	Light Transmission, % at t = 0.25 minute	1.0 minute
Usibelli Feed	20.3	26	59
D-38 Feed	14.3	24	49
D-44 Feed	15.9	16	41
D-52 Feed	12.8	20	49
D-17	0.6	99	100
D-22	0.3	99	100
D-29	0.7	99	100
D-32	0.1	99	100
D-35	0.7	100	100
D-36	0.8	100	100
D-38	0.9	100	100
D-43	0.4	95	98
D-46	0.5	95	99
D-48	0.3	100	100
D-50	0.6	96	100
D-52	0.6	95	99

The test results confirmed that the dried coal products contained very low levels of dust compared to the feed coals. In general, the dried Usibelli coal samples exhibited lower dust levels than the dried Eagle Butte coal samples. Lower moisture contents in the feed coals led to greater amounts of dust generation, particularly for the Eagle Butte coal.

Subtask 4.3: Spontaneous Heating

Spontaneous heating tests were performed using selected test products representing different IFB dryer slopes and temperatures. Figure 4.2 shows the self-heating characteristics for these samples. Surface area analyses were performed on these same samples as discussed in a later section of the report. Self-heating data are also included in Table 4.9 for additional samples.

A spontaneous heating test was run under standard conditions (70°C starting temperature; 160 cm^3/min O_2 saturated with moisture) using the D-28 Eagle Butte dried coal. This sample began to ignite and testing was stopped when the bed temperature reached 300°C. A weight loss of 3.6 percent occurred during the test. No visible ash was present in the sample.

Spontaneous heating tests were also run to determine the effects of moisture reabsorption separately from the effects of oxidation. For these tests, 300 grams of Eagle Butte D-31 feed and dried product were exposed to moisture saturated nitrogen at a flow rate of 160 cm^3/min after equilibrating with dry nitrogen gas at about 70°C. The feed coal was pre-dried to less than 1 percent moisture prior to the test. Maximum bed temperatures of 92 and 100°C were obtained for the feed and dried product, respectively. Weight gains of 2.3 and 1.6 percent were observed for the same samples during the tests. The actual average bed temperatures at the beginning of these tests were 68 and 73°C for the feed and dried coal, respectively. The greater starting temperature probably accounts for the greater temperature increase observed for the dried coal. Note that the dried coal reabsorbed less moisture than the feed coal. These tests did verify that the initial temperature increase observed during spontaneous heating tests is due almost entirely to moisture reabsorption.

Surface Area and Particle Density Analyses

Surface area and particle density determinations were performed on selected Eagle Butte and Usibelli feeds, products, and fines samples. Table 4.8 summarizes the results. Two sets of feed, product, and fines samples representing the two coal types, different dryer reactor slopes, and different drying temperatures were analyzed. In general, the surface areas of the products were observed to be somewhat lower than the feed coals. The entrained fines generally exhibited lower surface area than either the feed or the dried products. The Eagle Butte coal samples contained greater surface area than the Usibelli coal samples. Standard surface area analysis procedures using nitrogen were conducted. Reduction in the surface area was probably caused by tar generated from particle pyrolysis.

Table 4.8 Eagle Butte and Usibelli Feed and Dried Coal Surface Areas and Particle Densities

Coal Type	Test Number	Reactor Slope	Drying Temp, °F	Sample Location	Surface Area, m^2/g	Particle Density, kg/l at 0% H_2O	Particle Density, kg/l at equilibrium Moisture content
Eagle Butte	D-39	9°	611	Feed	4.0	----	----
				Product	3.0	1.36	1.30
				Fines	2.4	1.38	1.28
	D-53	15°	731	Feed	4.2	1.46	1.30
				Product	3.2	1.36	1.30
				Fines	1.1	1.39	1.29
Usibelli	D-38	9°	631	Feed	1.7	----	----
				Product	.4	1.42	1.34
				Fines	0.8	1.46	1.36
	D-52	15°	752	Feed	1.6	1.46	1.33
				Product	2.3	1.40	1.33
				Fines	0.8	1.43	1.33

Particle densities were determined by displacement of kerosene. The values shown in Table 4.8 were calculated from densities determined using the as-received feeds and dried coals. This was accomplished by adjusting for moisture content. The calculated densities at the equilibrium moisture content will be utilized for subsieve analyses, which are performed using a sedimentation technique. Equilibrium moisture contents of the entrained fines were estimated based on the average of the feed and product values.

