5.0 EVALUATION OF DEEPLY-CLEANED COAL AS BOILER FUELS

The objective of this activity was to evaluate deeply-cleaned coals produced in DOE's Premium Fuel Program as industrial boiler fuels. Cleaned coals from Cyprus/AMAX Research & Development Center's and CQ Inc.'s programs were received for this activity. The CQ Inc. coals, which were found not to be deeply cleaned, were tested as pulverized fuels with the emphasis on trace elements emissions. CQ Inc. provided coals from the Pittsburgh, Kittanning, and Upper Freeport seams (all from Pennsylvania) that were cleaned down to ≈10 wt.% ash using a combination of heavy media cyclones, water spirals, and froth flotation. Since the CQ, Inc. coals were not deeply cleaned, they are not discussed in Section 5.0 but the results are provided in the trace elements discussion in Section 3.0. Consequently, the work for this activity focused on using deeply-cleaned filter cakes from AMAX where the handling characteristics, combustion performance, and emissions were determined.

The objectives of DOE's Premium Fuel Program were to: 1) produce an alternative fuel which will produce less toxic emissions (by cleaning); 2) move advanced cleaning technologies from the laboratory to a fine-coal cleaning plant; and 3) produce a highly-loaded micronized coal-water mixtures (MCWM), which is to be competitive with fuel oil. Penn State complemented the Premium Fuel Program by performing combustion and emissions testing on the coals cleaned and provided by AMAX. AMAX provided coals from the Taggart seam (Virginia), Indiana VII (also referred to as 7) seam (Indiana), and the Hiawatha seam (Utah), cleaned using column flotation and selective oil agglomeration. A comprehensive discussion of AMAX's coal cleaning DOE-funded program is given elsewhere (Jha et al., 1997).

To accomplish the overall objective, Penn State's MCWM circuit was modified to handle filter cake to produce MCWMs, the MCWMs' atomization performance, stability, and rheological characteristics were determined, the handling characteristics of the filter cakes were evaluated through bench-scale evaluations, and pilot-scale and demonstration-scale combustion tests were conducted to evaluate their combustion performance and emissions, specifically trace elements.

5.1 Modification of the MCWM Preparation Circuit

Penn State's MCWM production circuit was modified to enable the preparation of highly-loaded MCWMs from advanced coal cleaning filter cakes. The MCWM production facility is extremely versatile in that it is capable of producing highly-loaded MCWMs from both coarse beneficiated clean coals (e.g., 2 inch x 0) as well as deeply-cleaned fine coal filter cakes (e.g., -100 mesh). Installing the filter cake reentrainment circuit included the following: 1) circuit design, 2) ribbon mixer procurement, 3) installation of electrical, water, and air to the ribbon mixer, 4) replumbing of MCWM transfer piping, and 5) installation of a low-profile platform scale. A generalized schematic of Penn State's modified MCWM production facility is presented in Figure 5.1.1.

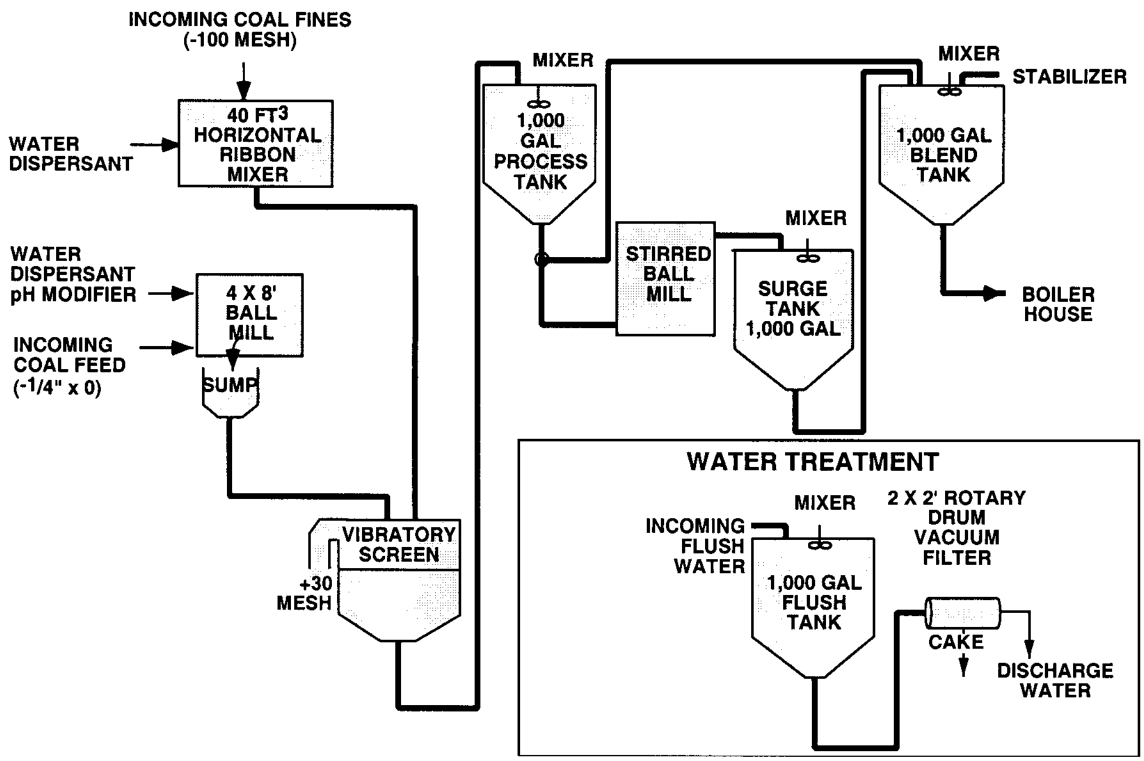


Figure 5.1.1 SCHEMATIC DIAGRAM OF THE HYBRID MCWM DOUBLE-STAGE GRINDING / MIXING CIRCUIT LOCATED IN THE FUEL PREPARATION FACILITY

The Munson Model HD-36-MS mixer is skid mounted with a capacity of 40 ft^3. The mixer has a 40 HP motor, which can be operated at variable speed, and a flanged double helical ribbon style agitator.

The system was engineered to produce 1 ton/h of MCWM. The MCWM preparation procedure that was developed included the following steps. The supersacks were weighed on a 2,500 lb capacity, Aegis low profile 4 x 4 ft platform scale to weigh the amount of coal fines to the nearest 0.5 lb. The supersacks were then hoisted above the ribbon mixer and allowed to discharge into the mixer's 4 x 5 ft receiving hopper. The supersacks had a pull bottom, spouted discharge chute. After the filter cake was discharged into the ribbon mixer, it was sampled for moisture content. The moisture content and the weight of the cake were entered into a spreadsheet to calculate the amount of water and dispersant needed for the formulation.

Process water was introduced using an internal spray manifold. The MCWM was mixed and pumped to a 1,000 gallon, baffled process tank, which was equipped with a five horsepower, center mounted Lightnin mixer. The Lightnin mixer had a lower 18-inch six bladed R-100 impeller and an upper 30-inch three bladed A-305 impeller. The process tank was used in addition to the Munson ribbon mixer to thoroughly reentrain the filter cake and at this point the stabilizer was added.

5.2 Fuels Characterization

Fuels characterization consisted of analyzing the filtercakes, determining their handling performance, forumulating them into MCWMs, preparing MCWMs for the demonstration and pilot-scale testing, and evaluating atomization performance of the MCWMs.

5.2.1 AMAX Filter Cakes

Six filter cakes were received from Amax Research & Development Center of Golden, Colorado. AMAX shipped 206 supersacks of deeply-cleaned filter cake from the Taggart, Indiana VII, and Hiawatha seams that were cleaned by two cleaning methods – column flotation and selective oil agglomeration. AMAX shipped 50 and 31 supersacks of deeply-cleaned Taggart seam filter cake cleaned by column floatation and oil agglomeration, respectively, one supersack of Indiana VII seam column flotation filter cake and seven supersacks of Indiana VII seam oil agglomeration filter cake, and 50 and 66 supersacks of Hiawatha seam filter cake cleaned by column flotation and oil agglomeration, respectively. A limited quantity of Indiana VII was received since its moisture content was greater than ~ 50 wt.%. It was decided not to test this filter cakes as a MCWM because previous experience at Penn State had indicated that a solids loading of at least 55 wt.% is preferred.

5.2.2 MCWM Preparation – Shakedown

Prior to beginning pilot-scale production, the MCWM circuit was operated in a batch mode to gain general operating experience aimed at identifying and resolving any technical and/or logistical hurdles, which may affect the MCWM production. The selective oil agglomeration cake of the Hiawatha seam coal was used for the initial shakedown effort. This cake varied from a nominal 30 to 35 wt.% moisture content.

Supersacks were lifted by inserting forklift forks through the supersack lifting straps and then were weighed using a platform scale. After the supersack was weighed, the supersack was lifted above the receiving hopper on the ribbon mixer. Although the supersack had a centered, bottom discharge chute, the bottom of the bag had to be cut to allow the coal fines to discharge. After the supersack bottom was cut, the filter cake discharged as discrete chunks ranging from a less than one inch to several inches in diameter. The filter cake was then “chopped” to allow it to flow through the grizzly screen into the ribbon mixer chamber. After several bags of filter cake were converted into MCWM, the grizzly opening was increased to 3.5 x 3.5 inches to allow the filter cake to more easily flow into the ribbon mixer. This enlargement significantly improved the ability for the filter cake to be fed into the ribbon mixer. As the filter cake was discharged onto the grizzly screen, representative samples were taken to determine the moisture content. Moisture was determined using a CEM AVC-80 microwave moisture analyzer. Two moisture contents were determined for each supersack. The moisture content was entered into a spreadsheet along with the sample weight. The spreadsheet had prespecified solids loading and dispersant concentration targets. The spreadsheet automatically calculated the amount of water and dispersant needed to convert the filter cake into a MCWM that met the predetermined formulation. Approximately 50% of the water and dispersant was added to the ribbon mixer prior to dumping the filter cake into the hopper. The water volume was controlled using a water meter. Dispersant was weighed out and mixed with the water prior to dumping the filter cake. The remaining portion of the water and dispersant was added after the majority of the filter cake had been transferred into the hopper.

The MCWM was allowed to mix for approximately 15 to 20 minutes in the mixer. The MCWM was then pumped across a Liquidtix screen to remove the plus 20 mesh oversize particles. After screening the MCWM was thoroughly mixed in a series of process and storage tanks prior to its use.

5.2.3 MCWM Formulation

A series of filter cakes was formulated prior to full-scale production. Baseline formulations were preformed on the Taggart (selective agglomeration), Indiana VII (column flotation) and Hiawatha (column flotation) seam filter cakes. Baseline formulations were geared to obtain a relative indication of the slurryability of these feedstocks. The MCWM were formulated without the use of dispersant or stabilizer to determine the feedstock's inherent slurryability. The analyses and slurryability behavior of these feedstocks are presented in Table 5.2.1 and Figures 5.2.1 through 5.2.3, respectively.

The Hiawatha seam selective agglomeration filter cake was formulated with and without viscosity and stability modifiers. The Hiawatha seam selective agglomeration filter cake represented the first premium coal filter cake supplied by AMAX that was converted to a highly-loaded MCWM using Penn State's MCWM preparation facility. The Hiawatha seam selective agglomeration filter cake was formulated using a bench-scale variable speed mixer. The Hiawatha seam supersacks were sampled and a 55 gallon drum composite sample prepared. The Hiawatha seam filter cake was systemically diluted with water to determine the effect of solids loading on apparent viscosity for MCWMs not having a viscosity modifier (dispersant). In addition to the baseline testing, the Hiawatha seam filter cake was converted into a MCWM using 1.0, 0.75, 0.5, and 0.35 wt.% A-23-M dispersant. Figure 5.2.4 provides a comparison between the Hiawatha seam MCWM prepared with and without viscosity modifiers. Figures 5.2.5 and 5.2.6 show the MCWM characteristics when prepared using varying quantities of the A-23-M dispersant. Despite the dispersant concentration, the solids loading could only be adjusted to a nominal 54 to 55 wt.% to meet a 200 cp apparent viscosity target. The effect of stabilizer concentration on the MCWM's apparent viscosity and static stability was determined by varying the stabilizer concentration from 0 ppm to 200, 400, and 800 ppm while holding the solids loading and dispersant constant at 54.0 and 0.5 wt.%, respectively. Flocon 4800C was the stabilizer used throughout the stability testing. Figure 5.2.7 illustrates the relationship between the concentration of Flocon and the apparent viscosity of the MCWM. Apparent viscosity increased significantly as the Flocon concentration was increased with minimal improvement in

Table 5.2.1 Analysis of the Taggart, Indiana VII, and Hiawatha Seam Filter Cakes

	Taggart Seam		Indiana VII		Hiawatha	
	Column Flotation	Selective Agglomeratio n	Column Flotation	Selective Agglomeratio n	Column Flotation	Selective Agglomeratio n
~ # Bags	50	31	0.5	7	50	66
Grinding Required	Yes	No	No	No	Yes	No
Proximate Analysis[a]						
Volatile Matter	-	34.9	36.6	-	42.7	-
Fixed Carbon	-	63.4	60.0	-	53.5	-
Ash	-	1.7	3.4	-	3.8	-
Ultimate Analysis[b]						
Carbon	-	84.0	76.8	-	77.0	-
Hydrogen	-	5.4	5.3	-	5.8	-
Nitrogen	-	1.5	1.6	-	1.3	-
Sulfur	-	0.6	0.8	-	0.8	-
Oxygen	-	8.5	12.1	-	11.3	-
HHV, Btu/lb[a]	-	14,975	13,653	-	13,633	-
Particle Size Distribution (µm)[b]						
Top Size	315	106	97.8	164	219	132
D (v, 0.9)	96.0	48.3	34.5	68.9	78.3	53.2
D (v, 0.5)	33.4	13.0	13.3	22.1	31.0	16.4
D (v, 0.1)	7.5	4.6	4.1	5.2	7.1	5.2
Slurry pH	-	5.6	6.9	-	7.8	-

[a] Reported on dry basis

[b] The D(v, 0.9), D(v, 0.5), and D(v, 0.1) values are the particle sizes where, respectively, 90, 50, and 10 of the particles, by volume, are less than the indicated size.

