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**STORAGE, TRANSPORTATION, AND ATOMIZATION
OF CWF FOR RESIDENTIAL APPLICATIONS**

Quarterly Status Report No. 6

Report Period: January 1, 1991 to March 31, 1991

**By
M.P. Grimanis and R.W. Breault**

June 1991

**Work Performed Under Contract No. DE-AC22-89PC89796
September 27, 1989 to July 27, 1991**

**Tecogen Inc.
45 First Avenue
P.O. Box 9046
Waltham, Massachusetts 02254-9046**

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**Prepared for
PETC Project Manager: Anthony Mayne
Pittsburgh Energy Technology Center
U.S. Department of Energy
P.O. Box 10940
Pittsburgh, Pennsylvania 15236-0940**

**Prepared by
M.P. Grimanis and R.W. Breault
Tecogen Inc.
45 First Avenue
P.O. Box 9046
Waltham, Massachusetts 02254-9046**

MASTER

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EXECUTIVE SUMMARY

In light of the increased interest to decrease SO_2 emissions, one of the main causes of acid rain, and considering the large market potential for use of coal in residential/small-scale applications, the following program was undertaken. The work investigated the properties and behavior with regard to handling, storage, and atomization in small-scale applications of different CWFs prepared from different parent coals and various beneficiation techniques. The CWFs that were prepared included Upper Elkhorn No. 3, Illinois No. 6, and Upper Wyodak coal cleaned by heavy media separation. Also, several CWFs were prepared with Upper Elkhorn No. 3 coal cleaned by heavy media separation with filtration, chemical cleaning, oil agglomeration, and froth flotation.

Pressure drop measurements in tubes and viscometer measurements were used to construct rheograms of the seven CWFs that were prepared for shear rates up to 1000 1/s. It was shown that tube material does not have an effect on the friction losses in the tubes. Analysis of each CWF included proximate, ultimate, and ash fusion temperatures. A two-month stability could be obtained with the CWFs. The CWF made with lower ranked coals and with wider particle size distributions required less stabilizer to maintain stability. Different tank configurations and resuspension schemes were investigated for both bulk and small-scale storage. Two externally mixed atomizers were tested, as was one internally mixed atomizer. A fully automatic demonstration storage facility was designed and fabricated.

The viscosity at higher shear rates (150,000 1/s) will be measured in a capillary viscometer to determine the viscosity at shear rates typically obtained with atomizers. The demonstration storage/handling facility will be tested. A cost analysis of a residential facility will be conducted. The seven CWFs will be burned in the residential combustor developed by Tecogen under contract DE-AC22-87PC79650.

1. INTRODUCTION

There are continuing pressures in the United States to reduce SO₂ emissions in order to control acid rain and its damage to the environment. Advanced beneficiation processes are under development to provide low-ash, low-sulfur coals to allow combustion performance approximately equal to that of oil or gas. A major benefit of this development will be the contribution of these technologies to the abatement of acid rain precursors.

In addition to the industrial applications of beneficiated coal products, there is a large market potential for use of these fuels in small-scale applications, including small industrial, commercial, and residential combustion systems. However, it is important to transmute this beneficiated fuel into a more acceptable form for the small-scale user; a coal-water fuel (CWF) similar to oil is needed. Although much work has been done on the development of components and systems for the formulation and use of CWF for large industrial and utility applications, the results of these R&D efforts are not directly applicable to smaller combustors. It is essential to develop a data base for future use of CWF for these applications.

Under a contract with the Department of Energy's Pittsburgh Energy Technology Center (PETC), Tecogen Inc., developed a CWF-fired advanced combustor for commercial and residential applications. In order to expeditiously bring the technology to the point of commercial readiness, it is important to develop components and systems for storage, transportation, and handling of these fuels for end use. The work conducted in this program included fuel preparation, bulk storage, residential storage, and handling and atomization. This research and development effort is designed to augment the data base on the use of CWF for residential and other smaller scale applications.

A highly qualified team was assembled to perform the contract. The primary responsibilities of the team members were as follows:

1. Tecogen Inc. is a subsidiary of Thermo Electron Corporation, Waltham, Massachusetts. As the prime contractor, Tecogen managed and directed the program. The CWF storage and handling tests were carried out in their advanced combustor facilities for residential applications.
2. AMAX R&D of Golden, Colorado assessed formulations of CWF and prepared the fuel from the beneficiated coal products supplied by DOE in order to conduct tests in the program. AMAX R&D focused on bulk storage requirements prior to distribution for regional residential use.

3. Carnegie-Mellon University of Pittsburgh, Pennsylvania, compared the atomization characteristics of the CWFs prepared in the program. The effects of beneficiation on atomization were examined, and spray characteristics were studied by means of high-speed photography and a Malvern Particle Size Analyzer.