The Usibelli coals exhibited greater particle density values than the Eagle Butte coals. The coal densities at their equilibrium moisture contents were similar for the feed, product, and fines samples within each coal type. The dry coal densities were greatest for the feed coals (which contain the greatest levels of equilibrium moisture). The lower dry coal densities exhibited by the products suggest that some change in structure takes place during drying. Removal of moisture combined with inaccessibility of pores (plugged by tars) would result in reduced particle density values.

Additional surface area analyses were performed to provide information which could help to determine whether any relationships with dryer conditions and self-heating characteristics exist. Table 4.9 summarizes these results. Earlier spontaneous heating tests indicated that the feed coals were the most stable in terms of self-heating. The feed coals also exhibited relatively high surface area values, although surface area alone apparently cannot be used to predict self-heating characteristics. The higher drying temperatures generally resulted in the greatest self-heating rates. Dried coal surface area may depend on the drying temperature as well as residence time.

Table 4.9 Effect of Drying Conditions on Surface Area and Self-Heating Characteristics

Coal Type	Test Number	Reactor Slope	Drying temp, °F	Sample Location	Surface Area m^2/g	Self-heating Time, min, to reach 200°C
Eagle Butte	--	--	--	Avg. Feed	4.1	160
	D-2	3	586	Product	4.8	145
	D-30	3	531	Product	4.7	70
	D-31	3	695	Product	4.2	45
	D-37	6	684	Product	3.5	--
	D-39	9	611	Product	3.0	75
	D-53	15	731	Product	3.2	60
Usibelli	--	--	--	Avg Feed	1.7	>150
	D-29	3	494	Product	0.7	130
	D-32	3	705	Product	0.9	40
	D-35	3	611	Product	0.9	75
	D-36	6	664	Product	1.9	52
	D-38	9	631	Product	1.4	60
	D-52	15	752	Product	2.3	50

Subtask 4.4: Surface Treating

Not scheduled in the fourth quarter.

Other Activities

Particle size analyses of the feed, products, and fines from tests D-38, D-39, D-52, and D-53 are being run to determine the degree of particle degradation or agglomeration which takes place during inclined fluidized-bed drying under different conditions. A coal-derived tar is being evaluated as a surface treatment to reduce moisture reabsorption, dust, and spontaneous heating tendencies in dried coal samples.

Task 5: Technical and Economic Evaluation

Not scheduled in the fourth quarter.

SUMMARY, STATUS AND PLANNED ACTIVITIES

The project technical achievements are primarily related to understanding of the behavior of the two coals in the IFB reactor. The solids residence time and solids entrainment can be correlated using the Reynolds number. The gas produced from the coal during drying and the product composition can be correlated to the average dryer temperature. We also found that a dry product with minimal proximate moisture and substantially increased heating value can be produced from either of these coals under a wide variety of fluidizing gas-to-solids ratios and IFB operating temperatures. The product characterization indicates that moisture reabsorption can be significantly reduced and that fugitive dust contents can be almost completely reduced.

The project financial status is summarized by the fact that the total project expenses are 80% of the planned cost at the end of the fourth quarter.

No problems exist in keeping to the project schedule. Tasks 1 and 2 are complete. Tasks 3 and 4 are very near completion. No problems are expected that would delay the start of Task 5 at the beginning of the fifth quarter.

Activities planned for the fifth quarter are:

(1) Complete all analyses of the IFB bench-scale test samples, and evaluate the experimental data. Atomic C and H balances and experimental energy balances will be performed for the 12-hr experiments.

(2) Complete the characterization of the IFB bench-scale experimental products with respect to moisture reabsorption, dustiness, and spontaneous ignition. Investigate the benefit of oil treatment of the experimental products.

(3) Perform the economic evaluation of the process.

In closing, the project is being performed in a manner that is close to schedule and budget. No schedule problems exist at this time. Project completion is expected to be on time and on budget.

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