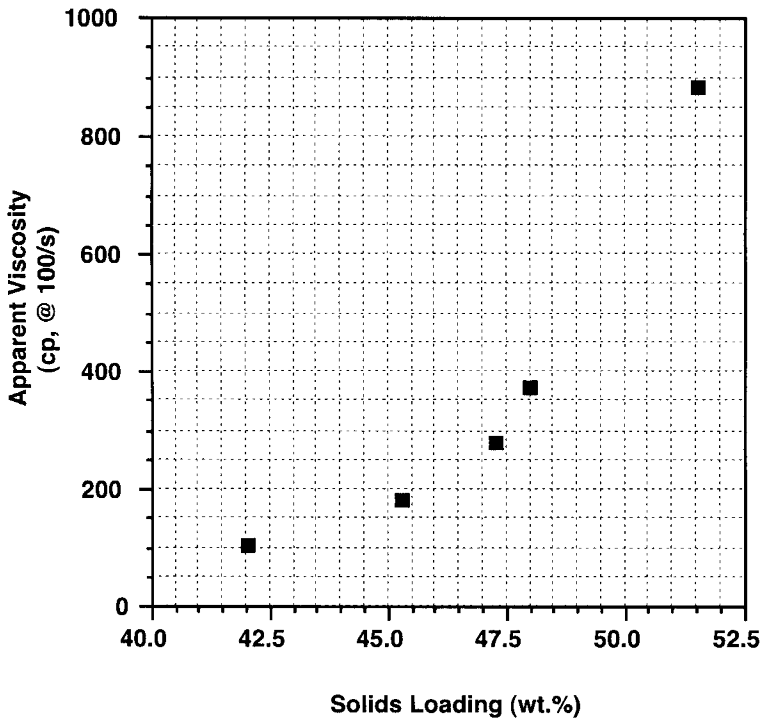


Figure 5.2.1 APPARENT VISCOSITY VS SOLIDS LOADING FOR THE TAGGART SEAM SELECTIVE AGGLOMERATION FILTER CAKE

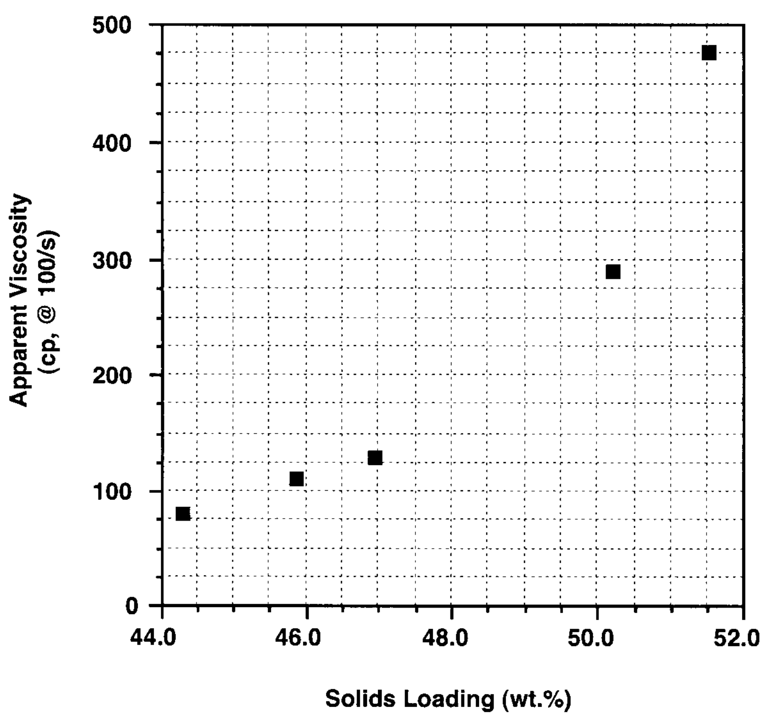


Figure 5.2.2 APPARENT VISCOSITY VS SOLIDS LOADING FOR THE HIAWATHA SEAM COLUMN FLOTATION FILTER CAKE

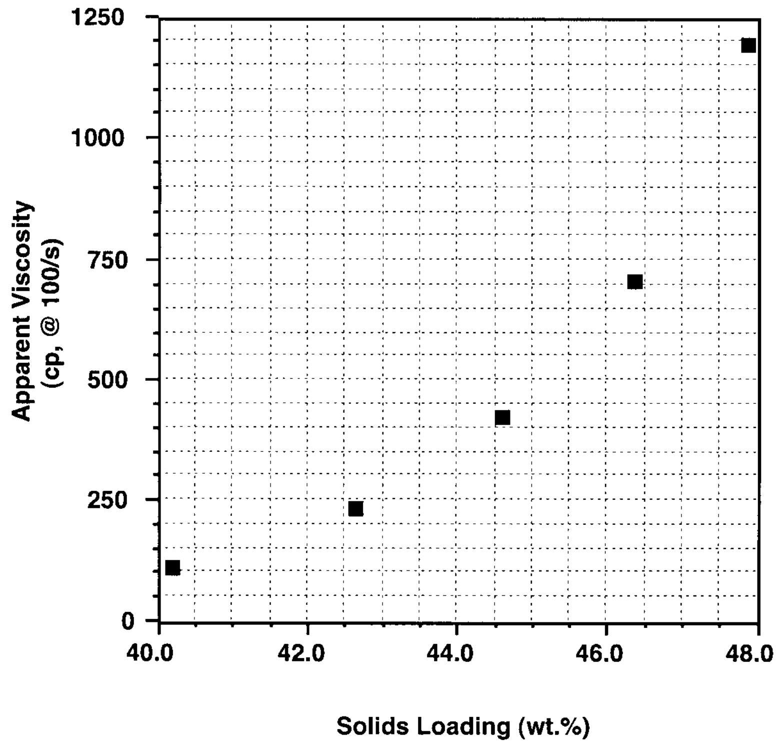


Figure 5.2.3 APPARENT VISCOSITY VS SOLIDS LOADING FOR THE INDIANA VII SEAM COLUMN FLOTATION FILTER CAKE

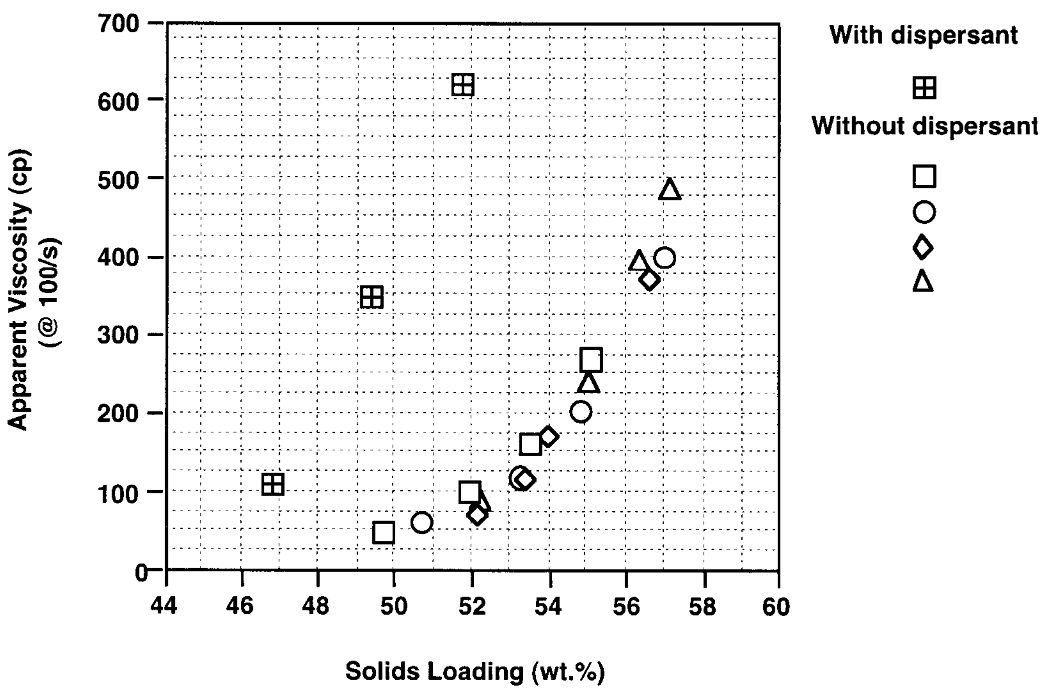
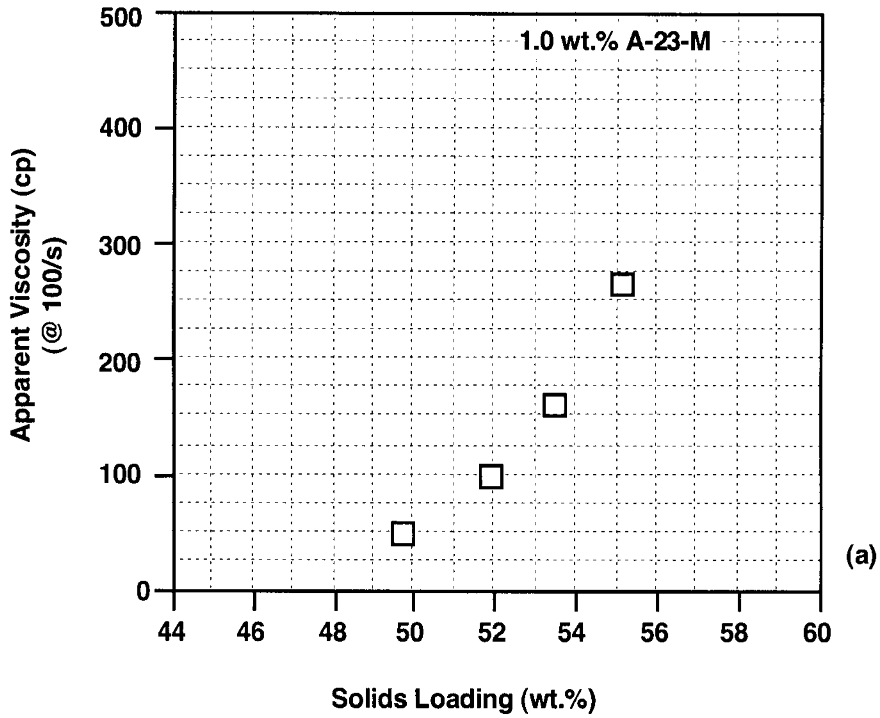


Figure 5.2.4 APPARENT VISCOSITY VS SOLIDS LOADING FOR THE HIAWATHA SEAM MCWM PREPARED WITH AND WITHOUT DISPERSANT



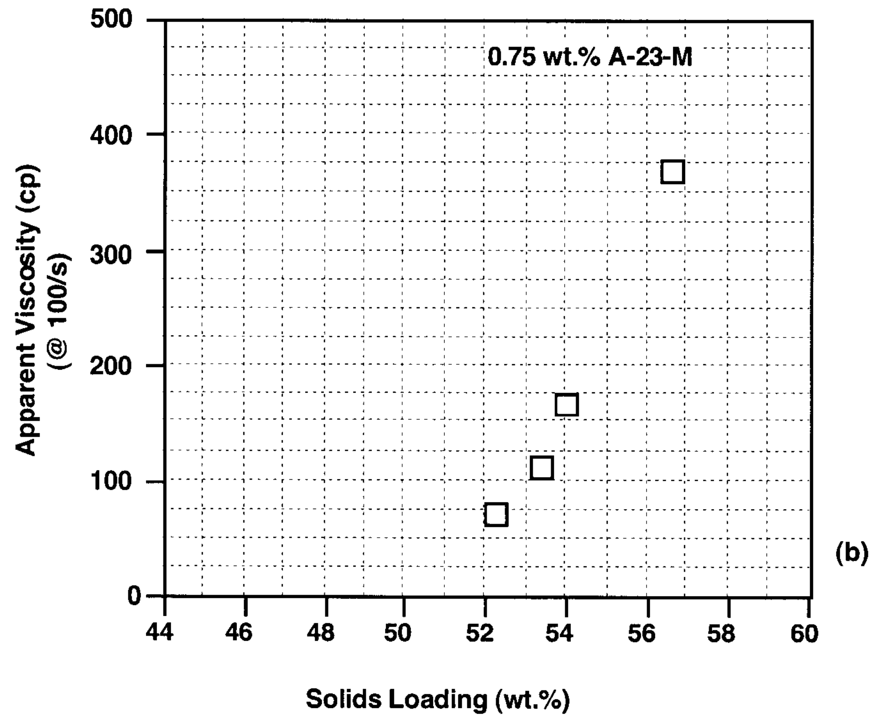


Figure 5.2.5 DISPERSANT CONCENTRATION VS APPARENT VISCOSITY OF THE HIAWATHA SEAM SELECTIVE AGGLOMERATION FILTER CAKE (a: 1.0 wt.% dispersant; b: 0.75 wt.% dispersant)

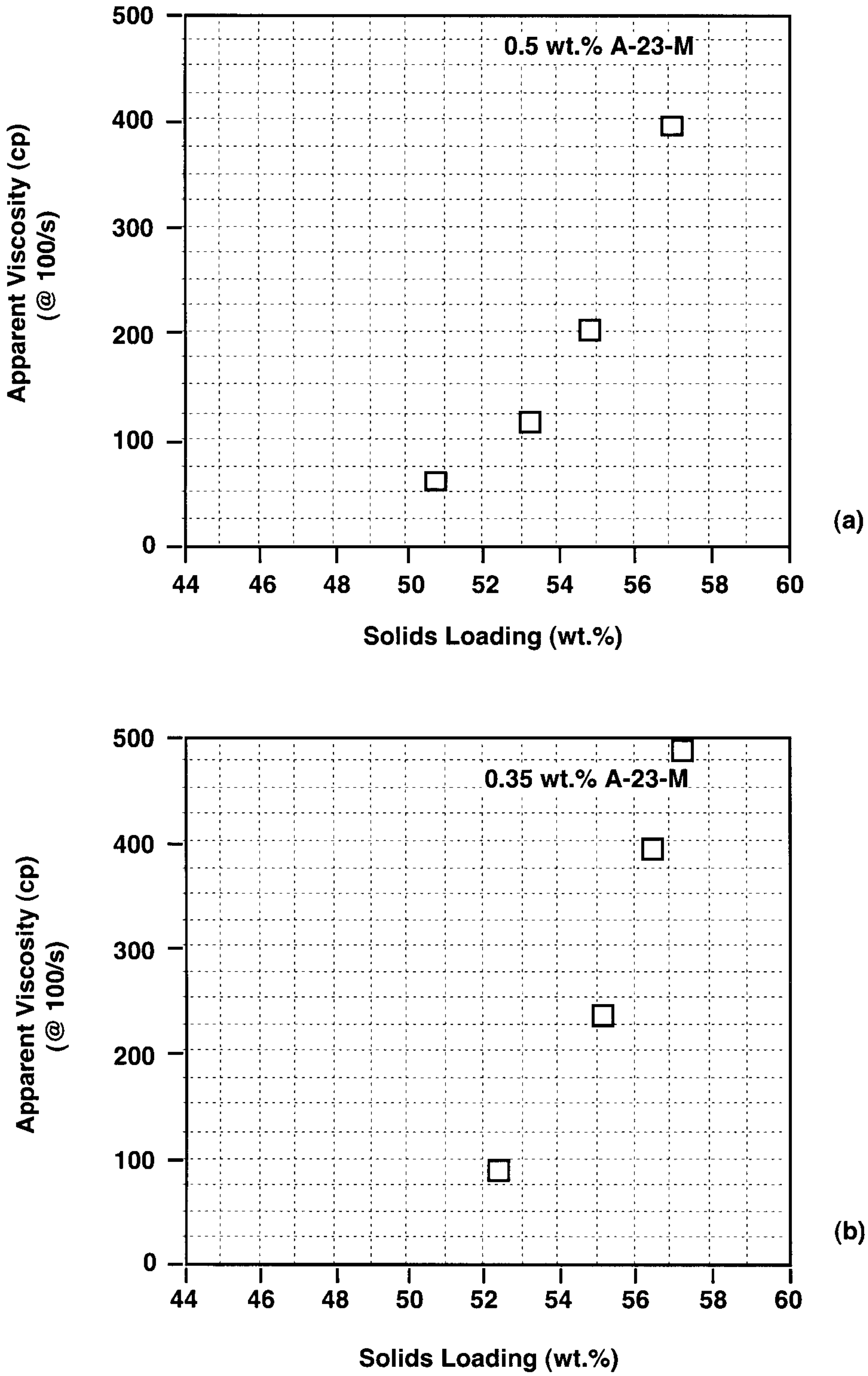


Figure 5.2.6 DISPERSANT CONCENTRATION VS APPARENT VISCOSITY OF THE HIAWATHA SEAM SELECTIVE AGGLOMERATION FILTER CAKE (a: 0.5 wt.% dispersant; b: 0.35 wt.% dispersant)

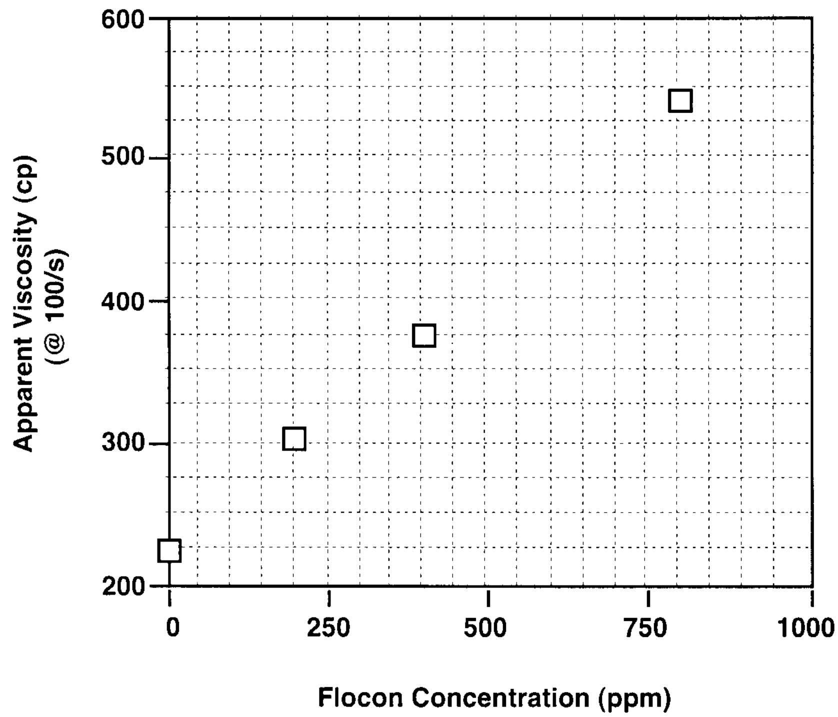


Figure 5.2.7 FLOCON CONCENTRATION VS APPARENT VISCOSITY OF THE HIAWATHA SEAM SELECTIVE AGGLOMERATION FILTER CAKE

the MCWM's static stability. The static stability of the Hiawatha seam MCWMs was very poor and hardpack was noted for each sample. In light of the poor stability and apparent minimal impact of dispersant concentration on apparent viscosity, the formulation targeted for the demonstration-scale CWSF production efforts were: 1) 54 to 55 wt.% solids, 2) 0.35 wt.% dispersant, 3) no stabilizer, and 4) use immediately after production.

5.2.4 MCWM Full-Scale Production

Demonstration-scale production of ton quantities of MCWM was performed using four of the AMAX filter cakes sent to Penn State. The MCWMs were prepared to characterize their slurryability, combustion performance, and trace element emissions. The as-received filter cakes were converted into highly-loaded MCWMs by using a viscosity modifier (dispersant) marketed under the tradename A-23M. Stabilizers were not used since the MCWMs were tested immediately. Particle size distributions were not modified because the objective of the testing was to determine if these filter cakes produced by advanced deep-cleaning technologies can be directly used as a MCWM after the filter cake has been entrained. Ton quantities of MCWM were prepared from the following filter cakes: 1) Hiawatha seam column flotation cake, 2) Hiawatha seam selective agglomeration cake, 3) Taggart seam column flotation cake, and 4) Taggart seam selective agglomeration cake. The production summary is given in Table 5.2.2.

The MCWMs were prepared using the procedure discussed in Section 5.2.2 with some slight modifications. The number of moisture contents that were determined for each supersack during emptying into the hopper was increased from two up to four. This was done because some supersacks exhibited more heterogeneity than others. In addition, a pH modifier, ammonium hydroxide, was used on the Taggart seam column flotation filter cake to raise the pH above 7.

The MCWMs were allowed to mix for approximately 15 to 20 minutes in the ribbon mixer. The MCWM was then pumped across a Liquidtix screen to remove the plus 20 mesh oversize particles. One of the major components in the oversize particles is degraded supersack fragments. Small pieces (e.g., 1 to 3 mm in size) of supersack littered the MCWM. These particles were removed to ensure that no plugging of the in line strainers and/or in the atomizer tip occurred. In addition, two supersacks contained debris (e.g., rope, extraneous metal) from AMAX's coal cleaning plant. After screening, the MCWM was thoroughly mixed in a series of process and storage tanks before transfer to the day-tank located in the boilerhouse.

5.2.5 MCWM Atomization Performance

The atomization characteristics of the MCWMs produced from the AMAX filter cakes were determined in support of the combustion performance and trace element emissions testing. The atomization testing was performed using the equipment shown in Figures 5.2.8 and 5.2.9. The fuel gun was removed from the boiler and the MCWM was sprayed into a modified fly ash hopper. A Malvern 2600C Droplet and Particle Size Analyzer was used to determine the droplet PSD (Figure 5.2.8). PVC piping was installed from the top of the hopper to the inlet of the baghouse in order to create a negative pressure on the chamber, using the induced draft fan, to eliminate back misting (Figure 5.2.9). The atomization tests were conducted after the combustion tests were performed to ensure that the same solids loading and atomizing air-to-fuel (A/F) ratio were used.