The test program examined the stability and rheology of the CWFs prepared from the beneficiated coal products supplied by DOE and made from various coals representing geographical regions in the United States. The following represents the source coals and their rank and origin.

Source Coal	Rank	Location of Mine
Upper Elkhorn No. 3	Bituminous, hvA	Wentz Plant, Virginia
Illinois No. 6	Bituminous, hvB	Marion, Illinois
Upper Wyodak	Subbituminous, Group C	Gillette, Wyoming

The fuel characterization included: particle size distribution, ultimate and proximate analyses of coal, ash composition, ash fusion temperature, and solids concentration. For rheological characteristics, data were obtained at varying shear rates, agitation, or recirculation in the bulk storage tanks. The effect of freeze-thaw on the stability and rheology of the CWF was also evaluated.

The bulk storage studies involved testing CWF stability characteristics with and without agitation or recirculation. Different tank configurations were tested by AMAX R&D. The residential CWF storage and handling tests were carried out in Tecogen's CWF-fired advanced combustor facilities.

Carnegie-Mellon University evaluated the atomization characteristics of the various atomizers as a function of coal type, formulation, and operating conditions.

Tecogen Inc., and its subcontractors were aware of the work previously carried out and currently under way in the formulation of CWF using beneficiated coal products as well as the data available in the public domain. No attempt was made to duplicate the work funded previously by DOE or through other research organizations such as EPRI.

2. WORK PERFORMED DURING THE SIXTH QUARTER

2.1 FUEL PREPARATION (TASK 2)

Preparation of the last CWF was completed in the fourth quarter. The ash properties and fusion temperatures of the CWFs were determined in this quarter. Tables 2.1 and 2.2 give the ash properties and general characteristics of the CWFs, respectively

2.2 BULK STORAGE (TASK 3)

Bulk storage is defined as the operation following the preparation of the CWFs and prior to transportation to user sites. There exists commonality between bulk and residential storage. Residential storage consists of storage of CWF at a smaller scale. In both cases, the main objective of storage is to maintain the CWFs in a fully suspended state or ready-to-use status. Two methods can be used to keep a CWF fully suspended: resuspension by mechanical agitation and/or chemical stabilization.

Tests under this task looked at CWF resuspension and chemical stabilization. Two hundred fifty (250) gallons of each slurry were used to prepare the samples. The 250 gallons consisted of four batches of each slurry ground by differing degrees. Particle size distributions were made on each batch and the batches were blended to give mass mean diameters of 9 μ m and 13 μ m with comparable size distributions.

2.2.1 Chemical Stabilization

Additional storage tests were completed on beneficiated Upper Elkhorn slurries containing 600 and 800 ppm of Flocon. Table 2.3 gives these results along with the other CWF characteristics. The Flocon additions listed in the table were also calculated to be on a slurry basis rather than on a coal basis so that they would be on the same basis as the A-23 additions in the table.

The results of all the chemical stabilization storage tests were examined. Slurries of each of the beneficiated test coals were formulated with two particle size distributions and varying additions of Flocon stabilizer and were stored for two months. The condition of the sediment in each of the containers was determined periodically and a rating was given concerning its resuspension properties. The best rating, 3, was assigned to slurries in which most of the sediment occurred as a soft-pack cake which could be resuspended very easily. The poorest rating, 0, was assigned to slurries in which a very hard-pack cake formed which was

TABLE 2.1
ASH PROPERTIES OF CWFs

Source Coal	Batch						
	A	B	C	D	E	F	G
	Illinois No. 6	Upper Wyodak	Upper Elkhorn	Upper Elkhorn	Upper Elkhorn	Illinois No. 6	Upper Elkhorn
Beneficiation:	HMS	HMS	HMS	HMS/Filtration	Chemical	Agglomeration	Froth Flotation
Coal Loading	54.5	42.2	54.1	54.2	53.8	53.0	54.6
Dry Ash, %	5.89	5.75	1.52	1.62	0.39	3.54	1.50
Ash Composition, %							
SiO ₂	44.58	16.82	39.39	40.18	21.27	31.53	36.35
Al ₂ O ₃	21.54	11.69	28.85	29.70	17.96	15.71	26.50
Fe ₂ O ₃	20.76	9.42	14.84	17.19	19.10	25.59	20.22
CaO	2.8	22.55	3.39	3.24	5.97	3.77	3.88
MgO	1.24	5.52	0.97	1.00	1.10	1.36	0.97
SrO	0.05	0.32	0.48	0.41	0.92	0.06	0.40
Na ₂ O	0.44	1.57	2.68	2.54	8.89	1.98	1.65
K ₂ O	2.49	0.70	1.09	1.12	0.86	2.37	1.73
TiO ₂	1.29	0.94	1.82	1.84	4.35	2.56	2.29
P ₂ O ₅	0.01	0.18	0.04	0.01	0.21	0.01	0.01
SO ₃	1.73	28.00	2.55	2.68	14.20	3.71	2.32
Ash Fusion Temperature, °F:							
Oxidizing Atmosphere:							
Initial	2494	2424	2403	2463	2482	2336	2498
Softening	2531	2430	2546	2577	2489	2461	2590
Hemispherical Fluid	2540	2435	2631	2602	2491	2501	2525
	2594	2443	2700+	2634	2505	2582	2700+
Reducing Atmosphere:							
Initial	2086	2404	2322	2269	2182	1942	2167
Softening	2108	2442	2387	2357	2185	1991	2317
Hemispherical Fluid	2245	2448	2625	2537	2188	2057	2500
	2442	2466	2700+	2631	2229	2437	2553

TABLE 2.2
PROPERTIES OF BENEFICIATED COAL WATER FUELS

	Illinois No. 5 Heavy Media Separated	Wyodak Heavy Media Separated	Upper Elkhorn No. 3 Heavy Media Separated	Upper Elkhorn No. 3 Heavy Media Separated and Filtered	Upper Elkhorn No. 3 Chemically Cleaned	Illinois No. 6 Oil Agglomeration	Upper Elkhorn No. 3 Froth Flotation
Fuel Analysis, %							
Coal	54.00	40.60	53.90	53.90	53.60	51.80	54.32
Water	45.55	57.78	45.87	45.81	46.18	47.03	45.43
Additives	0.45	1.62	0.23	0.29	0.22	1.17	0.25
Dry Coal Composition, %							
Ash	5.89	5.75	1.52	1.62	0.39	3.54	1.50
Volatile Matter	37.92	44.86	34.60	34.70	34.56	40.63	34.77
Sulfur	2.5	1	0.8	0.8	0.8	2.8	0.8
Fixed Carbon	53.69	49.39	63.08	62.88	64.75	53.03	62.93
Additives, % of Dry Coal							
A-23 Dispersant	0.83	4.00	0.37	0.47	0.043	2.20	0.47
Flocon Stabilizer	None	None	0.05	0.08	0.06	0.00	0.00
Fuel Viscosity, cP							
at 100 1/s	200	410	190	200	200	175	200
at 500 1/s	275	290	240	310	355	240	240
at 1,000 1/s	285	255	240	260	345	245	240
Mass Mean Diameter, Micrometers	11.4	17.0	12.1	13.2	12.0	10.3	10
Particle Size Distribution, % Passing							
75 Micrometers	99.8	95.4	99.7	99.7	99.63	99.71	99.73
45 Micrometers	98.7	93.2	98.2	98.3	97.93	99.57	98.47
30 Micrometers	95.7	87.7	93.1	93.9	93.18	99.34	94.69
20 Micrometers	86.9	74.4	83.2	81.6	86.53	97.28	86.52
10 Micrometers	53.0	51.8	55.2	47.9	52.31	53.12	58.96
4 Micrometers	38.3	29.7	28.2	22.6	23.97	22.36	27.48
1 Micrometer	5.1	5.2	2.8	2.7	2.68	2.30	3.74
Heat Value, Btu/lb							
Slurry	7,390	4,935	8,190	8,166	8,201	7,109	8,243
Dry Basis	13,572	11,688	15,131	15,070	15,238	13,421	15,105
Moisture and Ash-Free	14,089	12,401	15,365	15,318	15,298	13,914	15,335