Figure 5.2.10, which is typical of the atomization results, shows the atomization performance using the Hiawatha advanced column flotation (CF) MCWM. The tests were

Table 5.2.2 Production Summary of the Amax Filter Cakes

	Hiawatha		Taggart	
	Column Flotation	Selective Agglomeration	Column Flotation	Selective Agglomeration
MCWM Targets				
Solids Loading (wt.%)	55	55	60	60
Dispersant	0.35	0.35	0.30	0.30
pH Modifier Used	No	No	Yes	No
Production Summary				
Production Dates	8/12/98 – 8/19/98	4/6/98 – 6/19/98	6/24/98 – 8/10/98	6/4/98 – 8/10/98
Moisture Content	33 – 43 wt.%	22 – 41 wt.%	20 – 43 wt.%	18 –31 wt.%
Nominal lbs/ bag	~ 1800	~ 2300	~ 1300	~ 2100
Estimated lbs of cake entrained	36,192	106,400	42,344	54,113
Particle Size Distribution (µm)				
Top Size	219	132	315	106
D (v, 0.9)	78.3	53.2	96.0	48.3
D (v, 0.5)	31.0	16.4	33.4	13.0
D (v, 0.1)	7.1	5.2	7.5	4.6

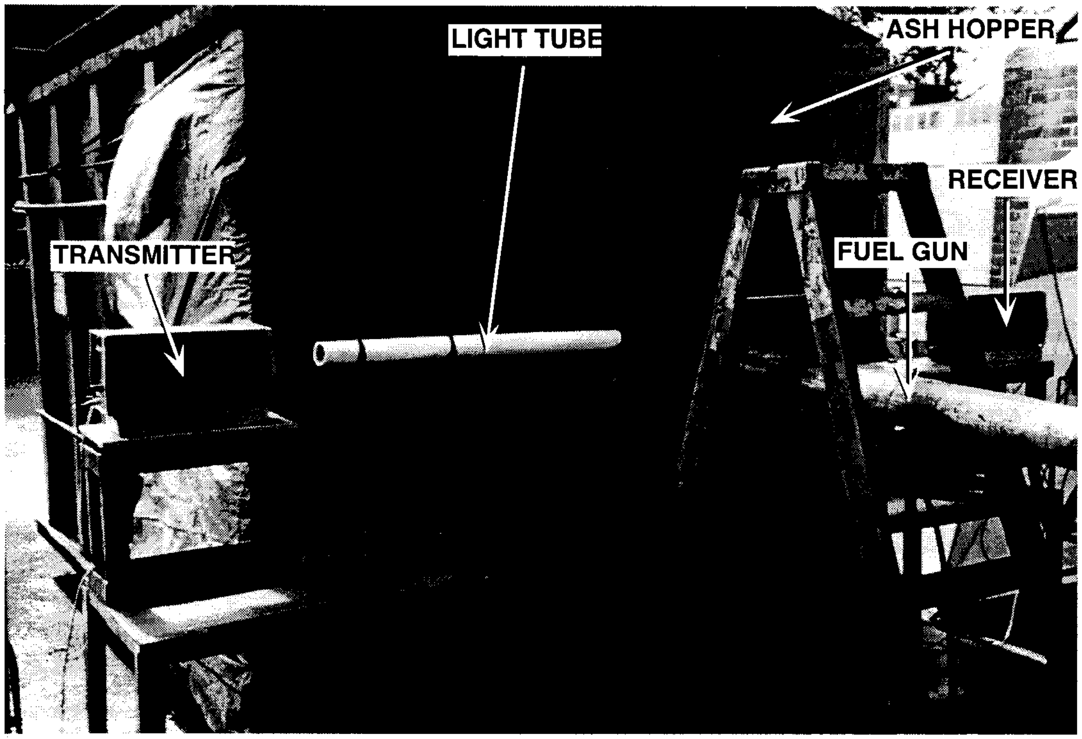


Figure 5.2.8 FRONT VIEW OF THE ATOMIZATION TEST CHAMBER

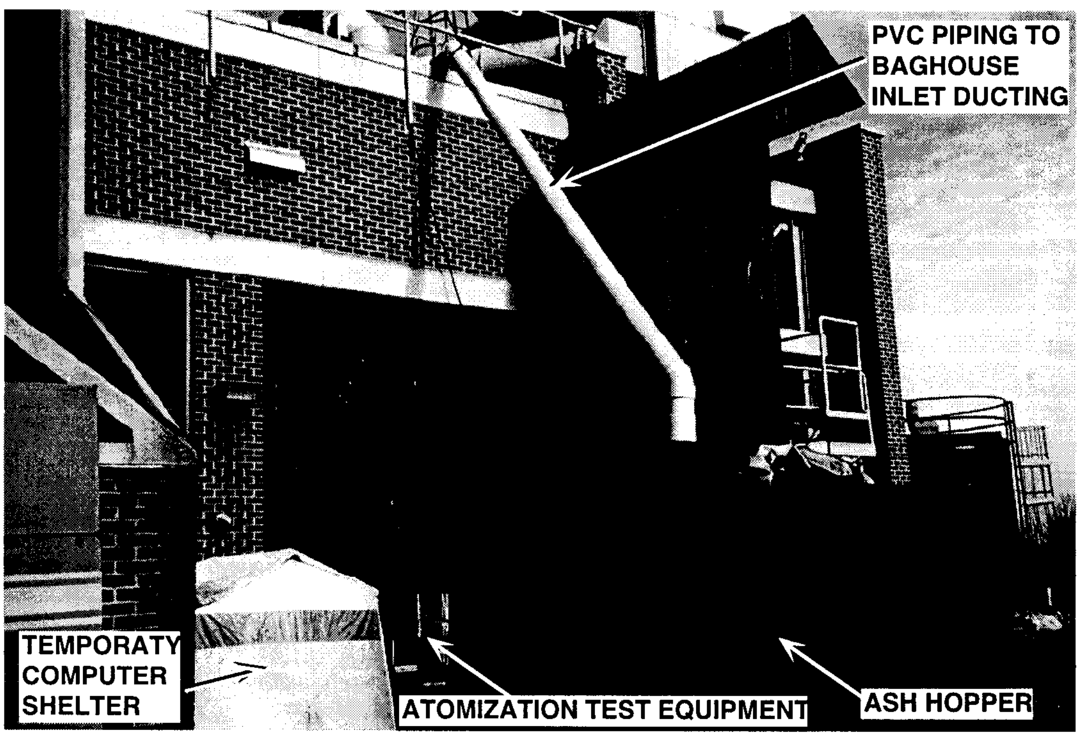


Figure 5.2.9 SIDE VIEW OF ATOMIZATION CHAMBER

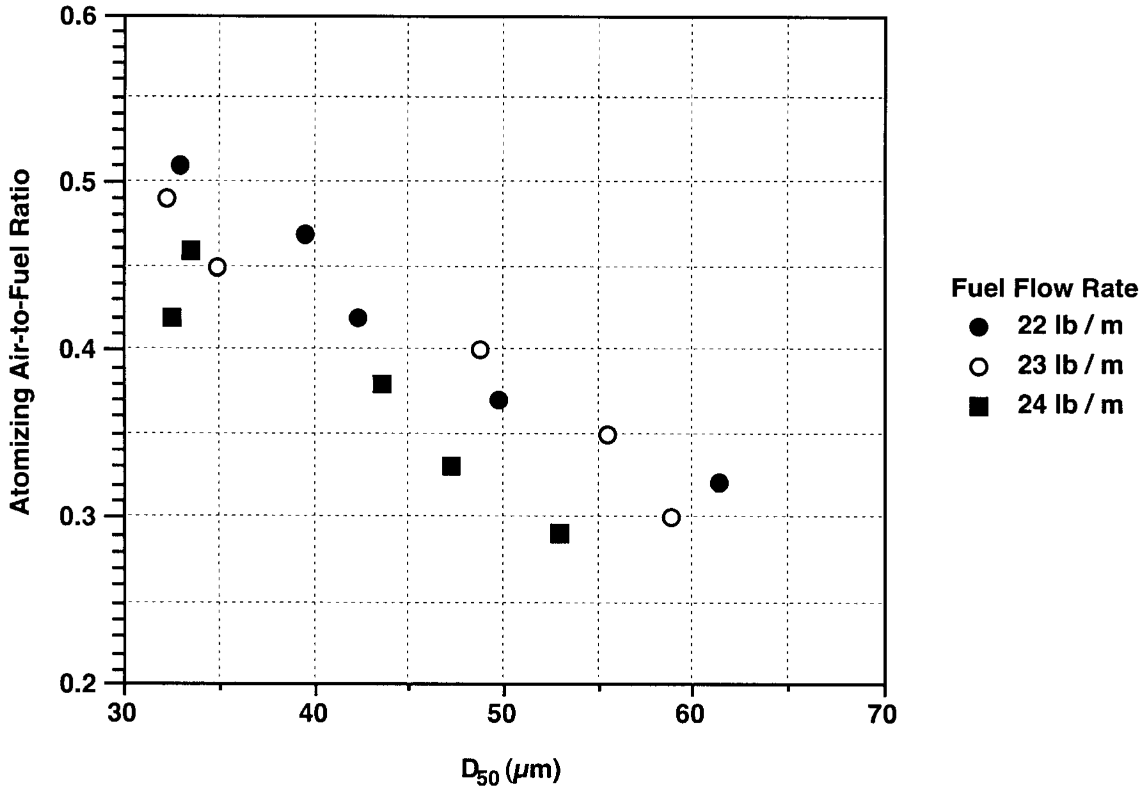


Figure 5.2.10 ATOMIZATION RESULTS FOR THE MCWM PRODUCED FROM THE HIAWATHA SEAM ADVANCED COLUMN FLOTATION FILTER CAKE

conducted by varying the atomizing air pressure (i.e., the atomizing air flow) for three flow rates of MCWM. This set of curves brackets the fuel flow rates and A/F ratios of the Hiawatha-CF MCWM tests. The atomization tests for the other three MCWMs were conducted similarly.

The atomization results for the four filter cake MCWMs are summarized in Figure 5.2.11, which illustrates the relationship between A/F ratio and the volume median diameter (D_{50}). The atomization characteristics of the Hiawatha-CF, Hiawatha selective agglomeration (SA), and Taggart-CF MCWMs were similar; however, the Taggart-SA MCWM behaved quite differently. The droplet size distribution of the Taggart-SA MCWM was much coarser. This was due to the narrow coal PSD, which results in a higher apparent viscosity (see Table 5.2.3) and dilatant rheology (i.e., viscosity increases as shear increases) (Miller et al., 1997b). Note that Table 5.2.3 contains MCWMs produced during other test programs at Penn State and are included as part of the combustion performance discussion in Section 5.4.

Table 5.2.3 Coal and MCWM Analyses

Coal Seam / Circuit Mode	Hiawatha-SA[a]	Hiawatha-CF[b]	Taggart-SA[c]	Taggart-CF[d]	Coalberg		Middle Kittanning		
	FCR[e]	FCR	FCR	FCR	Single-Stage	Double-Stage	Single-Stage[f]	Double-Stage[f]	Single-Stage[g]
Coal Properties									
Proximate Analysis (wt. %, dry basis)									
Volatile Matter	43.8	41.7	33.3	33.3	35.2	35.2	31.0	31.0	31.5
Ash	2.2	2.5	1.5	1.7	3.1	3.1	4.5	4.5	4.5
Fixed Carbon	54.0	55.8	65.2	65.0	61.8	61.8	64.5	64.5	64.0
Ultimate Analysis (wt. %, dry basis)									
Carbon	80.0	83.2	87.3	88.2	80.5	80.5	81.9	81.9	85.4
Hydrogen	5.8	6.1	6.4	5.7	5.2	5.2	5.1	5.1	5.5
Nitrogen	1.5	1.5	1.4	1.5	1.5	1.5	1.6	1.6	1.4
Sulfur	0.5	0.7	0.8	0.7	0.7	0.7	0.7	0.7	0.9
Oxygen	10.0	6.0	2.6	2.2	9.0	9.0	6.3	6.3	2.3
Higher Heating Value (Btu/lb, dry)	14,130	14,255	15,012	14,975	13,612	13,612	14,049	14,049	14,488
HGI	44[h]	44[h]	49[h]	49[h]	44[i]	44[i]	57[j]	57[j]	Not Det.
CWSF Properties									
Dispersant Conc.(wt.%)	0.35	0.35	0.30	0.30	0.70	0.70	0.80	0.80	0.80
Stabilizer Conc. (wt.%)	None	None	None	None	0.04	0.04	0.04	0.04	0.04
pH	7.2	7.1	5.7	6.2	8.5 to 9.5	8.5 to 9.5	8.5 to 9.5	8.5 to 9.5	9.4
Solids Loading (wt.%)	54.3	55.2	59.5	57.7	61.5	60.1	63.4	65.0	60.6
Apparent Viscosity (cp, @ 100 sec^{-1})	372	384	1,088	291	454	592	483	518	295
Particle Size Distribution (μm)									
Top Size	207	189	119	250	273	273	190	114	274
D(v,0.9)	70.7	73.2	57.7	101.0	147.1	82.7	87.6	47.8	107.1
D(v,0.5)	21.5	28.4	15.0	34.0	34.4	24.7	22.4	13.7	24.2
D(v,0.1)	5.5	6.1	4.6	6.1	5.6	5.4	4.6	2.7	5.0

[a] Hiawatha Seam Selective Agglomeration; test on June 23, 1998
[b] Hiawatha Seam Column Flotation; test on August 17, 1998
[c] Taggart Seam Selective Agglomeration; test on June 16, 1998
[d] Taggart Seam Column Flotation; test on August 11, 1998
[e] Filter Cake Re-entrainment
[f] Testing performed during a previous project (Miller *et al.*, 1997b)
[g] Test performed during this project to compare with filter cakes
[h] From Jha *et al.*, 1997
[i] Average of December 1995 to February 1996 Samples
[j] Average of August to November 1995 Samples

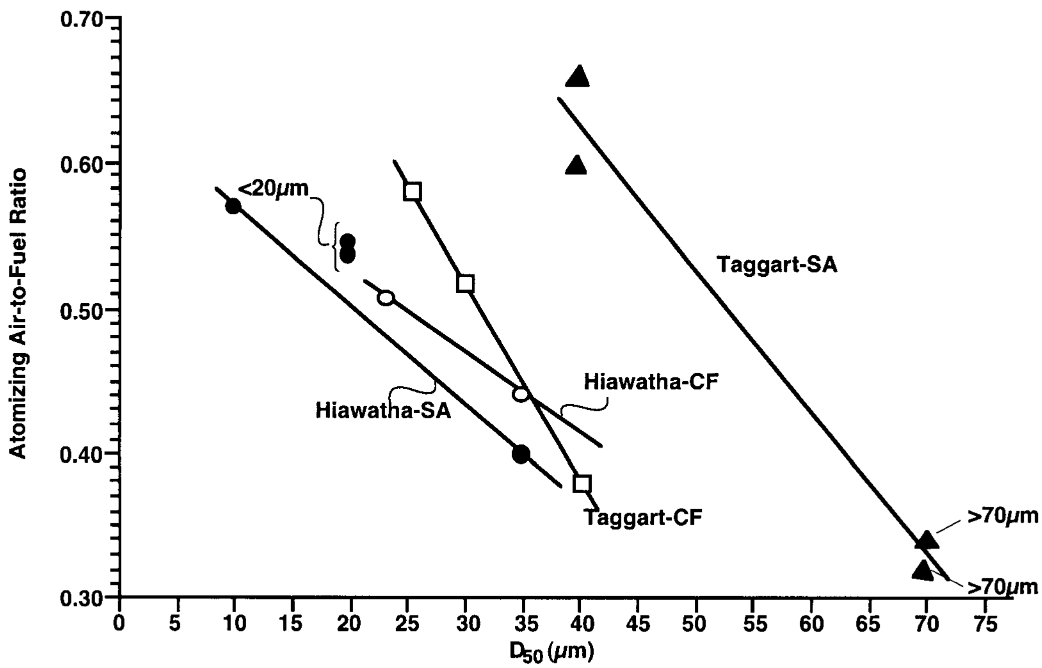


Figure 5.2.11 SUMMARY OF ATOMIZATION RESULTS

5.2.6 Fine Coal Handleability

Deep cleaning of coal usually involves grinding to fine sizes to ensure liberation of sulfur and ash-forming minerals. Such material, especially when wet, can present serious problems in handling and storage. This study has been concerned, primarily, with investigation of the flow characteristics of fine coal "filter-cake" materials and their influence on handling and storage behavior. Particular emphasis has been placed on the role of particle size distribution and moisture content and on the effects of blending with coarser material.

5.2.6.1 Background

The flow characteristics of powders such as fine coal are governed by friction between adjacent particles – *internal friction* – and against confining surfaces – *wall friction* – and by attractive forces between particles – *cohesion.* The latter is especially important for very fine material and is usually further enhanced by the presence of moisture. Flow of a powder occurs in response to applied stress – shear stresses generally promote flow, while normal stresses tend to increase frictional opposition to flow. In order to initiate flow in a bed of powder, the applied shear stress must be sufficient to overcome both the frictional forces and cohesion. Typically, this condition can be expressed in terms of the Mohr-Coulomb relationship:

$$\tau = \sigma \tan\phi + c \qquad (5.2.1)$$

where τ is the shear stress needed to initiate flow, σ is the normal stress acting on the powder, ϕ is the angle of internal friction and c is the cohesion. A standardized procedure for evaluating and characterizing powder flow behavior was developed by Jenike (1964; 1970) based on measurements obtained in a simple shear cell.

The Jenike shear cell consists of a short cylinder, split across the axis and mounted with its axis vertical. The lower half of the cell is fixed, while the upper half is free to move in response to an applied horizontal force. The cell is filled with powder and pre-consolidated by a standard procedure. A normal force is applied to the top of the bed of powder and the bed is sheared by applying the horizontal force. The test results are used to establish a set of flow criteria as defined by Jenike.