TABLE 2.3

STABILITY OF SLURRIES CONTAINING ADDED CHEMICAL STABILIZER

Source	Batch	Beneficiation	Coal By Wt	MMD	Rosin-Rammler Parameters		Reagents, ppm		Viscosity, cP			2-Month Stability Rate
					n	k	A-23	Flocon	100 s ⁻¹	500 s ⁻¹	1000 s ⁻¹	
Wyodak	B	HMS	40.6	17.0	0.798	14.71	16200	0	410	290	255	3
Wyodak		HMS	35.8	12.6	1.002	12.23	7160	0	310	130	100	3
Wyodak		HMS	34.0	9.0	0.856	7.98	10200	0	325	130	100	3
Illinois 6	A	HMS	53.1	11.4	1.097	11.35	5310	0	200	275	285	1
Illinois 6		HMS	54.4	13.0	1.074	13.01	3910	0	200	280	280	2.5
Illinois 6		HMS	54.3	13.0	1.074	13.01	4450	100	200	340	370	2.5
Illinois 6		HMS	54.2	13.0	1.074	13.01	4710	200	200	300	280	2.5
Illinois 6		HMS	54.1	13.0	1.074	13.01	5100	400	220	260	260	3
Illinois 6		HMS	53.1	8.8	0.916	8.20	7530	0	200	250	260	3
Illinois 6		Agglom	51.8	10.3	1.195	12.60	11400	0	175	240	245	2
Illinois 6		Agglom	51.7	10.3	1.195	12.60	12410	100	200	360	330	3
Illinois 6		Agglom	51.4	10.3	1.195	12.60	13620	200	190	240	260	3
Up Elk		HMS	53.9	12.1	1.081	11.94	1990	500	190	240	240	0.5
Up Elk	C	HMS	54.6	13.0	1.083	12.88	1640	0	200	250	260	0
Up Elk		HMS	54.5	13.0	1.083	12.88	1770	100	200	250	255	0
Up Elk		HMS	54.5	13.0	1.083	12.88	1800	200	225	270	250	0
Up Elk		HMS	54.4	13.0	1.083	12.88	1850	400	250	300	320	0
Up Elk		HMS	54.3	13.0	1.083	12.88	2040	600	210		450	1.5
Up Elk		HMS	54.3	13.0	1.083	12.88	2200	800	200		435	2
Up Elk		HMS	54.5	9.0	0.933	8.45	2290	0	150	300	335	1
Up Elk		HMS	54.4	9.0	0.933	8.45	2290	100	180	295	275	2
Up Elk		HMS	54.4	9.0	0.933	8.45	2290	200	180	300	285	2
Up Elk		HMS	54.4	9.0	0.933	8.45	2340	400	200	300	300	3
Up Elk	D	HMS/FL	53.9	12.1	1.152	12.22	2530	800	200	310	260	1
Up Elk		HMS/FL	54.6	13.0	1.179	13.24	1800	0	200	270	280	0
Up Elk		HMS/FL	54.6	13.0	1.179	13.24	1990	100	210	280	240	0
Up Elk		HMS/FL	54.5	13.0	1.179	13.24	2070	200	200	300	255	0
Up Elk		HMS/FL	54.5	13.0	1.179	13.24	2210	400	240	255	255	0.5
Up Elk		HMS/FL	54.4	13.0	1.179	13.24	2390	600	210		510	0.5
Up Elk		HMS/FL	54.3	13.0	1.179	13.24	2550	800	190			1.5
Up Elk		HMS/FL	53.9	9.0	0.958	8.49	2700	0	190	330	340	2
Up Elk	E	Chemi	53.5	12.0	1.157	12.54	2300	600	200	355	345	1.5
Up Elk		Chemi	53.7	13.0	1.128	13.18	1660	0	200	285	270	0
Up Elk		Chemi	53.7	13.0	1.128	13.18	1770	100	200	260	260	0
Up Elk		Chemi	53.6	13.0	1.128	13.18	1820	200	210	300	280	0
Up Elk		Chemi	53.6	13.0	1.128	13.18	1980	400	220	380	380	0
Up Elk		Chemi	53.5	13.0	1.128	13.18	1980	600	185			1.5
Up Elk		Chemi	53.4	13.0	1.128	13.18	2220	800	200			2
Up Elk		Chemi	53.8	9.2	1.021	8.93	2850	0	220	480	535	1.5
Up Elk		Chemi	53.7	9.2	1.021	8.93	2980	100	225	450	600	2
Up Elk		Chemi	53.7	9.2	1.021	8.93	3060	200	275	560	530	3
Up Elk		Chemi	53.6	9.2	1.021	8.93	3220	400	200	420	460	3
Up Elk	G	Flotat	54.3	11.1	1.116	11.16	2530	0	200	240	240	2.5
Up Elk		Flotat	54.3	13.0	1.086	13.10	2530	0	210	300	340	2
Up Elk		Flotat	54.2	13.0	1.086	13.10	2660	100	200	240	2230	2
Up Elk		Flotat	54.2	13.0	1.086	13.10	2710	200	210	295	315	2
Up Elk		Flotat	54.1	13.0	1.086	13.10	2900	400	225	280	270	3
Up Elk		Flotat	53.4	9.9	1.091	10.02	3550	0	200	280	320	2
Up Elk		Flotat	53.4	9.9	1.091	10.02	3600	100	190	240	240	3
Up Elk		Flotat	53.3	9.9	1.091	10.02	3650	200	200	260	240	3
Up Elk		Flotat	53.2	9.9	1.091	10.02	3750	400	200	260	240	3
Up Elk		Flotat	53.2	9.9	1.091	10.02	3750	400	200	260	240	3

extremely difficult to resuspend. Table 2.4 gives a detailed breakdown of the rating system.

Adding Flocon (a xanthan gum) to a slurry formulation changed the properties of the sediment as it formed from a hard-pack type to a soft-pack type. A few slurries without Flocon remained easy to resuspend over the entire 2-month storage period, but most did not. All of the slurries that did form a hard-pack cake without Flocon benefitted from the addition of Flocon. The minimum amount of Flocon required for maintaining an easily resuspended soft-pack sediment for at least 2 months could be estimated from the storage data and was found to depend on the coal type beneficiation process and particle size distribution. Table 2.5 contains a summary of the chemical stabilization for 2-month storage test results.

Figures 2.1 to 2.11 are graphs of the stabilizer (Flocon) required to provide 2-month stabilization versus several different parameters. Figure 2.1 gives the stabilizer required for all the CWFs that were prepared with two (2) MMDs - 9 μm and 13 μm . The CWF with the smaller MMD, 9 μm , had better stability than the 13 μm -MMD CWFs. A comparison of the effect on source coal type can be seen from Figure 2.2. The lower ranked CWFs were inherently more stable. Wyodak, a low ranking subbituminous coal, required no stabilizer at all. The Illinois No. 6, a low ranking bituminous coal, required substantially less stabilizer for its 13 μm -MMD CWF than the Upper Elkhorn fuel and required none for the 9 μm -MMD grind. The effect of the beneficiation process on CWF stability can be seen from Figure 2.3, which is a plot of CWFs made with Upper Elkhorn No. 3 and cleaned by heavy separation, heavy media separation/filtered, chemical cleaning and froth flotation. The 9 μm -MMD CWFs cleaned by froth flotation and heavy media separated/filtered exhibited the best stability. The chemically cleaned CWF required about one half the amount of stabilizer for 2-month stability as that required by the heavy media separated CWF. Figure 2.4 gives a graph of the Flocon required for 2-month stability versus the Rosin-Rammler slope parameter, n. The Rosin-Rammler distribution is described by the following

$$\% \text{ PASSING} = 100 \left[1 - \exp \left(\frac{-x}{k} \right)^n \right]$$

where

- x = particle size, μm
- n = slope parameter
- k = size parameter

TABLE 2.4
STABILITY RATING
(Volume of Sediment Layer, %)

Stability Rating	Soft-Pack	Medium-Pack	Hard-Pack	Very Hard-Pack
3.0	>90	<10	<5	<5
2.5	any	10-35	<5	<5
2.0	any	>35	<10	<5
1.5	any	any	10-25	<10
1.0	any	any	>25	<10
0.5	any	any	any	10-25
0.0	any	any	any	>25

TABLE 2.5

SUMMARY OF CHEMICAL STABILIZATION 2-MONTH STORAGE TEST RESULTS

Note: Test slurries were blended to have the same nominally minus 45-micrometer top size but have the two different mass mean particle sizes.

Coal	Beneficiation	Amount of Flocon Required, ppm Coal	MMD, μm	Coal in Slurry		Viscosity cp	Mid-Size ^a Weight %	R-R "n" ^b	-2 μm Weight %	Calculated Specific Surface sq m/g
				Weight %	Volume %					
Upper Wyodak	HMS	0	12.6	35.8	43.6	310	41.6	1.002	15.83	1.261
Upper Wyodak	HMS	0	9.0	34.0	41.2	325	28.9	0.856	24.55	1.802
Illinois No. 6	HMS	400	13.0	54.1	51.7	220	46.2	1.074	13.06	1.114
Illinois No. 6	HMS	0	8.8	53.1	50.6	200	37.3	0.916	22.85	1.664
Illinois No. 6	Agglomeration	100	10.3	51.7	49.5	200	45.2	1.195	10.66	0.969
Upper Elkhorn	HMS	900 ^c	13.0	54.3	49.8	200	45.2	1.083	11.79	1.047
Upper Elkhorn	HMS	400	9.0	54.5	50.0	200	36.9	0.933	20.02	1.531
Upper Elkhorn	HMS/Filtration	1,000 ^c	13.0	54.3	49.7	190	49.5	1.179	9.90	0.968
Upper Elkhorn	HMS/Filtration	200 ^c	9.0	53.9	49.3	190	34.8	0.958	19.91	1.560
Upper Elkhorn	Chemical	900 ^c	13.0	54.3	50.1	200	46.8	1.128	10.57	0.972
Upper Elkhorn	Chemical	200	9.2	53.7	49.5	275	36.2	1.021	16.46	1.317
Upper Elkhorn	Flotation	400	13.0	54.1	49.7	225	47.0	1.086	11.13	0.997
Upper Elkhorn	Flotation	100	9.9	53.4	49.0	190	42.2	1.091	14.50	1.251

^aWeight % in particle size range approximately 50% of MMD (6 – 20 μm for 13.0 μm MMD and 5 – 15 μm MMD for 9.0 μm MMD coal).

^bSlope parameter in Rosin-Rammler particle size distribution.

^cEstimated amount required to obtain stability rating of 3 instead of 2 or 2.5 after 2 months.