Powder Flow Characteristics

The Effective Yield Locus

While an initial or consolidation load is applied to the pre-consolidated powder, a force is applied in a horizontal direction to promote shearing of the bed. Eventually, the shear force reaches a constant level and is a measure of the stress needed to maintain steady motion. This value, together with the applied normal stress, defines one point on the *Effective Yield Locus*, EYL, for the bulk solid. Tests over a range of consolidation loads typically result in a roughly linear plot of shear stress *versus* normal stress. The slope of the line gives the *Effective Angle of Internal Friction,* δ (slope = tan d). An example is given in Figure 5.2.12. Mohr's Circles, drawn through the individual consolidation points, tangent to the effective yield locus and centered on the normal stress axis, define the major principal stresses, σ_{1c} and s_{3c}, needed to maintain steady flow at a particular consolidation level. The values can be obtained graphically from the plot or they can be calculated using the following procedure. First t_{c0} is determined from the plot. This is the point estimated from the graph where the EYL intercepts the shear stress axis at zero consolidation stress. Next, the value where the shear stress is zero is calculated using

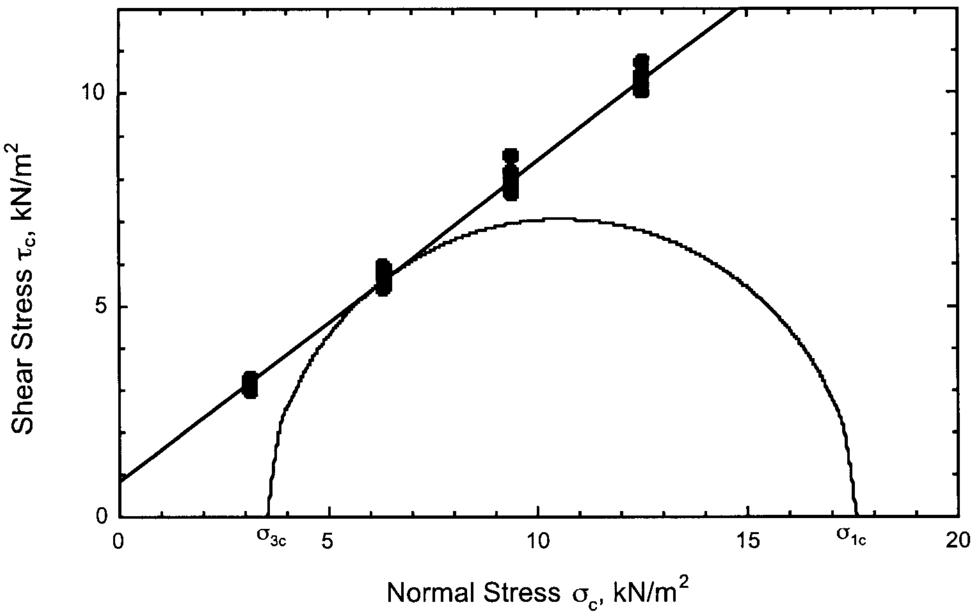


Figure 5.2.12 EXAMPLE OF AN EFFECTIVE YIELD LOCUS (EYL) FOR THE TAGGART COAL SHOWING THE MAJOR AND MINOR PRINCIPAL CONSOLIDATION STRESSES, σ_{1c} AND σ_{3c}

$$\sigma_{c0} = -\frac{\tau_{c0}}{\tan\delta} \tag{5.2.2}$$

which in turn is applied to

$$\sigma = \sigma_c\left(1 + \tan^2\delta\right) - \sigma_{c0}\tan^2\delta \tag{5.2.3}$$

to determine the center point, s, of each Mohr's Circle on the EYL plot. Now, the radius of the Mohr's Circle can be derived from

$$r = \left(\sigma - \sigma_{c0}\right)\sin\delta \tag{5.2.4}$$

Finally, the major and minor principal stresses, s_{1c} and s_{3c}, can be determined from:

$$\sigma_{1c} = \sigma + r \tag{5.2.5}$$

and

$$\sigma_{3c} = \sigma - r \tag{5.2.6}$$

The Yield Locus

The *Yield Locus* (YL) represents the change in shear strength of the material with the extent of consolidation. After each consolidation shear, the bulk material is again sheared but with a smaller normal stress than that used for consolidation. This shear stress needed is also normally less than that used in the consolidation stage. Another difference is that the force peaks and drops off rather than remaining constant as was evident in the consolidation shear. For a set of constant consolidations with differing shear loads, a plot of the shear stress *versus* the normal stress gives the yield locus. The slope of the YL gives the *Static Angle of Internal Friction,* ϕ, and the intercept at zero normal stress is the *Cohesion,* c. An example is shown in Figure 5.2.13.

A Mohr's Circle, tangent to the YL, centered on the normal stress axis and passing through the origin, defines the stresses acting at on a plane in the powder where the minor

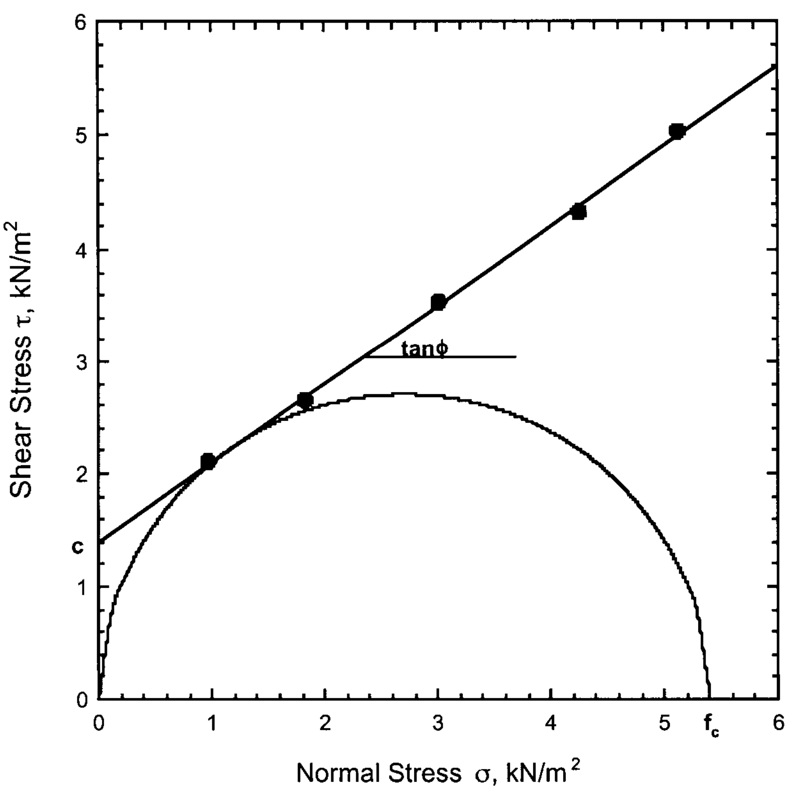


Figure 5.2.13 YIELD LOCUS (YL) FOR TAGGART COAL CONSOLIDATED AT 6.3 KN/M² SHOWING THE UNCONFINED YIELD STRESS, F_C

principal stress is zero and the major principal stress is just sufficient to initiate flow. Using the values of the cohesion c and the angle of internal friction ϕ estimated from the YL, the *Unconfined Yield Stress*, f_c, can be evaluated graphically as shown in Figure 5.2.13 or by:

$$f_c = \frac{2c\cos\phi}{1-\sin\phi} \tag{5.2.7}$$

This *Unconfined Yield Stress* represents the major principal stress necessary to cause failure of a dome or arch in the material at that particular degree of consolidation.

The Flow Function

The *Flow Function*, FF of a powder describes the relationship between unconfined yield stress, f_c, and the degree of consolidation. Specifically, it is represented by a plot of the unconfined yield stress, f_c, determined from the yield loci *versus* the major consolidation stress, σ_{1c}, obtained from the effective yield loci. The flow function, illustrated in Figure 5.2.14,

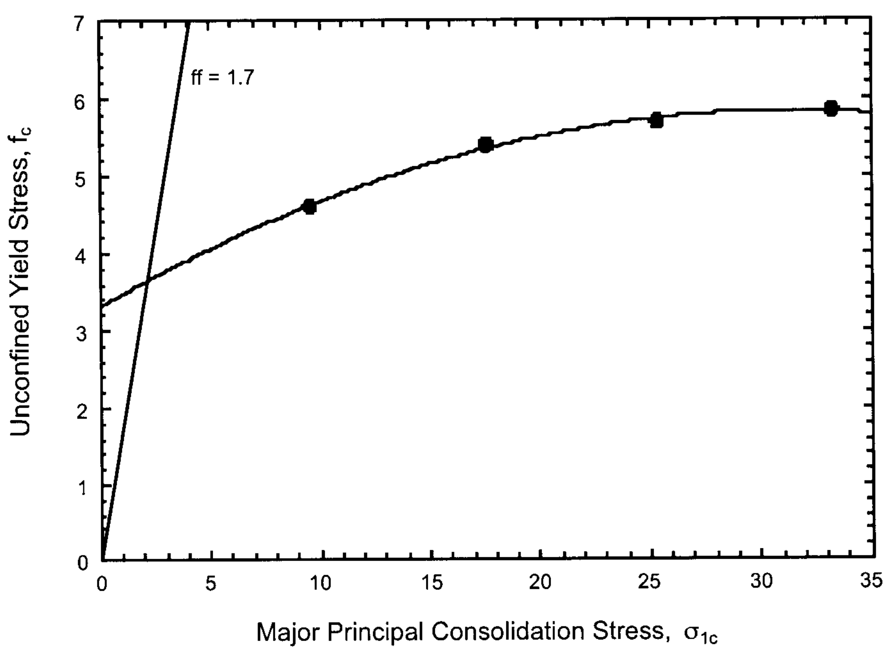


Figure 5.2.14 FLOW FUNCTION (FF) FOR TAGGART COAL WITH LINE CORRESPONDING TO A FLOW FACTOR (ff) OF 1.7

provides a basis for predicting the flow behavior of the powder in storage devices, particularly the tendency for blockages (stable arches) to form. For a free-flowing powder (c = 0), the flow function is zero for any degree of consolidation. The more cohesive the material, the higher the unconfined yield stress for a given degree of consolidation.

Wall Friction

As a material flows, it not only comes in contact with the other bulk material, it also contacts solid surfaces such as the walls of a bin or hopper. Testing is, therefore, required for estimating the effects on flow of the relative roughness of the wall material. Jenike shear tests can be performed in much the same manner as those used to determine internal friction. In this case, however, the bottom cell (cup) is replaced by a sample of the wall material. Typically, wall friction tests lead to an expression analogous to equation 6.2.1, i.e.,

$$\tau = a + \sigma \tan \phi_w \qquad (5.2.8)$$

where a is the *adhesion* and ϕ_w is the *angle of wall friction*. In many cases, the adhesion is negligibly small, but it may be significant for wet, sticky materials.

Bulk Density

The bulk density of a powder plays an important role in gravity flow. Since bulk density depends on consolidation, it is useful to include its measurement as part of the shear testing procedure. A simple way to determine the bulk density in the Jenike Shear Cell is to weigh the cell, empty and after performing the test, and measure the final depth of the powder. The bulk density is then determined from the mass of powder and the relationship between cell height and volume.

Application to Bin Design

Mass Flow/Funnel Flow

Flow through a bin generally falls between two extremes. *Mass flow* occurs primarily by sliding of the material at the walls, while *funnel flow* occurs in a channel formed within the material itself. Mass flow is usually the preferred mode since it tends to be more reliable, does not lead to "dead zones" and is less likely to cause segregation. The type of flow occurring in a bin depends on the flow characteristics of the powder and the bin geometry.

The Flow Factor

A major concern in the design of storage devices such as bins or silos is to ensure that blockages, due to the formation of stable arches or domes in the powder, do not occur. The weight of powder in a bin leads to the stresses that promote flow. At the same time, these stresses cause consolidation of the powder, increasing its resistance to flow. If, at some location in the bin, the strength of the consolidated powder exceeds the stresses that would act in an arch, a stable arch will form, leading to an obstruction to flow. Based on an analysis of stress distributions in bins, the relationship between consolidation stress and the stress in an arch has been determined by Jenike for a variety of material types and hopper geometries.
The results are presented in terms of a *flow factor* ff, defined by:

$$ff = \frac{\sigma_{1c}}{\sigma_1} \tag{5.2.9}$$

where σ_{1c} is the major principal *consolidation* stress and σ_1 is the major principal stress that *would* act in an arch under the same, but static, conditions. Flow factors are assumed to be constant for a given material/geometry. Flow factor charts are available for various bin geometries and material characteristics (Jenike, 1970). Examples (schematic), for conical and plane-flow hoppers, are given in Figure 5.2.15. For conical hoppers, mass flow is possible only in the region where the ff contours are shown. The mass-flow region is generally more extensive for plane-flow hoppers. However, Jenike (1970), recommends that wall angles be selected so as to fall to the left of the dashed line shown on the chart.

Obstructions to flow are more likely to occur if the flow factor is large. The limiting conditions for ensuring that obstructions do not form can be determined by superimposing on the plot of the flow function FF a line through the origin with slope equal to 1/ff (see Figure 5.2.14). Obstructions can be expected to form if conditions exist where the flow function lies above the 1/ff line. If the two lines intersect, the intersection point defines a critical stress σ_{cr} that must be exceeded to prevent blockage. Since the stresses generally decrease towards the apex of a

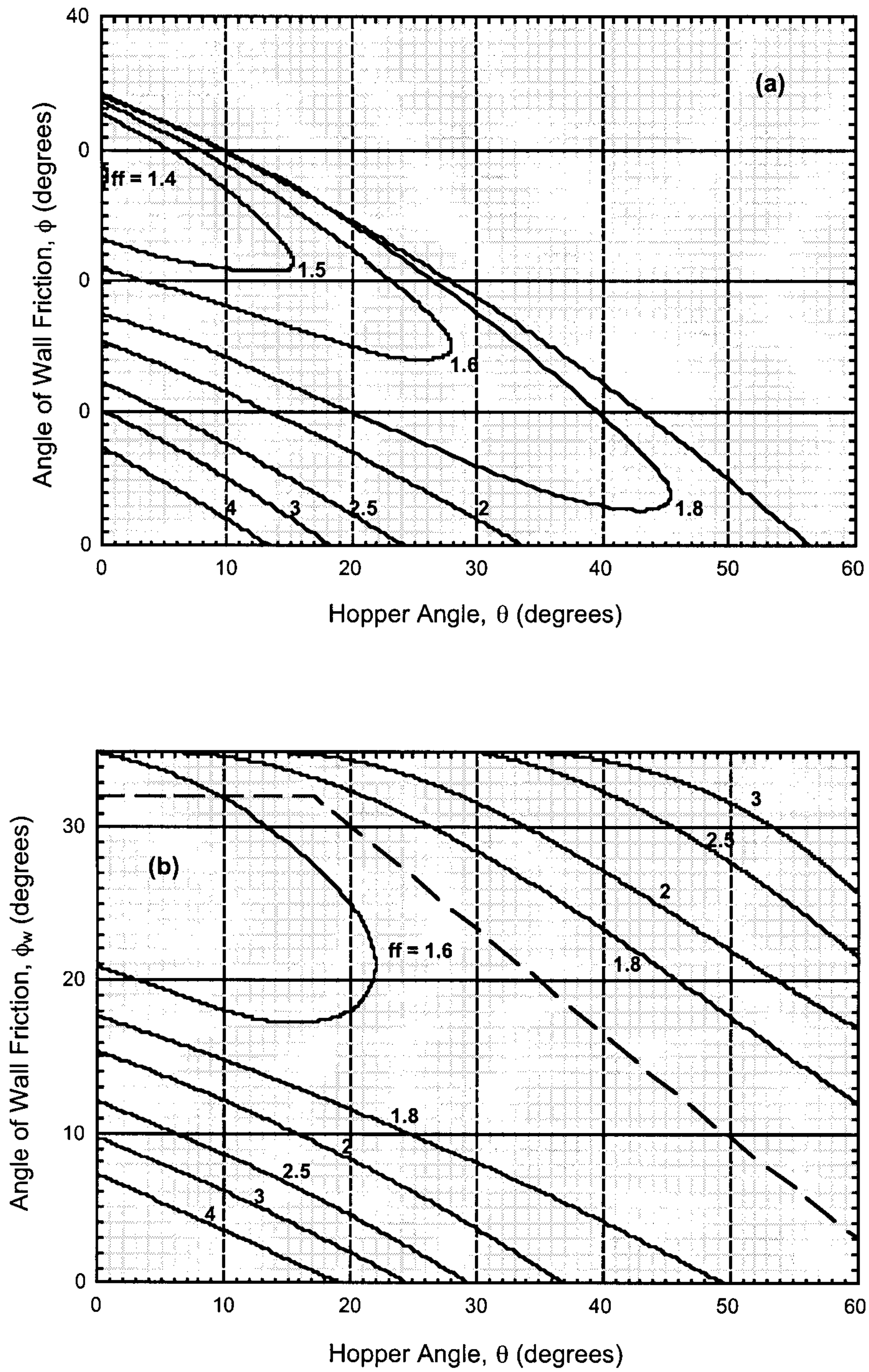


Figure 5.2.15 **ESTIMATED FLOW FACTOR CONTOURS FOR δ = 35° BASED ON INTERPOLATION FROM CHARTS PUBLISHED BY JENIKE (1970) (A) CONICAL; (B) PLANE FLOW**

converging hopper, the critical stress can be used to establish a minimum outlet dimension – ensuring that stresses less than σ_{cr} do not occur. The minimum outlet dimension can be obtained from:

$$B = \frac{\sigma_{cr} H(\theta)}{g\rho_b} \qquad (5.2.10)$$

where g is the acceleration due to gravity, ρ_b is the bulk density of the solid and $H(\theta)$ is a factor that depends on outlet shape (circular, square or rectangular) and the wall angle θ. Values of $H(\theta)$ are presented by Jenike (1970) and typically range from 2.0 – 2.5 for circular outlets, from 1.8 – 2.2 for square outlets and from 1.0 – 1.2 for rectangular outlets with length-to-width ratios greater than 3.0. The dimension B is defined as the diameter of a circular outlet, the side of a square or the width of a rectangular opening.

Similar conditions apply to the development of obstructions such as stable pipes or ratholes in funnel flow. No-piping flow factors ff_p are available (Jenike, 1970) expressed as functions of the effective angle of internal friction δ and the static angle ϕ. These can be used to establish critical stresses and minimum outlet dimensions as before. In this case, the minimum outlet dimension is given by

$$D = \frac{\sigma_{cr} G(\phi)}{g\rho_b} \qquad (5.2.11)$$

where the factor $G(\phi)$, analogous to $H(\theta)$, depends only on the angle of internal friction ϕ which determines the shape of the internal flow channel. Values of $G(\phi)$ range from about 2 – 10 and are available graphically from Jenike (1970). D is the diameter of a circular outlet or the diagonal of square or rectangular openings.

5.2.6.2 Experimental

Samples

Initial tests were conducted using filter-cake coal from the Taggart seam from Southwestern Virginia; however, this coal was dropped from the project due to a lack of availability of coarse coal from the same seam that could be blended with the filter cake. Attempts were made to acquire more material by contacting regional mining companies, but they were unable to supply a duplicate coarse material. Practical training and initial tests were therefore conducted using Taggart filter-cake coal, but Indiana-7 coal was chosen for blending experiments due to an abundance of both coarse, labeled as *Indiana-7 Parent* and fine particles, labeled merely as *Indiana-7*. Tests were run for *Indiana-7* at: *Indiana-7 filter-cake* coal, and blends of 1, 5, 10, 20, 80, 90, and 100% *Indiana-7 Parent* (by weight). Also, in later experiments, the percent moisture was increased for the 20 and 80% *Indiana-7 Parent* blends from the moisture of approximately 17 to 25%. This was done to simulate the more realistic scenario in which the filter cake coal would be air-dried in large piles after being dredged from the refuse ponds with the use of heavy equipment.