Figure 2.1 Stabilizer Required to Provide 2-Month Stabilization for All Coals

Figure 2.2 Stabilizer Required to Provide 2-Month Stabilization by Source Coal

ppm Flocon Required for Stabilization
(Upper Elkhorn Only)

Figure 2.3 Stabilizer Required to Provide 2-Month Stabilization by Beneficiation Process

Figure 2.4 Stabilizer Required to Provide 2-Month Stabilization versus the Rosin-Rammler Slope Parameter by MMD

Figure 2.5 Stabilizer Required to Provide 2-Month Stabilization versus the Rosin-Rammler Slope Parameter by Source Coal

Figure 2.6 Stabilizer Required to Provide 2-Month Stabilization versus Weight Fraction in Mid-Range by MMD

Figure 2.7 Stabilizer Required to Provide 2-Month Stabilization versus Weight Fraction in Mid-Range by Source Coal

Figure 2.8 Stabilizer Required to Provide 2-Month Stabilization versus Calculated Specific Surface by MMD

Figure 2.9 Stabilizer Required to Provide 2-Month Stabilization versus Calculated Specific Surface by Source Coal

Figure 2.10 Stabilizer Required to Provide 2-Month Stabilization versus Weight Percent Under 2 μm by MMD

Figure 2.11 Stabilizer Required to Provide 2-Month Stabilization versus Weight Percent Under 2 μm by Source Coal

The slope parameter, n , indicates the particle size distribution. Low values of n indicate a wider distribution or the presence of more fines. Also, n , is generally similar for materials ground in a similar manner. The size parameter, k , changes depending on the degree of grinding. Figure 2.4 gives the amount of stabilizer needed for 2-month stability versus the Rosin-Rammler slope parameter, n , for the two MMDs that were used – 9 μm and 13 μm . As can be seen in the graph, the lower the slope parameter, n , the more stable the CWF. The wider distribution also implies a more bimodal size distribution. Figure 2.5 shows a similar plot for the three different source coals. Figures 2.6 and 2.7 show the stabilizer (Flocon) needed versus the weight fraction in the mid-range. The mid-range is defined as follows

For 9 μm MMD: 5 μm < mid-range < 15 μm

For 13 μm MMD: 6 μm < mid-range < 20 μm

The calculated specific surface is graphed with the 2-month stabilization required in Figures 2.8 and 2.9 by MMD and coal type, respectively. The figures show that the greater the specific surface, the better the stability. A larger specific area is indicative of smaller particle size. Figures 2.10 and 2.11 are graphs of stabilizer versus the weight percent of particles in the CWF that is under 2 μm . These plots indicate that the larger amounts of fines in the CWF increase their stability.

An effort was made to relate these minimum Flocon requirements to the properties of the coals and slurries by plotting the data in various ways and by regression analyses. The variables considered were weight loading, volume loading, viscosity, particle size distribution (mass mean diameter, weight fraction in mid-size range, calculated specific surface, Rosin-Rammler parameters, amount of minus 2 micrometer fines), coal rank (MAF volatile matter), A-23 dosage, and beneficiation method.

Of the variables considered, the coal rank, particle size distribution parameter, and one of the beneficiation methods showed any significant correlation with the amount of Flocon required to form a stable slurry. Slurries made from the beneficiated higher rank Upper Elkhorn coal required larger additions of Flocon than those made from the lower rank coals. The best correlations were obtained when using the mass mean diameter (MMD) as the particle size distribution parameter, and slurries formulated from 13.0- μm MMD coals required more Flocon than slurries formulated from 9.0- μm MMD coals. This is shown in Figure 2.12. Figure 2.12 also shows that slurries prepared from Upper Elkhorn coal cleaned by froth flotation required considerably less Flocon than did comparable slurries prepared from Upper Elkhorn coal cleaned either by HMS (heavy media separation) or chemical procedures. It did not appear that the amount of Flocon required when

Figure 2.12 Regression Analysis of Stabilizer Required to Obtain 2-Month Stability
(Heavy Lines Show Result of Regression Analysis)

Illinois No. 6 coal was cleaned by the Bechtel agglomeration process was much different from the amount that would be needed if the same coal were cleaned by HMS. A regression analysis of MMD, coal rank (i.e., volatile matter), and beneficiation was done to relate the amount of Flocon needed for 2-month stability. The following algorithm was determined.

$$\begin{aligned} \text{Required Flocon, ppm} = & 597.0(\text{MMD}) - 12.5(\text{MMD})(\text{VM}) - 256.6(\text{VM}) \\ & + 4.18(\text{VM})^2 + 2,719.8 - 415 F (\text{cleaning}) \end{aligned}$$

where:

F (cleaning) = 1 for froth flotation and 0 for other.

The ranges of coal loading and slurry viscosity observed in the data set were not large enough to allow detection of any influence that these variables might have on the stability of the fuel. The amount of A-23 added to each slurry in order to obtain a nominally 250-cP viscosity was too closely related to the rank of the coal for its effect to be distinguished from the effects of differing coal rank.

Table 2.6 lists the densities and some rank related properties of the test coals that were used when the correlations were made. It is interesting to observe that the calculated densities of ash-free water-saturated particles of the three coals were all about the same. (These calculations do not take into account any swelling that might occur when coal particles absorb water.)

The heavy media separation/filtration (HMS/filtration) sequence was included in the comparison of the beneficiation processes so that it could be determined whether washing certain metal ions from the coal would improve the dispersion and stability of the product slurries. As it turned out though, very little difference was observed between the properties of the Batch C (HMS) and Batch D (HMS/filtration) fuels and also between the blended HMS and HMS/filtered slurries during storage tests with and without chemical stabilization. This similarity is probably to be expected since the particle size distributions of the Batch C and D fuels and also the ion concentrations in the aqueous phase are very similar. The metal ion concentrations in Table 2.7 were determined by ICP spectroscopy on filtrates from the respective slurries. These data were for Upper Elkhorn coal. Certain other coals are known to contain soluble materials (such as sodium chloride and ferrous sulfate) which would be removed by such a filtration procedure.

TABLE 2.6
SIGNIFICANT PHYSICAL PROPERTIES OF BENEFICIATED COALS

Property	Upper Wyodak	Illinois No. 6	Upper Elkhorn
ASTM Rank	Subbituminous "C"	High Volatile Bituminous "C"	High Volatile Bituminous "A"
Volatile Matter, MAF %	47.6	40.3	35.2
Equilibrium Moisture, AF % ^a	29.73	7.32	2.14
Density Dry Coal, MAF g/cc	1.429	1.286	1.253
Estimated Pore Volume, Wet Coal, AF cc/cc	0.377	0.092	0.027
Calculated Density, Wet Coal, AF g/cc	1.267	1.260	1.246
Estimated Effective Density of Ash, g/cc	2.70	2.70	2.70

^aAt 96 to 98% relative humidity and 30°C.

MAF = Moisture and ash free.

AF = Ash free.

TABLE 2.7
CONCENTRATION OF COMMON ELEMENTS IN AQUEOUS PHASE
OF COAL SLURRY FUELS PREPARED FROM BENEFICIATED UPPER ELKHORN COAL

Element	Concentration, ppm	
	HMS	HMS/Filtered
Ag	<0.03	<0.03
Al	0.08	0.21
As	<0.01	<0.01
B	0.47	0.35
Ba	<0.05	<0.05
Bi	<0.01	<0.01
Ca	13	19
Cd	<0.005	<0.005
Co	0.01	0.01
Cr	<0.005	<0.005
Cu	0.09	0.04
Fe	0.02	0.01
K	17	12
Mg	2.3	2.8
Mn	0.03	0.07
Mo	0.77	0.27
Na	103	88
Ni	0.14	0.05
P	0.18	0.08
Pb	<0.05	<0.05
S	106	110
Sb	<0.01	<0.01
Se	<0.01	<0.01
Si	<0.77	<0.75
Sn	<0.02	<0.02
Sr	1.0	1.4
Ti	<0.01	<0.01
V	<0.01	<0.01
W	0.11	0.07
Zn	0.008	0.027
Zr	<0.01	<0.01

2.2.2 Mechanical Resuspension

The mechanical resuspension activities were divided into three parts:

Part 1 - investigate periodic agitation for maintaining slurry fuels in good condition.

Part 2 - investigate the effects of storage tank configuration on the ease of remixing the slurry fuel.

Part 3 - develop a recycling pumping strategy.

The basic parameters defined by these activities were used to design a specific program for comparing and optimizing the resuspension characteristics of slurries prepared from the various beneficiated coals.

Part 1

The first part of the mechanical resuspension task was to investigate a periodic agitation strategy for maintaining slurry fuels in good condition for use. Eight slurries were selected from those left from the chemical storage testing to represent those that settled to a hard-pack condition in one month (Type A) and those that settled to a medium-pack condition in one month (Type B). Four of the slurries contained Flocon and four did not. The individual remixing experiments were on 1-liter splits of the slurries stored in wide-mouth screw-cap plastic bottles. A laboratory stirrer with a three-blade propeller was used for remixing the samples (at 540 rpm).

The objective of these experiments was to determine whether the amount of residual hard-pack and very hard-pack sediment remaining after frequent and infrequent remixing schedules would increase with time over a 2-month storage period. A further objective was to determine whether frequent or infrequent remixing would have an effect on the rheology of the slurries.

The remixing schedules varied according to the previously observed stability of the slurries as follows:

Slurry	Remixing, Times per Month			
	Frequent	Intermediate	Infrequent	Control
Type A	21 ^a	4	2	0
Type B	8 ^b	4	1	0

^a5 per week.

^b2 per week.