Sample Preparation

Initial samples of the filter-cake material were contained in two large 55-gallon barrels, which were, in turn, kept at a sample storage facility. Due to the samples' excess moisture content and small particle size, they were removed from the barrels and spread on a clean concrete floor where they were occasionally mixed with a rake to ensure surface exposure. This is a common drying procedure that produces a consistent moisture content throughout the sample. After two to four days of drying, the material from the two barrels was reduced to one 55-gallon barrel, a 25-gallon barrel, and a number of 5-gallon buckets that would ease transport and use. Initially, riffling was considered as the method for the sample size reduction, but the idea was quickly dropped in favor of "long-piling", a method of random sampling, which is primarily used when particle sizes are small enough to cause loss from air-borne particles. It is a process in which the coal is spread into a pile that is approximately 1 foot wide, a few inches high, and as long as necessary to include the entire sample. The sampler shovels the material into the first barrel, skips one shovel's width of the spread material to where a second sample is taken, which is placed in the next barrel and so on until the desired number of samples is collected. At this time the entire process is repeated starting with the first barrel and continues until the entire pile is sampled.

Samples of the parent (coarse) coal were prepared by the same procedure as descibed above except that, in the absence of significant amounts of fines, the simpler, riffling process was used for the splitting operation.

Jenike shear testing is typically considered unreliable when particles with a top size larger than 16 US Mesh are used, due to data repeatability inconsistencies. Larger particles tend to shear erratically, thus causing large fluctuations in the resulting data obtained from the tests. Also, larger particles tend to have less natural cohesiveness and therefore play little or no role in preventing flow. In order to remove the coarse particles, approximately 100 grams of the oven-dried coal was randomly selected and wet screened at 325 US Mesh (44 mm). Size distributions of the –325 mesh material were determined by laser diffraction using a Leeds and Northrup *Microtrac X-100*™ Size Analyzer. Size distributions of the +325 mesh material were determined by sieving at standard sieve sizes. After determining the size characteristics, and knowing that the top size of the material should not exceed the aforementioned 16 US Mesh, all samples were screened at this size. The oversize material was discarded while the undersize (approximately 80% of the raw material screened) was stored in one-gallon zip-top bags for later use.

Sample Analysis

Proximate and Ultimate analyses were performed on each coal type. The proximate analysis determines the moisture, ash, volatile matter, and fixed carbon as weight percent while the ultimate analysis determines weight percent the carbon, hydrogen, nitrogen, and sulfur in the coal.

Blending

One of the goals of this project was to determine what amounts, if any, of coarse coal added to filter-cake would be required to reduce bin failures or, alternatively, how much filter-cake material could be added to coarse coalwithout causing such failures. For the blending experiments, a coarser material from the same coal seam was introduced to the blend at different percentages of the entire sample weight. A volume of approximately 300 ml of powdered coal is needed for each Jenike test. Because of substantial variations among the bulk densities of different samples, the corresponding weights depend on the sample being tested. Empirically it was found that about 160 g of filter cake material was needed to fill the cell, while only 130 g of the coarser, or 16 US Mesh x 0, material was needed. When compiling samples of the filter cake, repeated tests determined that varying the sampling method had no effect on the shear cell results and, therefore, it was decided that random sampling would be adequate for the fine coal sample selection. However, this method was not acceptable for the coarse material sample preparation due to natural segregation. In this case, the sample was riffled down to the weight needed for each test. To create blended combinations, the fines were weighed and placed aside, and then coarse coal was riffled to the desired weight, added to the fines, and then thoroughly mixed and sealed in a zip-top bag until required.

In cases where the moisture content was adjusted, individual amounts of distilled water were measured and added to each separate sample, blended thoroughly to ensure proper mixing, and the samples were sealed in zip-top bags for later use. Most samples were prepared the day the testing was scheduled to occur in an attempt to eliminate inconsistencies.

Shear Cell Testing

Equipment Modification

The test equipment used in prior tests at Penn State included a pneumatically driven pressure sensor attached to a circular chart recorder. Although this was a reliable system, it limited the range over which the tests could be performed. Also, the chart was difficult to interpret reliably, thereby introducing human errors in the data. This was corrected by installing an electronic pressure transducer with a range of 4-20 milliamps attached via a screw drive to an electric motor. A data acquisition card that, after being calibrated using known constants, could transmit the milliamp signal provided comprehensive data that could later be converted by computer to a force basis. Computer programming also provided the ability to record each individual test thus removing the need for interpolation of charts, which inevitably leads to guessing. Human error is attributed to many of the problems associated with Jenike shear tests and through the "modernization" of the existing equipment many of these problems were eliminated.

Calibration

The data or raw output sent from the force transducer is a signal (in milliamps) of pressure that represents the resistance interpreted by the computer data acquisition card. By hanging known weights from a custom lever, the LabView™ program can be mathematically set to read the current and convert this reading to usable data in the form of kilograms. The data must be converted to a stress σ with units of kN/m^2, and this is done by:

$$\sigma = \frac{Wg}{A} \tag{5.2.12}$$

where W is the weight in kilograms, g is the acceleration due to gravity and A is the cross-sectional area of the cell (0.0071 m^2 for the 9.5 cm cell). Thus, the stress is given by:

$$\sigma = 1.38W \tag{5.2.13}$$

In order to simplify the calculations and setup procedure, the consolidation and test loads were standardized so that the weights used for each sample were identical. The weights include the addition of the hanging bracket (500 g) and the test lid (174.4 g), which must be accounted for as they are part of the load applied to the sample.

Test Procedure

One of the main concerns with the use of the Jenike Shear Cell system for determining the flow characteristics of powders is the difficulty of reproducing test results for identical conditions unless the operator is well trained in the operation of the equipment. Other test cells such as the Peschl Rotational Cell are available (Peschl and Colijn, 1976) and claim more ease of use and reliable results. However, the Jenike cell is widely accepted for industrial applications. The procedure recommended by Singhal (1984) was the basis for the method used on all the tests performed for this thesis. Due to the difficulty in repeating tests with consistent results, in the first few months after updating the Jenike equipment and prior to actual testing, numerous tests were performed and repeated in an attempt to produce reliable results from the procedure. This ensured that every test was performed accurately and with confidence. Each test, however, was duplicated to ensure validity.

When using material containing less than 50% of the coarse coal, about 160-180 gram samples (total weight) were individually prepared and stored in zip-top bags. When using more than 50% coarse material, about 140-g samples were required to fill the cell completely. The coal was scooped out of the bag at about 20 grams per scoop. It was not poured from the bag, as that may have caused segregation within the cell. The cell itself (see Figure 5.2.16) consists of:

- a cup-like container with an inside diameter of 9.5 cm (3.75 in), which rests on the base;
- a ring-like cylinder of equal inside diameter, which sits on the cup but is slightly closer to the stem; and
- a fill ring, or the mold, which sits on the ring.

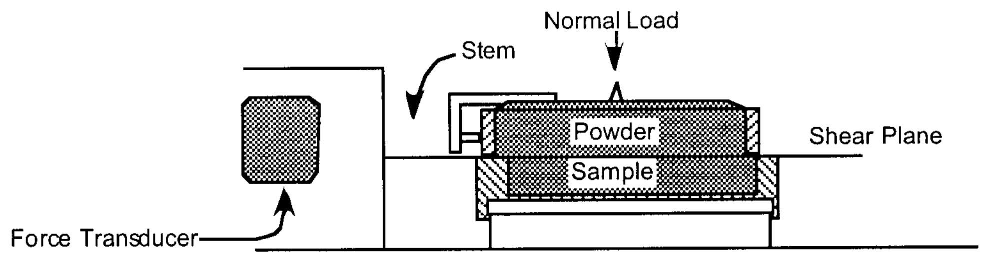


Figure 5.2.16 SCHEMATIC DIAGRAM OF THE JENIKE SHEAR CELL

The fill ring allows the operator to place extra material in the cell in order to compensate for consolidation and ensures an equal height of the sample. The weight chosen was sufficient to fill the cell without overflowing. After filling the cell, the material was gently prodded with a spike fifty times. This created an air passage that aids in compaction by allowing excess air to exit the sample. The material was scraped flush with the top of the mold and a consolidation lid, or twisting ring, was temporarily placed on the material within the cell. This lid differs from the lid used in the tests in that it has a smooth surface that sits on the coal in the cell, and has a pointed center pin with square edges surrounding the pin with which a wrench-like tool can be used to rotate the lid while a consolidation load, s_c, is applied from a hanging bracket. The lid was rotated ± 30° approximately 30 times to ensue even consolidation within the cell. The consolidation load was removed from the pin, the consolidation lid and the fill cell were removed, and the excess coal was again scraped off flush with the top surface of the cell using a straightedge. The test lid is then placed on the cell and the hanger and the same consolidation load was reapplied. The test was labeled in the LabView™ program on the computer along with the identification of the test weight applied during the second stage of the test.

The first stage of the test is consolidation. This represents the stress required for the material to overcome its own cohesive strength and begin to flow. As is evident in Figure 5.2.17, the initial forces increased rapidly until steady flow of the material was achieved, at which time the pressure did not increase any further. After the consolidation force leveled off, implying that the material was in a state of steady flow, the drive motor was reversed to remove all pressure on the transducer, and a new, lighter weight was applied to the hanger. The lighter weights used for the test load stage of the experiments were selected at intervals as near as possible to 1/5 of the consolidation weight. This new weight represented a normal stress applied to the consolidated material. The motor was once again placed in the "forward" direction, and as the stem contacted the cell, the amount of force needed to begin the motion was again recorded. The force reached a maximum as indicated, where the line peaked and then dropped off indicating that the specimen had "failed" i.e., that the strength of the consolidated powder had been overcome. In Figure 5.2.17 the force returns to zero due mainly to the fact that the test weight had been removed and the transducer was no longer in contact with the cell. LabView™, when told, automatically recorded the resulting data as a "Data File", which can easily be opened in a Microsoft Excel™ spreadsheet file. Because data points were recorded 8 times per second, they provided a very detailed description of the applied shear forces. The data were averaged in an attempt to smooth over the sensitivity of the pressure transducer. By taking the average of a set of five consecutive samples, the roughness of the curve was eliminated so that the resulting data better represented what actually occurred and the small fluctuations in the curve were ignored.

Measurements of wall friction were carried out using a flat piece of 16-gage steel as a standard reference material. The steel plate was placed upon a spacer to ensure that the overall height of the steel and spacer did not exceed the height of the cell used in previous experiments. In an attempt to prevent the plate from slipping on the base, an adhesive tape was applied to the bottom side creating a solid, immovable surface. The ring and retaining ring were then placed upon the steel plate and the filling and consolidation steps continued as usual. When it came to the actual test, however, the consolidation weight was added as a stack of smaller weights to the top of the lid. As each failure occurred, the next weight was removed until only the lid remained. Testing for wall friction was only performed on 1, 80 and 90% parent coal blends.

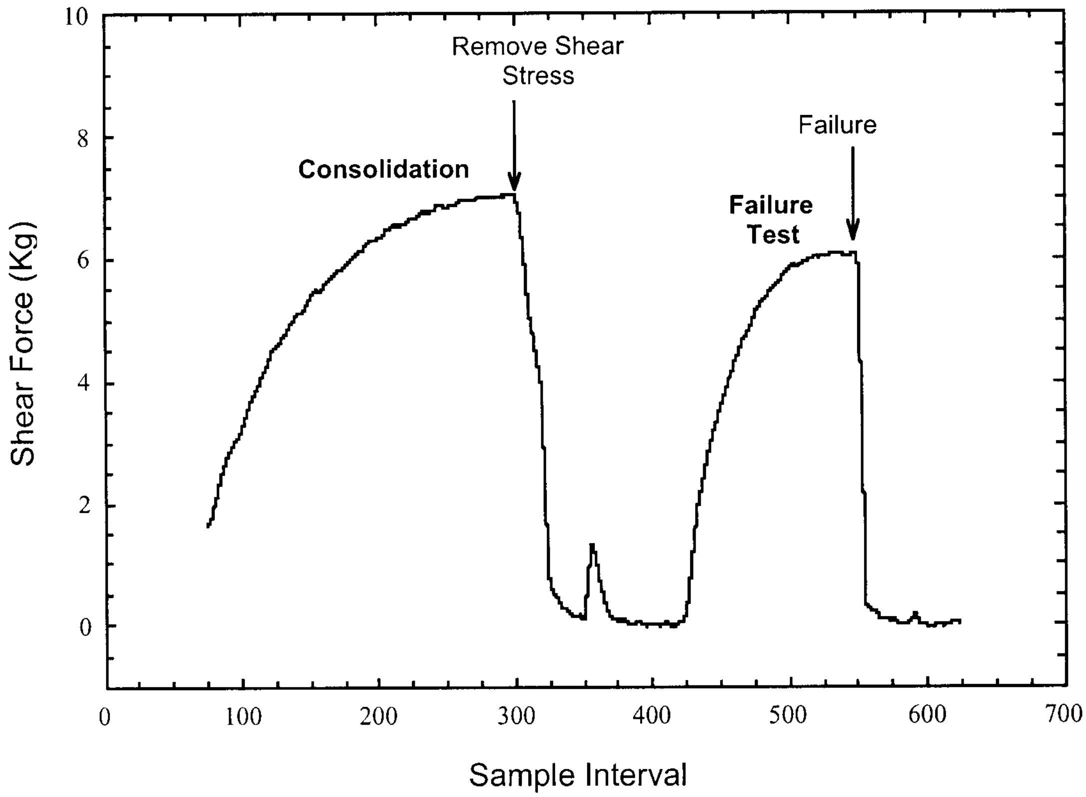


Figure 5.2.17 EXAMPLE OF A SHEAR FORCE/TIME PROFILE

5.2.6.3 Shear Cell Test Results

Sample Characteristics

Particle size distributions for the Indiana-7 filter-cake material and the parent coal (after screening at 16 US mesh) are shown in Figure 5.2.18. The filter cake material is considerably finer (70% passing 325 US mesh) than the parent coal (6% passing 325 US mesh). The results of the proximate and ultimate analyses are listed in Tables 5.2.4 and 5.2.5.

Shear Cell Test Data

Effective Yield Loci

The Effective Yield Locus EYL defines the stresses needed to maintain a continuous flow through a channel or hopper. A Mohr's circle, tangent to the EYL at some point σ, τ and centered on the σ-axis gives the major and minor principal consolidation stresses: s_{1c} and s_{3c}, respectively. The slope of the line gives the effective angle of internal friction δ. As seen in Figure 5.2.19, δ increases slightly as the percentage of parent coal increases from 0 to 100%,

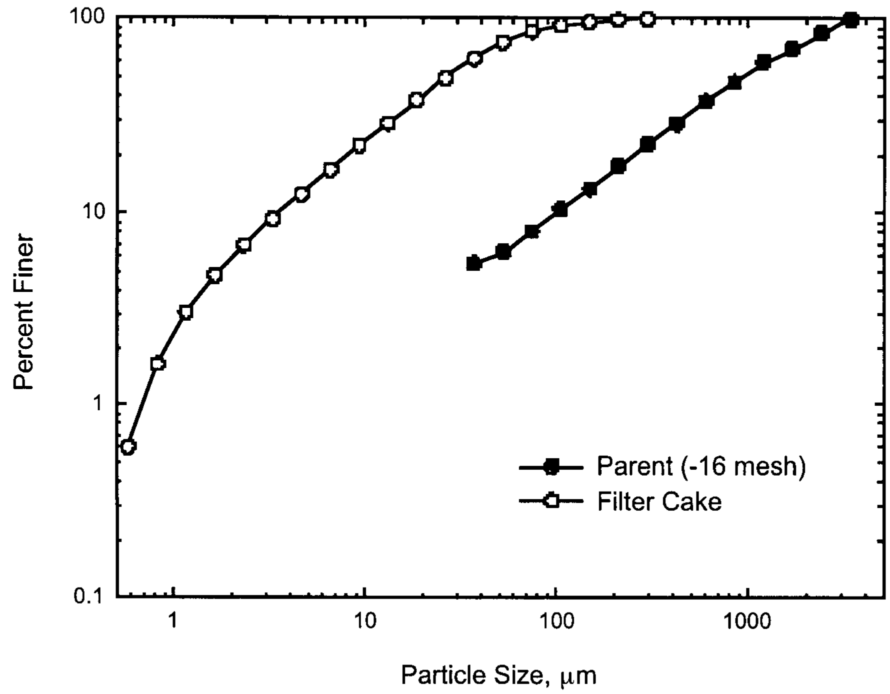


Figure 5.2.18 SIZE DISTRIBUTIONS OF INDIANA 7 COAL SAMPLES

Table 5.2.4 Proximate Analyses of Coal Samples

Sample	Moisture	Ash	Volatile Matter	Fixed Carbon
Indiana 7 Parent	9.885	33.305	10.0175	56.6775
Indiana 7 Filter cake	1.4775	36.08	4.065	59.8525
Taggart	2.745	33.4275	1.58	64.9925

Table 5.2.5 Ultimate Analyses of Coal Samples

Sample	Carbon	Hydrogen	Nitrogen	Sulfur
Indiana 7 Parent	63.26	5.89	1.47	0.31
Indiana 7 Filter cake	59.31	6.82	1.31	0.45
Taggart	76.78	6.07	1.31	0.55

while the shear stress needed to maintain flow also increases. These results imply that, as the material becomes coarser, the force needed to maintain a steady flow increases due to increased internal friction.

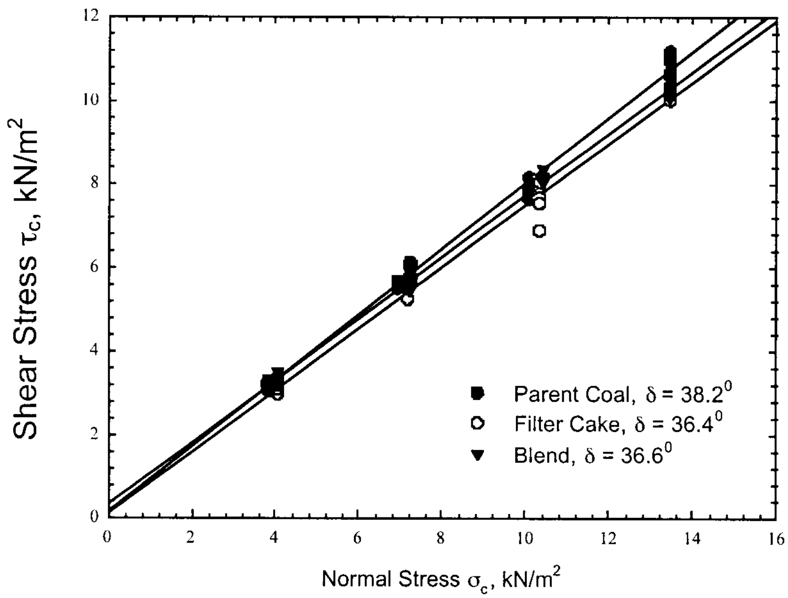


Figure 5.2.19 EFFECTIVE YIELD LOCI FOR INDIANA 7 PARENT COAL, FILTER CAKE AND A BLEND OF THE FILTER CAKE MATERIAL WITH 20% OF THE PARENT COAL

The effects of moisture content are illustrated in Figure 5.2.20, using a blend of 20% parent coal as an example. With the increase of moisture, the consolidation shear stresses decrease slightly. This may be due to the lubrication effect of the liquid.

Yield Loci

The yield locus, YL, is a measure of the stresses required to initiate flow in a consolidated powder. Yield loci for the filter-cake material, the parent coal, and several blends were determined over a range of consolidation levels. A typical set for a blend containing 80% of the parent coal is shown in Figure 5.2.21. It can be seen that the angle of internal friction ϕ is essentially constant, at about 35°, independent of consolidation. The cohesion c increases slightly as the material becomes more consolidated. The effects of size consist on the yield loci at a constant consolidation stress σ_c of about 4 kN/m^2 are illustrated in Figure 5.2.22. As would be expected, the filter-cake material is more cohesive than the coarser parent coal. However, the blends, especially those containing 80% of the coarse (parent) fraction, are generally more cohesive than either of the single components. This may be a consequence of denser packing in the coarse/fine mixtures used and may have important consequences in practical applications.

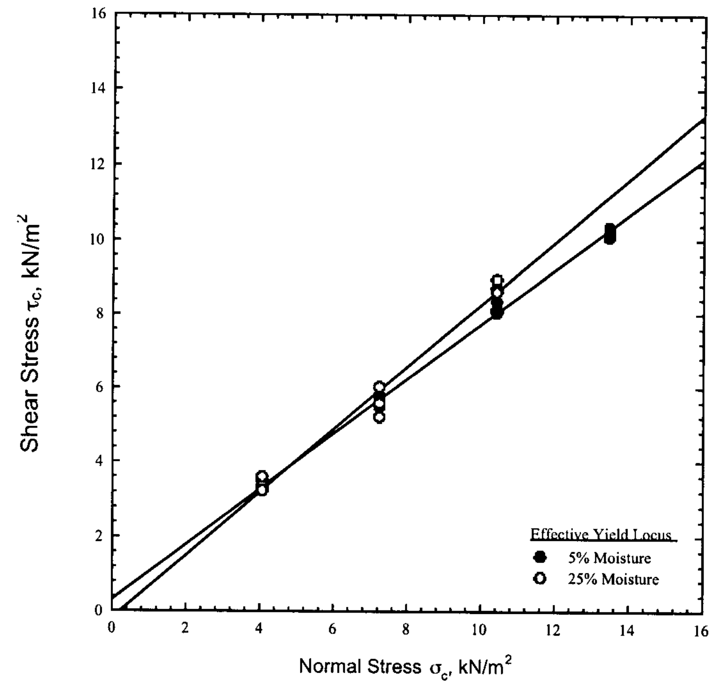


Figure 5.2.20 EFFECTIVE YIELD LOCI FOR 20% INDIANA-7 PARENT COAL BLEND AT 5% AND 25% MOISTURE

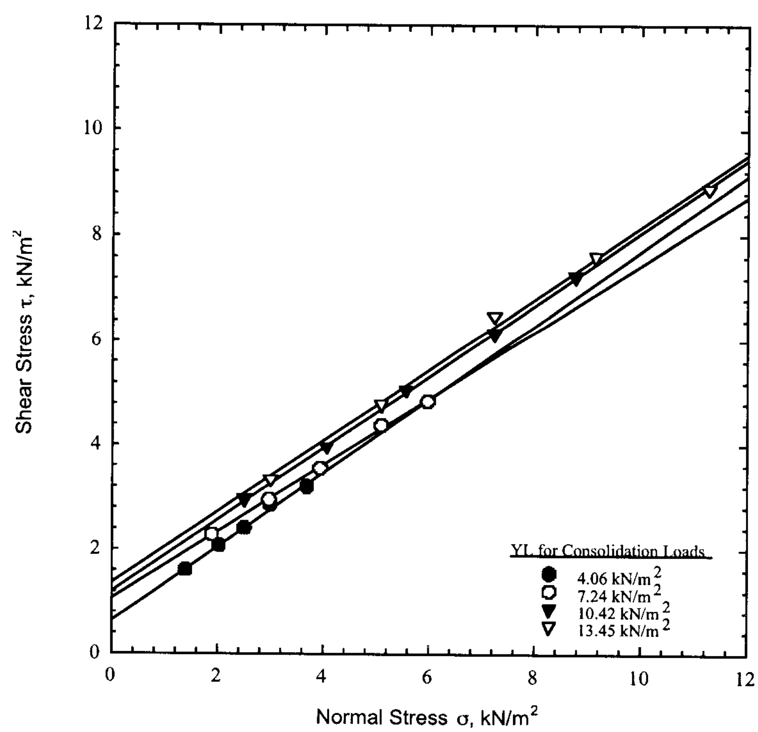


Figure 5.2.21 TYPICAL YIELD LOCI PLOTS AT VARYING CONSOLIDATION LOADS FOR A 20% INDIANA-7 PARENT BLEND

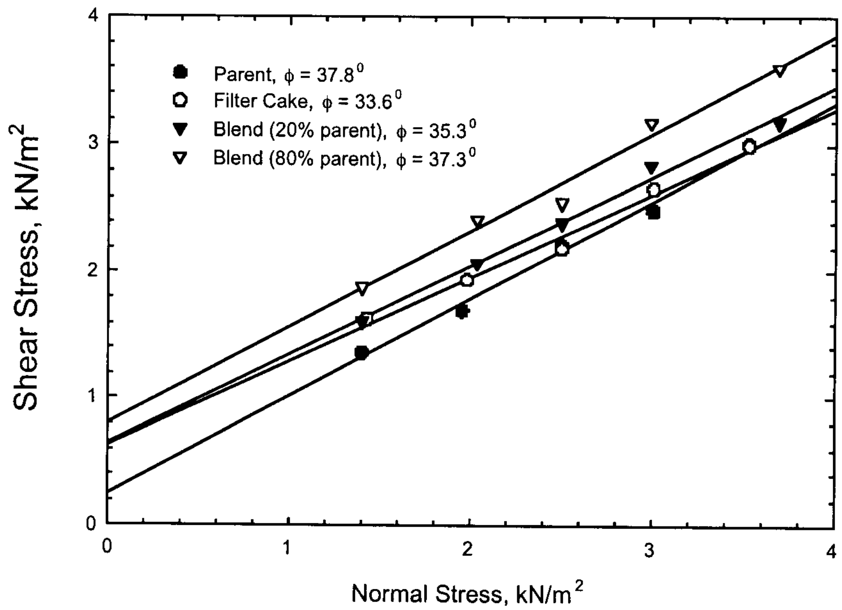


Figure 5.2.22 THE EFFECT OF COMPOSITION ON YIELD LOCI FOR BLENDS OF INDIANA 7 COAL CONSOLIDATED UNDER A NORMAL STRESS OF 4 KN/M^2

Blending of small amounts of filter cake material into a power-plant feed could potentially lead to increased materials-handling problems.

The effects of moisture content on the yield loci for the 80% blend are shown in Figure 5.2.23. It can be seen that additional moisture increases the cohesion but decreases the angle of internal friction. These effects could be attributed to enhancement of capillary bonding between particles combined with lubrication by the liquid.

Bulk Density

Examples of the effect of consolidation on the bulk density of test specimens are given in Table 5.2.6. The finer materials (1% and 20% parent) show a slight increase in bulk density with increased consolidation stress, while the coarser sample is essentially incompressible. The effects of particle size consist are shown in Table 5.2.7. As expected, the broad, bimodal size distributions of the blends, especially that containing 80% of the coarse, parent coal, lead to enhanced packing and higher bulk density.

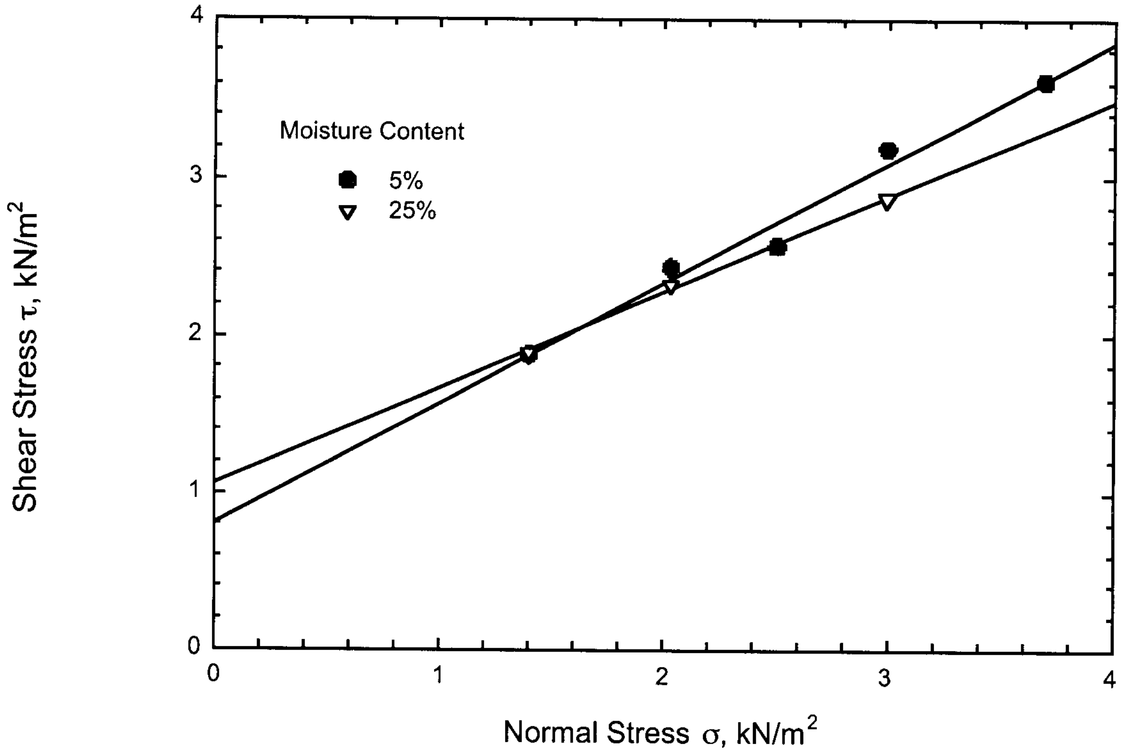


Figure 5.2.23 EFFECT OF MOISTURE CONTENT ON THE YIELD LOCUS FOR A BLEND CONTAINING 80% PARENT COAL CONSOLIDATED AT 4 KN/M^2

Table 5.2.6 Effect of Consolidation Stress on the Bulk Density of Filter Cake/Parent Coal Blends

Consolidation Stress, kN/m^2	**Average Bulk Density, kg/m^3**		
	1% Parent	**20% Parent**	**80% Parent**
4.1	614	625	883
7.2	623	631	878
10.4	634	651	883
13.5	626	645	896

Flow Functions

The flow function FF provides an indication of the ability of a consolidated powder to support stable blockages such as domes or ratholes. Flow functions for the Indiana 7 coal system are presented in Figure 5.2.24. The trends essentially parallel those seen in Figure 5.2.22 for the yield loci with the coarse/fine mixtures exhibiting lower flowability than either

Table 5.2.7 Effect of Particle Size Consist (blend composition) on the Bulk Density of Consolidated Specimens

Material	Average Bulk Density, kg/m^3
Parent Coal	844
80% Parent	885
20% Parent	638
Filter Cake	624

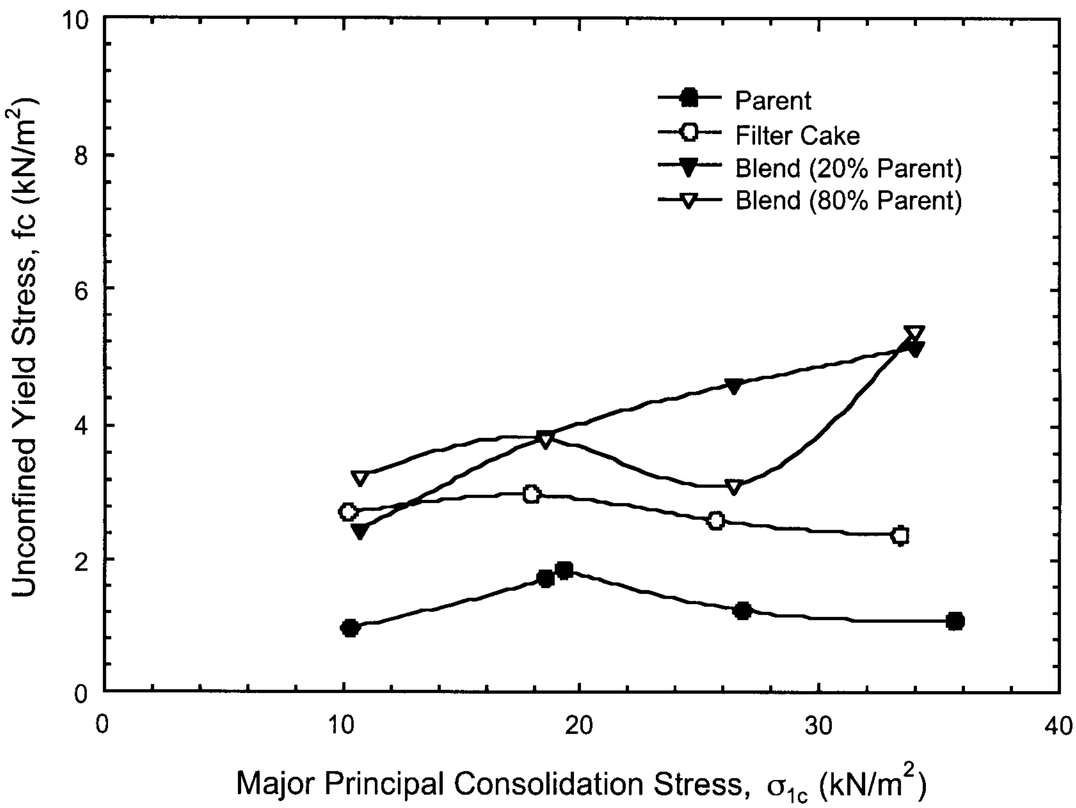


Figure 5.2.24 FLOW FUNCTIONS FOR BLENDS OF INDIANA 7 COAL

the parent coal or the filter-cake material. The flow function for the parent coal is essentially flat and close to the origin of the plot. This is to be expected for a material containing a relatively small amount of fines. The flow function for the filter cake material is also quite flat but shifted to higher values of the unconfined yield stress f_c than that for the parent coal. Because of the low compressibility of this material (see Table 5.2.6), cohesion is relatively unaffected by consolidation stresses. In the case of the 20% and 80% blends, internal friction plays a more important role (see Figure 5.2.22) leading to somewhat steeper flow functions. Again, these results imply that blending the filter-cake material with a relatively coarse coal feed could lead to problems in handling and storage.

The effects of moisture on the flow functions for the blend containing 80% of the parent coal are illustrated in Figure 5.2.25. The results indicate that additional moisture reduces the flowability of the coal. Again, this can probably be attributed to enhanced capillary bonding between particles.

Table 5.2.6 Effect of Consolidation Stress on the Bulk Density of Filter Cake/Parent Coal Blends

Consolidation Stress, kN/m^2	**Average Bulk Density, kg/m^3**		
	1% Parent	**20% Parent**	**80% Parent**
4.1	614	625	883
7.2	623	631	878
10.4	634	651	883
13.5	626	645	896

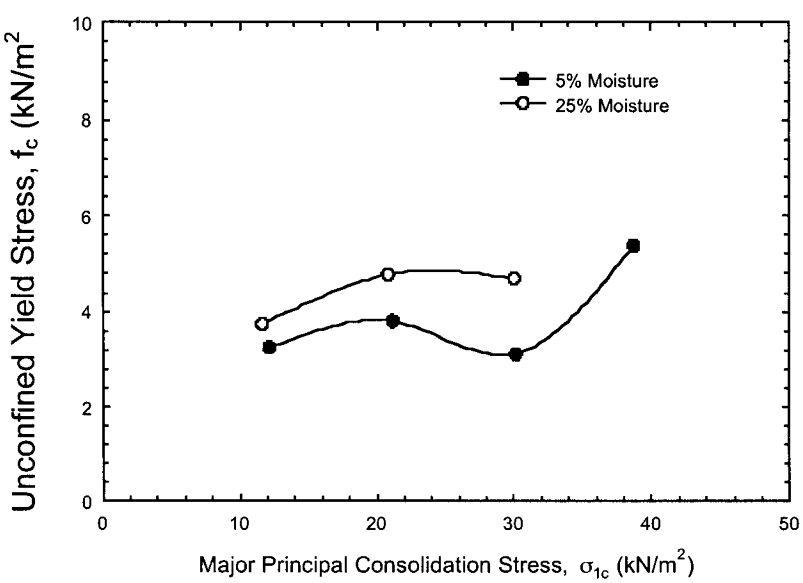


Figure 5.2.25 THE EFFECT OF MOISTURE CONTENT ON THE FLOW FUNCTION FOR 80% INDIANA 7 PARENT COAL

Wall Friction

Friction between the flowing material and the walls of a hopper is an important factor in determining both the type of flow (mass or funnel) that can be expected and the likelihood of blockages occurring. Examples of wall yield loci WYL for blends of Indiana 7 filter cake and the parent coal in contact with the standard 16-gage steel reference material are given in Figure 5.2.26. The curves for mixtures of widely different composition show only minor differences, with slightly higher friction for the finer material, especially at the higher normal stresses. In both cases, the angle of wall friction is about 27°. There appears to be a small degree of adhesion at the wall as indicated by the positive intercept at zero normal stress.

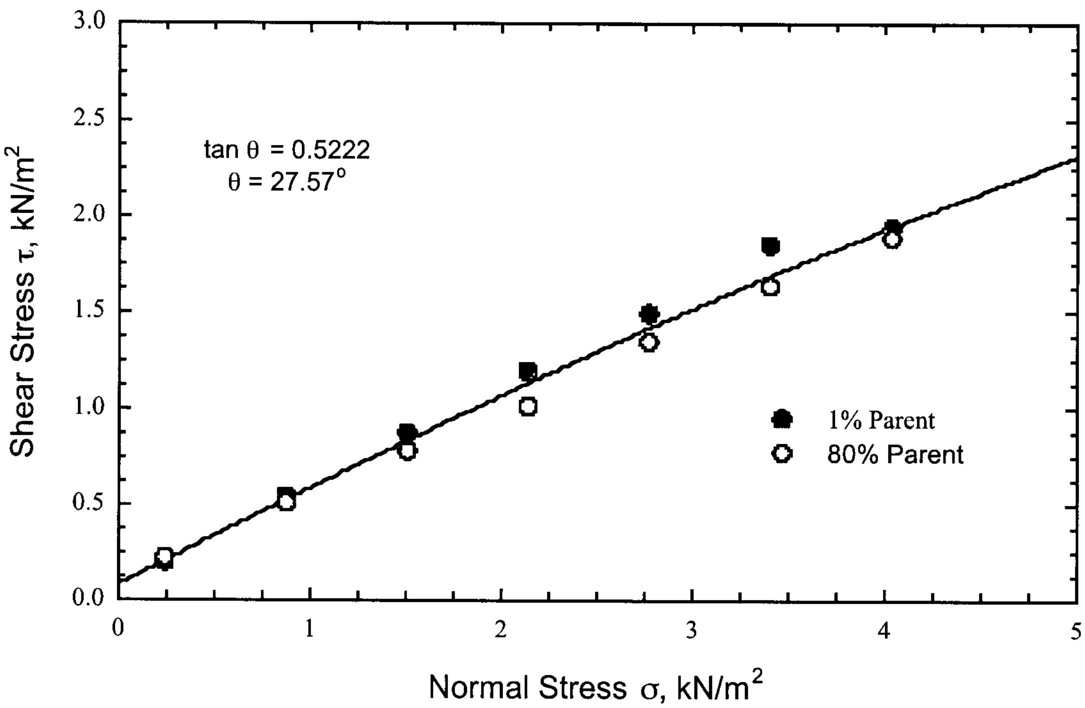


FIGURE 5.2.26 WALL YIELD LOCI FOR 1% AND 80% INDIANA 7 PARENT COAL

5.2.6.4 Design Criteria

The shear-cell test data provide a basis for the design of storage systems for these fine coal mixtures. In particular, it is possible to establish limiting hopper wall angles to ensure mass flow and minimum outlet dimensions to prevent the formation of obstructions to flow.

Flow Type

Mass flow is preferred for most applications. The conditions for mass flow through a hopper are determined by the effective angle of internal friction δ, the angle of wall friction ϕ_w, the shape of the hopper (conical, planar, pyramidal, etc.) and the slope of the hopper walls (angle θ from the vertical). The effective angle of internal friction for the materials studied varied between 35 and 40°, while the angle of wall friction was about 27°. Referring to Figure 5.2.15 and the equivalent charts for $\delta = 40°$ presented by Jenike (1970), mass flow for these materials would require hopper angles of less than 15° for conical hoppers or less than about 25° for plane-flow hoppers.

Selecting hopper angles of 12 and 20° for conical and plane-flow hoppers, respectively, the flow factors, from Figure 5.2.15, would be about 1.6 in both cases. The corresponding line is superimposed on the flow function plot in Figure 5.2.27. Best estimates of the critical stresses, obtained by linear regression and extrapolation of the flow functions, are presented in Table 5.2.8, together with the appropriate bulk densities and minimum outlet dimensions calculated from equations 5.2.10 and 5.2.11. The required opening sizes ranged from about 22 cm for the parent coal in a plane-flow channel to more than one meter for the filter cake in a conical hopper. The use of smoother walls (smaller ϕ_w) would allow less-steep walls to be used – increasing bin capacity for a given height – but would have little effect on outlet size requirements. It is interesting to note that, despite the apparently greater cohesion for the blends indicated in Figure 5.2.22, the filter-cake material requires the largest outlet openings. This is a consequence of the flat form of the flow function for that material.

It is clear from Table 5.2.8 that the addition of the filter-cake material to coarse coal can significantly increase the likelihood of obstructions forming in a bin. The use of such blends in existing systems, designed for coarse coal, could lead to serious materials handling problems.

The need to extrapolate the flow functions in order to estimate critical stresses is a common and often serious problem in the use of the Jenike test procedure for bin design. The situation arises because the equipment is insufficiently sensitive to measure shear stresses at very low normal-stress values. For example, to extend the data in Figure 5.2.27 close to the line corresponding to the flow factor of 1.6 would require consolidation of a sample at stresses as low as 2 kN/m^2, followed by shear testing at less than 1 kN/m^2. The latter value would correspond approximately to the weight of the hanging bracket, the cell lid and the coal itself.

Measurements of the shear force under such small normal loads tend to be highly erratic and unreliable.

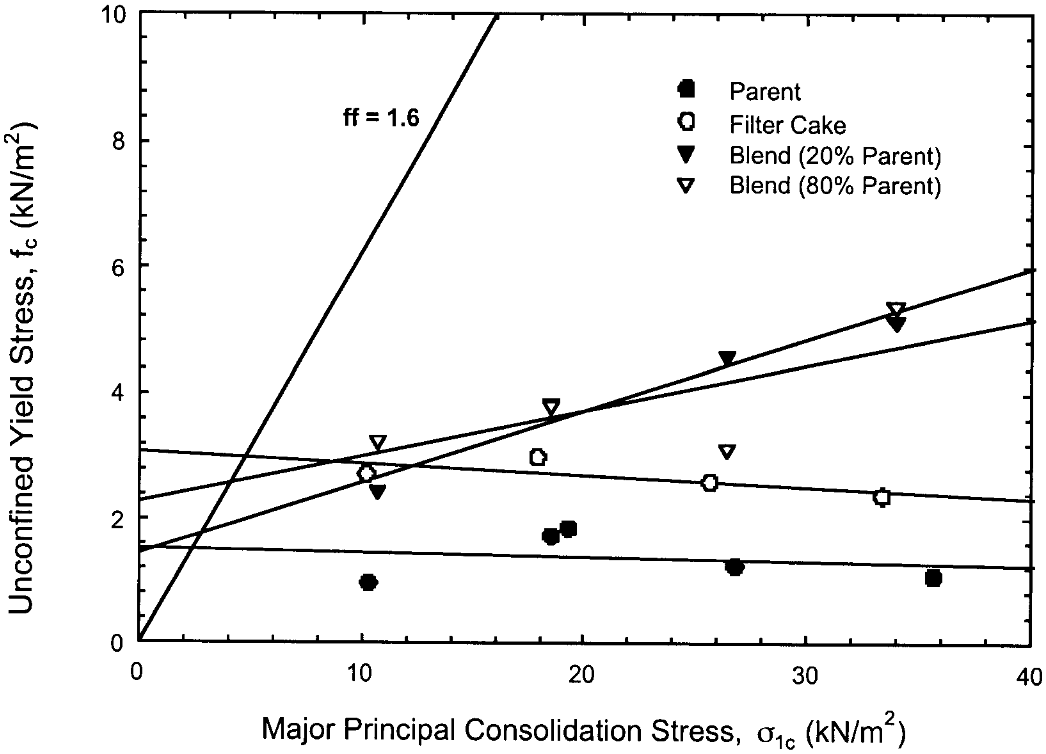


Figure 5.2.27 FLOW FUNCTIONS AND FLOW FACTOR FOR INDIANA 7 BLENDS

Table 5.2.8 Critical Stresses and Minimum Outlet Dimensions for Storage of Indiana 7 Blends in Conical and Plane-Flow Hoppers

Material	Critical Stress, σ_{cr} (kN/m^2)	Bulk Density, ρ_b (kg/m^3)	H(θ)		Outlet Dimension (m)	
			Circular	Rectangular	Circular	Rectangular
Parent Coal	1.5	844	2.2	1.2	0.399	0.218
Filter Cake	2.9	624	2.2	1.2	1.043	0.569
Blend (20% Parent)	1.8	645	2.2	1.2	0.626	0.342
Blend (80% parent)	2.5	885	2.2	1.2	0.634	0.346

5.2.6.5 Bin Testing

Some limited testing was carried out using a specially designed, adjustable bin. The primary objective was to provide a practical validation of the design criteria obtained from shear-cell testing.

Bin Design and Construction

The design of the bin needed to address a few, very important conditions. First, the angles for the sloped sides needed to be fully adjustable along with the bin opening at the bottom, and the design had to match the geometries indicated by the shear tests. Secondly, the bin had to remain a batch-type device, meaning that the bin would be filled with material and then lifted with the aid of a fork-truck, at which time all the bulk solids should exit the bin. One of the problems associated this approach is the possibility that vibrations caused by the lifting of the bin may aid in the release of the material from a stopped or stored position. Another potential problem is the inability to produce constant consolidation of the bulk material. As the bulk material exits a steady state bin, it moves vertically through the bin and more material is replaced on top of it, keeping the compression load constant. In the batch system, the material at the top does not have this compression force exerted upon it, therefore, the only realistic representation of the bin discharge would be the first material to exit the bin. This method was chosen mainly due to the difficulty of re-circulating the material from the opening at the bottom to the feed side. This could be done using a beltline to transport the material from the feeder back to the hopper but, for this project, the simpler batch approach was adopted.

Napotnic Welding Co. from Armaugh, Pennsylvania, aided in the design of the intended adjustability of the bin and constructed the final design. The design maintained the geometry needed enabling the bottom part of the hopper to be fully adjustable by hinging it to the vertical part of the bin. Screws attached to the base allowed the angle to be altered while a sliding mechanism constricted the upper portion at 90°. One major concern that had to be resolved prior to construction was the ability of the angles to be adjusted without changing the bin opening width or location on a flat ground surface. This was solved by fitting slides to the top screws while securely fastening the bottom screws to the sloping side of the bin. Thus the angles and the bottom opening width could be adjusted independently.

Bin Testing Procedure

Because of its ready availability and minimal tendency to segregate, the bin tests were performed on the Indiana-7 “filter-cake” material. Bin tests were carried out under the conditions given in Table 5.2.9. For practical purposes, tests were not performed on any blends. It was felt that the amount of material needed to conduct these experiments would exceed the amount of coal available and the ability to reliably blend the material at the laboratory scale would prove too difficult.

The general operational procedure for the tests was as follows:

1. The predetermined width of the opening was set using a standard tape measure;
2. An "angle finder" was attached to the bottom portion of the hopper and the sides were adjusted to the desired slope;
3. "Filter-cake" material was hand-shoveled into the bin;
4. The material was compacted in an attempt to simulate the pressure that would occur under normal load conditions;
5. Using a forklift, the bin was slowly raised at a constant velocity to avoid any jerking motion that may aid in flow. As the bin was raised, flow was observed and noted; and
6. Tests were repeated at a variety of angles and opening widths. The tests were performed in attempts to induce bin failure and to determine minimum requirements for flow.

Table 5.2.9 Bin Settings and Test Results

Test Number	**Bin Angle θ (degrees)**	**Opening Width (Inches)**	**Type of Flow**
1	30	34.00	Funnel
2	30	34.00	Funnel
3	30	34.12	Mass
4	30	34.12	Mass
5	40	32.75	Funnel
6	40	32.75	Funnel
7	35	32.75	Funnel
8	35	32.75	Funnel
9	25	32.75	Funnel
10	25	32.75	Funnel
11	25	33.38	Mass
12	25	33.38	Mass

Results

Due to constraints of time and material availability in the final stage of this project, only a limited amount of testing with the pilot-scale bin was possible. As noted above, the primary objective of the bin-test work was to validate the use of the Jenike test procedure for predicting flow type and the occurrence of bin failures for fine, deep-cleaned coal. The conditions corresponding to each test are indicated on the flow-factor chart for plane-flow hoppers with δ = 35° in Figure 5.2.28. It can be seen that the observed flow type is in general agreement with the predictions. For the steeper hopper angles (tests 1 – 4 and 9 – 12), conditions correspond to points close to or slightly to the right of the dashed line representing the mass flow/funnel flow transition. The results given in Table 5.2.9 show such transitions with small changes in bin geometry, leading to a switch from mass flow to funnel flow. In the case of the less steep angles (tests 5 – 8) conditions lie far to the right of the dashed line and funnel flow is observed in all cases.

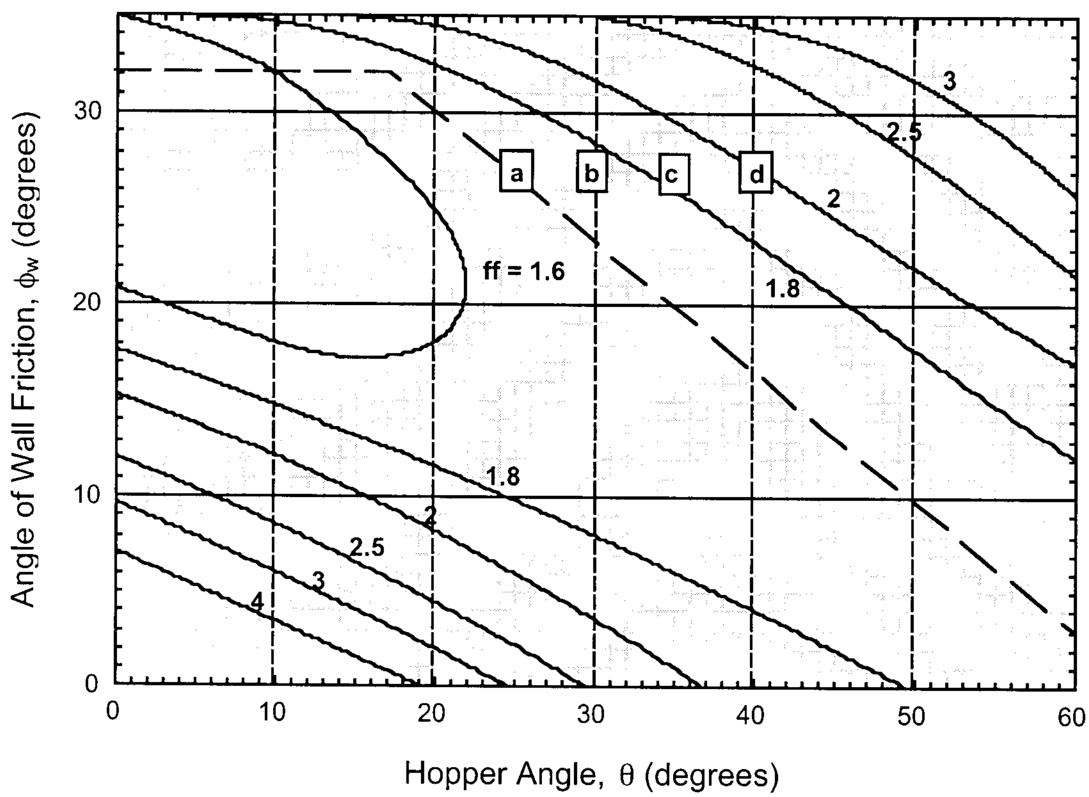


Figure 5.2.28 BIN TEST CONDITIONS INDICATED ON THE FLOW-FACTOR CHART FOR PLANE FLOW WITH δ = 35°
(A: TESTS 9 – 12; B: TESTS 1 – 4; C: TESTS 7 & 8; D: TESTS 5 & 6)

Because of the problems noted above regarding appropriate consolidation of the material during flow through the hopper, reliable data on the minimum outlet dimensions required to prevent blockage could not be obtained and this aspect of the study was inconclusive. Nevertheless, with further refinement, this general approach can provide a useful means of confirming the results of laboratory-scale tests.

5.2.6.6 Conclusions

The objective of this research was to evaluate the flow characteristics of fine, filter-cake coal using the Jenike shear-testing procedure and to investigate the use of a pilot-scale test bin for validation of the results. Revamping the Jenike shear tester through the use of an electronic force transducer and a digital data acquisition system was found to increase the sensitivity and range of the results. This eliminated one of the major weaknesses of the Jenike equipment as the data were numerically recorded rather than directly interpreted from data recording charts. The following conclusions can be drawn from the results of shear-cell testing of a fine, filter-cake material, the corresponding parent coal and various blends of the two:

- The effective yield locus (EYL) – a measure of the stresses required to maintain steady flow in a consolidated powder – appears to be relatively insensitive to mixture composition and moisture content. Increasing coarseness due to the addition of the coarser, parent coal causes a slight increase in the frictional resistance to flow while moisture addition reduces friction, probably by a lubrication effect;
- The effects of mixture composition, i.e., size consist, on the (static) yield locus (YL) – a measure of the stresses needed to initiate flow in a consolidated powder – reveal that blends of the filter-cake material with the parent coal tend to be more cohesive than either of the separate components. This rather surprising result is attributed to enhanced packing in the blends and indicates potential materials-handling problems if coal fines are added to the normal feed coal in an existing system. Increased moisture content increases cohesion – probably through capillary forces – but reduces internal friction, presumably by lubrication;
- Because of their bimodal size distributions, the coarse/fine blends generally pack to higher bulk density than the separate components. The filter-cake material is

slightly compressible – bulk density increases with applied stress – while the parent coal is essentially incompressible;

- Flow functions for these materials indicate that while the flowabilities of the filter cake and parent coal are relatively insensitive to consolidation, those for the blends tend to decrease as consolidation stresses are increased. It is postulated that consolidation stresses applied to the blends affect the fine component disproportionately, leading to enhanced cohesion despite very little change in overall bulk density; and
- Measurements of wall friction against a steel reference material show very little variation with mixture composition and lead consistently to angles of wall friction of about 27°.

Application of the shear-cell test data to the development of bin-design criteria lead to the following general conclusions regarding potential materials handling problems in industrial use of fine coal, such as the filter cake evaluated here:

- Mass flow can be ensured for the filter cake, parent coal or any of the blends provided sufficiently steep hoppers are used. For hoppers constructed from the standard reference steel angles less than about 15° for conical and 25° for plane-flow would be required;
- Because they involve convergence of the material in two rather than three dimensions, plane-flow hoppers can generally operate with smaller outlet dimensions than conical types;
- The filter-cake material is most prone to blockage by arching across the hopper. Blending with coarse coal can reduce this tendency. On the other hand, addition of the filter-cake material generally increases the likelihood of arch formation in storage of coarse coal; and
- Reducing wall friction, using smooth liners for example, can permit mass flow with less steep hopper walls but will not reduce outlet size requirements.

Shear-cell testing using the Jenike procedure can provide a sound basis for bin design or for fault diagnosis in existing units. However, this approach suffers from several limitations, particularly particle size restrictions on test samples, test reproducibility, the need to extrapolate test data (i.e., flow functions) in order to obtain important design parameters (critical stresses) and the inherent problems of scale-up from laboratory to industrial sizes. In practice, these problems are generally circumvented by the conservative nature of the design procedure, with built-in safety factors, etc. Typically, the result is over-designed systems that work successfully but at a cost in efficiency and expense. The availability of a low-cost, pilot-scale test procedure involving an actual bin would provide a useful extension to the laboratory-scale tests.

A rectangular bin with independently adjustable wall angles and outlet width was designed and constructed during this project. The system was successfully tested in terms of mass flow/funnel flow predictions using the Indiana 7 filter-cake material. However, further refinements of the system and test procedures are necessary for reliable evaluation of the outlet sizes needed to prevent arching in the bin.

5.3 Pilot-Scale Combustion Tests

Pilot-scale combustion tests were performed using the AMAX filter cakes and cleaned coals from CQ, Inc. The tests were performed in Penn State's research boiler as part of the trace element emissions study; therefore, the results are not presented here but are provided in Section 3.0.

5.4 Demonstration-Scale Combustion Tests

5.4.1 Demonstration Boiler System

The combustion testing was conducted using Penn State's demonstration boiler, which is shown schematically in Figure 5.4.1. The watertube boiler is of D-type design, manufactured by Tampella Power Corporation, and rated for 15,000 lb/h saturated steam (@300 psig). It is integrated into the University's steam distribution system. The boiler was designed to fire fuel oil but the overall system has been modified to fire coal-based fuels, i.e., MCWM and dry, micronized coal.

Modifications were made to the original system to provide combustion air and MCWM preheating, fly ash removal from the flue gas using either a conventional fabric filter baghouse

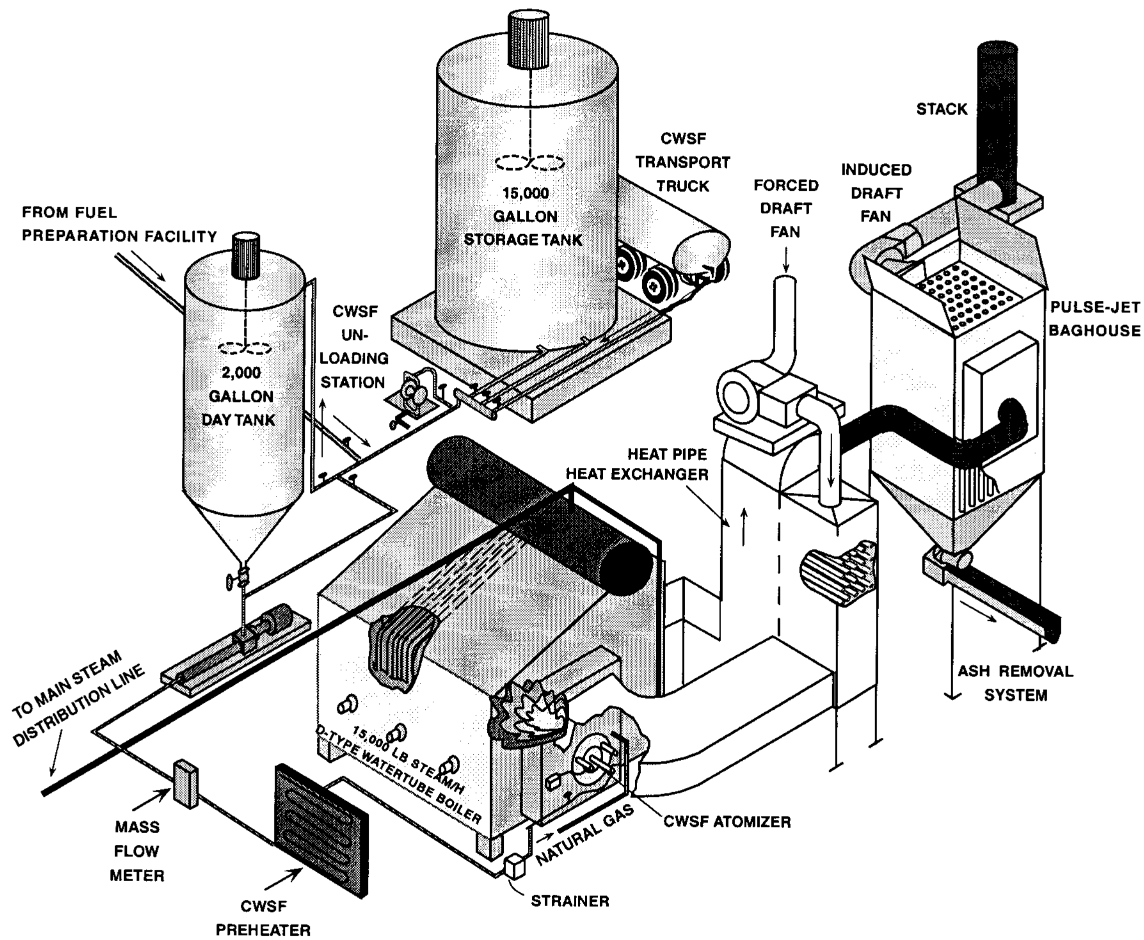


Figure 5.4.1 GENERALIZED DIAGRAM OF PENN STATE'S COAL-WATER SLURRY FUEL-FIRED DEMONSTRATON BOILER SYSTEM WITH A PULSE-JET BAGHOUSE (Note: Coal handling and coal-water slurry fuel preparation equipment are not shown)

a ceramic membrane filter chamber, coal unloading, storage, and crushing, and either MCWM preparation or dry coal micronization. Fuel preparation and handling facilities are not shown in Figure 5.4.1. The combustion chamber and convective pass have not been modified. The furnace is approximately 8 ft long by 6 ft wide, with a volume of 370 ft^3. The bulk gas residence time in the furnace is less than one second. Discussions of the equipment, program history, and a comparison between results when firing micronized coal and MCWM can be found elsewhere (Miller and Scaroni, 1990; Jennings et al., 1994; Miller et al., 1995).

When firing CWSF, it is pumped from the storage tank in the MCWM preparation facility to a 2,000-gallon surge tank located in the boiler room. From the surge tank, the MCWM is pumped through a preheater (tube and shell heat exchanger) to the burner.

The burner used during this test program was ABB Combustion Engineering's RSFC burner and it is shown in Figure 5.4.2. A detailed description of the burner can be found elsewhere (Miller et al., 1997b). This burner has been used in the demonstration boiler when firing natural gas, No. 6 fuel oil, micronized coal, and MCWM.

The atomizer that was used during the AMAX filter cake testing was a modified Faber oil nozzle. The nozzle, an XHC75° (extra-high capacity with a 75° spray angle) was found to produce the best results among several tested in the demonstration boiler and has been used for much of the reported testing. Details of the Faber atomizer and results from other atomizer testing can be found elsewhere (Miller et al., 1995; 1997a,b).

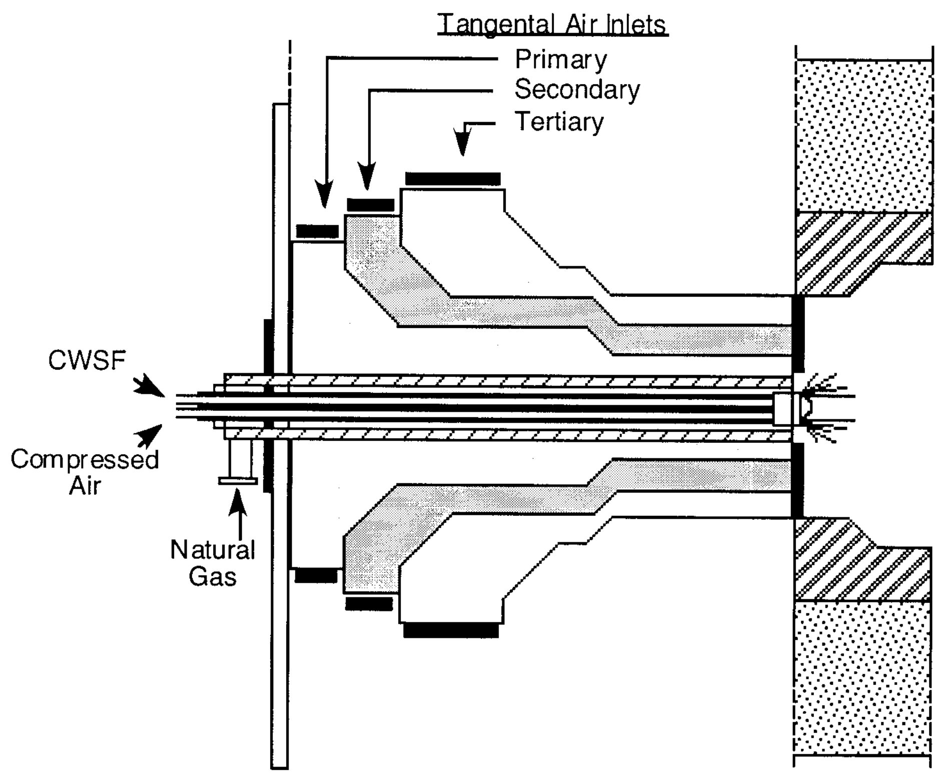


Figure 5.4.2 SCHEMATIC DIAGRAM OF THE RSFC BURNER AND ATOMIZER

5.4.2 Combustion Performance

This section discusses the combustion performance of the MCWMs produced from the AMAX filter cakes and compares them to previous testing that was performed on the demonstration boiler. Table 5.4.1 contains selected combustion results from the thirteen tests using the AMAX filter cakes along with results from six Middle Kittanning seam and Coalberg seam MCWMs.

Table 5.4.1. Selected Combustion Results[a]

Coal	Solids Loading (%)	Gas Cofire (%)	Atomization Pressure (psig)	Combustion Efficiency (%)
Hiawatha – SA[b]	55.5	30	135	98.7
	56.4	26	135	98.4
	54.3	30	135	98.2
	56.0	23	135	97.7
Hiawatha – CF[c]	55.0	30	135	97.5
	54.5	26	135	97.4
Taggart – SA	59.5	30	135	97.7
	58.5	30	80	95.1
	60.3	23	135	96.5
	59.9	30	80	93.0
Taggart – CF	58.6	30	135	93.7
	57.7	30	80	90.9
	59.3	30	135	92.5
Middle Kittanning – SS[d]	60.6	30	135	93.6
Coalberg – SS	61.8	38	90	79.7
Coalberg – DS[e]	57.5	27	150	79.9
Middle Kittanning – SS	60.9	30	150	82.7
Middle Kittanning – DS	60.9	29	150	85.8
Middle Kittanning – SS	60.2	10	120	85.4

[a] All combustion tests were performed using the RSFC burner. The XHC-75° atomizer was used for all the tests except for the Coalberg seam and two Middle Kittanning seam tests noted with asterisks, where an ABB 1-hole Tangential 30° atomizer was used.
[b] Selective Agglomeration
[c] Column Flotation
[d] Single-stage grinding circuit
[e] Double-stage grinding circuit

Many coals have been prepared into MCWMs in Penn State's hybrid MCWM double-state grinding/mixing circuit and tested in the demonstration boiler. These MCWMs were produced for projects in which the viability of retrofitting fuel oil-designed boilers to fire MCWM was determined (Miller et al., 1997a,b). The properties of five MCWMs and their parent coals, which have been selected for combustion performance comparison with the AMAX filter cakes, are given in Table 5.2.3. These MCWMs were produced using a Middle Kittanning seam coal from Pennsylvania and a Coalberg seam coal from Kentucky and fired in the demonstration boiler using the same burner. They have similar particle size distributions (PSDs) and hence similar slurryability characteristics to the AMAX filter cake MCWMs.

The Middle Kittanning and Coalberg seam coals were prepared into MCWMs using the double-stage grinding circuit. With this scheme, run of mine coal (≈2 inch x 0) is crushed and conveyed into a 4x8 ft ball mill (first stage), where it is ground with dispersant, water, and a pH modifier. The ball mill discharge is pumped across the vibratory screen to the 1,000-gallon process tank. When single-stage grinding is preferred, the stabilizer is added in the process tank and the MCWM is pumped to the blend tank and subsequently to the boilerhouse. When double-stage grinding is desired, all or a portion of the MCWM is pumped from the process tank (before stabilizer is added) to the stirred ball mill, surge tank, and blend tank. The blend tank is used to homogenize the MCWM when only a portion of the MCWM from the process tank is passed through the stirred ball mill, and the stabilizer is added at this point. Finally, the MCWM is pumped to the 2,000-gallon surge tank located in the boilerhouse.

5.4.2.1 AMAX Filter Cake MCWMs

As previously mentioned, the objectives of the AMAX filter cake MCWM testing were to evaluate the filter cakes as potential fuels for industrial boilers and to evaluate the effect of deep cleaning on trace element emissions. In order to determine the effect of combustion efficiency (i.e., char content and surface area) on trace element emissions, tests were conducted where the atomization pressure and level of natural gas cofire (as a percent of total thermal input) were varied. The trace element results are presented in Section 3.0; however, the combustion performance as a result of these changes will be discussed in this section. Previous results have indicated that the combustion efficiency tends to increase with increasing solids content and level of natural gas cofire (Miller et al., 1997a,b).

Prior to beginning the suite of tests, preliminary operation indicated that ≈30% natural gas cofire was necessary to maintain a stable flame. This was based on previous operating experience and by visually observing the flame character, steam generation rate, and gaseous emissions when firing Hiawatha-SA MCWM during preliminary operation. This level of natural gas cofire was chosen as the baseline level for the AMAX filter cake testing. Tests were then conducted where the level was decreased until the flame became too unstable for operation. The lowest level of natural gas cofire achievable was 23% when firing the Hiawatha-SA and Taggart-SA MCWMs and 26% when testing the Hiawatha-CF MCWM. When firing the Taggart-CF MCWM, the level of natural gas cofire could not be reduced below 30% without the flame becoming too unstable

Two atomizing air pressures were used during the testing. The University air compressors were used to deliver 80 psig atomizing air (low atomizing air pressure) while a rented air compressor delivered 135 psig atomizing air (high atomizing air pressure).

Hiawatha-SA and -CF MCWM Tests

Four tests were conducted firing Hiawatha-SA MCWM at three levels of natural gas cofire and one atomizing air pressure. The 30% natural gas cofire repeat tests resulted in a combustion efficiency difference of 0.5%, which indicates that the combustion efficiency of the 30 and 26% natural gas cofire cases are essentially the same and may be slightly higher than for the 23% natural gas cofire test. Likewise, two tests were conducted with the Hiawatha-CF MCWM and the combustion efficiency was not affected when decreasing the level of natural gas cofire from 30 to 26%. The combustion efficiencies for the six tests ranged from 97.4 to 98.7%.

Taggart-SA and -CF MCWM Tests

The Taggart fuels behaved differently than the Hiawatha fuels. The Taggart-SA MCWM test conducted at 30% natural gas cofire and high atomizing air pressure resulted in a combustion efficiency of 97.7%. However, the combustion performance decreased as the level of natural gas cofire decreased. In addition, the combustion performance decreased as the atomizing air pressure was decreased. Similarly, the combustion performance decreased as the atomizing air pressure was decreased when firing the Taggart-CF MCWM. Unlike any of the other three MCWMs produced from the AMAX filter cakes, the Taggart-CF MCWM could not be fired with less than 30% natural gas cofire. The reason for this is not clear as the atomization performance of the Taggart-CF MCWM was similar to the Hiawatha MCWMs, which performed well; however, the coal PSD of the Taggart MCWM was the coarsest of the four AMAX MCWMs. Interestingly, the Taggart-SA MCWM exhibited the worst atomization performance but its combustion performance, at 30% natural gas cofire and 135 psig atomizing air pressure, was still 97.7%.

General Conclusions

The MCWMs prepared from the selective agglomeration filter cakes exhibited higher combustion efficiency than the MCWMs produced from the column flotation filter cakes, especially for the Taggart seam filter cakes. A relative ranking, based on combustion efficiency, is that the Hiawatha-SA MCWM performed slightly better than the Hiawatha-CF MCWM, which performed similarly to the Taggart-SA MCWM, which performed much better than the Taggart-CF MCWM. Combustion efficiency decreased with decreasing atomizing air pressure, and the combustion efficiencies at 30 and 26% natural gas cofire were approximately the same but were higher than those at 23% natural gas cofire.

5.4.2.2 Comparison of the AMAX Filter Cake MCWMs with other MWMs Tested at Penn State

A direct comparison of the AMAX filter cake MCWMs with other MCWMs tested at Penn State is difficult because many MCWMs have been produced and tested using different burners, atomizers, and burner throat configurations, and each of these variations in hardware has an effect on the combustion performance. Several MCWMs are listed in Table 5.2.3, along with the AMAX MCWMs, and will be used for comparison. The MCWMs listed in Table 5.2.3 were conducted using the RSFC burner.

One MCWM test using Middle Kittanning seam coal was conducted during the AMAX MCWM test program. The MCWM was produced using the single-stage grinding circuit and the combustion efficiency was 93.6% when fired with 30% natural gas cofire and 135 psig atomizing air pressure. This combustion efficiency is similar to the Taggart-CF MCWM, which was much poorer than the Hiawatha seam CWSFs and the Taggart-SA MCWM.

The remaining five tests listed in Table 5.4.1 were selected from a previous program (Miller et al., 1997a), in which the effect of coal PSD on combustion efficiency was determined. Unfortunately, the Faber atomizer was only used during the last test listed, while the other tests used an ABB 1-hole tangential 30° atomizer.

As can be seen from Table 5.4.1, the combustion performance was poor when using the ABB atomizer as the combustion efficiencies ranged from ≈80 to 86%. What can be seen from these results though is the positive influence of fine grinding on combustion efficiency. Tests firing MCWMs produced from the double-stage grinding circuit resulted in higher combustion efficiencies. When firing the Coalberg seam MCWMs, the boiler could be operated with much less natural gas cofire even though the solids content was significantly less. It is acknowledged that the atomizing air pressure was higher for the MCWM produced from the double-stage grinding circuit; however, the level of natural gas cofire and the solids loading were much lower for the MCWM produced from the double-stage grinding circuit than for the MCWM produced from the single-stage grinding circuit.

The last test listed, the Middle Kittanning seam MCWM produced via single-stage grinding, was conducted using the Faber atomizer and 10% natural gas cofire, which was the lowest level of natural gas cofire achievable during the test program using the RSFC burner (Miller et al., 1997b). The combustion efficiency was low, compared to the AMAX MCWMs, but was as high as the best combustion efficiency obtained with an ABB atomizer.

5.4.3 Concluding Remarks

Penn State evaluated the use of deeply-cleaned coals, cleaned by AMAX Research & Development Center using advanced coal cleaning techniques, as industrial boiler fuels. Specifically, the combustion performance of filter cakes prepared into MCWMs was determined in Penn State's demonstration boiler.

The filter cakes were prepared into MCWMs that exhibited satisfactory handling and short-term storage properties (the MCWMs were prepared without stabilizers or particle size manipulation) for use as industrial boiler fuels. The combustion performance of the MCWMs was good, with the exception of the Taggart-CF MCWM, and combustion efficiencies ranged from ≈97 to 98%. The filter cake MCWMs performed as well or better than MCWMs prepared in the single- and double-stage grinding circuit. The level of natural gas cofire that was required to achieve these combustion efficiencies was 23 to 30%.

5.5 References

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