The position of the mixer blade and mixing time were selected for the first remixing of each schedule so that the blade would clear any hard-pack sediment and suspend essentially all of the cake from the bottom of the container. Whenever possible, the same blade position and stirring time were used for subsequent remixings. In a few cases, it was necessary to raise the blade or extend the stirring time in order to adequately remix a sample. Six blade position/stirring time configurations were possible, as follows:

Configuration	Position, Inches from Bottom	Stirring Time, Minutes
0	Control, No Mixing	
1	1	1
2	1-1/2	1
3	2	3
4	3	4
5	3-1/2	12

The samples were probed after remixing and the thicknesses of the various consistencies of cake were recorded. These results are summarized in the tables in Appendix A. The depths of the combined hard-pack and very hard-pack cakes accumulated in the eight slurries after a 2-month exposure to the various remixing frequencies are charted in Appendix B. Cake depths are shown as percentages of the total slurry depth in the figures, and if the slurries were not remixed during storage, the combined hard-pack and very hard-pack sediments accounted for between 20 and 60 percent of the total slurry volume of these samples. In all cases, a weekly or more frequent remixing schedule (more than 4 times per month) reduced the sediment accumulation to less than 5 percent of the slurry volume, and for 6 of the 8 slurries, a biweekly or monthly remixing schedule would have accomplished the same result. There was only one case (Figure B.8) in which frequent remixing (8 or more times per month) rather than infrequent remixing resulted in the accumulation of more rather than less sediment.

Brief statistical tests were made on the storage data to determine whether cake accumulations could be correlated with slurry properties. One pattern found to be significant was a small increase in the accumulation of sediment with an increasing amount of Flocon in the slurry formulation. This is shown in Figure 2.13 for the Upper Elkhorn slurry samples which were remixed weekly. The pattern shown in Figure 2.13 may not be a true cause-and-effect relationship, however, since more Flocon may have been used in certain slurries than in others in order to overcome these same settling tendencies. Figure 2.13 also shows that the slurry prepared from Upper Elkhorn coal beneficiated by froth flotation was completely resuspended by a weekly remixing schedule, whereas sediment accumulated in slurries prepared from Upper Elkhorn coal beneficiated by the HMS, HMS/filtration, and chemical procedures.

The viscosities of selected samples were also determined at the conclusion of the 2-month program and are reported in Table 2.8. Most of the slurry samples had somewhat dilatant rheology over the shear rates investigated ($<1000 \text{ s}^{-1}$). The average of the viscosities of the four samples which did not contain Flocon is plotted versus shear rate in Figure 2.14, and the average of the viscosities of the four which did contain Flocon is plotted versus shear rate in Figure 2.15. In both cases, remixing seemed to reduce the apparent viscosity of the slurry, and the effect seemed to be more pronounced for the samples that contained Flocon. The reduction in viscosity amounted to about 15 percent for the latter set of measurements on slurries which had been remixed frequently.

Part 2

The second part of Task 3.2 was also completed. Part 2 was to determine a preferred configuration for fuel storage/mixing tanks and specifically for the tanks to be used for the scheduled comparisons among the seven batches of fuel prepared from beneficiated coals. The principal strategy considered assumed periodic resuspension with a mechanical stirring mixer, but slow-speed continuous mixing, air sparging, and recycle pumping alternatives were also studied.

These tests were done on 35- to 39-gallon lots of slurry, and the mechanical remixing configuration parameters were the following:

- Flat bottom and conical bottom tanks.
- Zero, two, and four baffles in the tank.
- Remixing at 245 and at 410 to 445 rpm.

Figure 2.13 Sediment Accumulated in Slurries Prepared from Beneficiated Upper Elkhorn Coal After 2 Months of a Weekly Remixing Schedule

TABLE 2.8

VISCOSITIES OF SELECTED SLURRIES AFTER 2 MONTHS OF PERIODIC REMIXING

		Viscosity, Centipoise		
Frequency of Remixing	Time per Month	100 s ⁻¹ Shear Rate	500 s ⁻¹ Shear Rate	1,000 s ⁻¹ Shear Rate
Upper Elkhorn HMS Coal, 13.0 μm MMD, 0.34% A-23, 0.04% Flocon				
No Remixing	0	360	480	500
Infrequent	2	260	390	410
Frequent	21	270	410	445
Upper Elkhorn HMS Coal, 9.0 μm MMD, 0.42% A-23, No Flocon				
No Remixing	0	100	340	475
Infrequent	1	105	345	475
Frequent	8	100	285	410
Upper Elkhorn HMS/Filtered Coal, 13.0 μm MMD, 0.405% A-23, 0.04% Flocon				
No Remixing	0	300	480	545
Infrequent	2	250	440	485
Frequent	21	240	400	465
Upper Elkhorn HMS/Filtered Coal, 13.0 μm MMD, 0.47% A-23, 0.08% Flocon				
No Remixing	0	280	460	520
Infrequent	1	285	415	460
Frequent	8	280	400	460
Upper Elkhorn Chemical Coal, 13.0 μm MMD, 0.34% A-23, 0.02% Flocon				
No Remixing	0	400	535	540
Infrequent	2	400	535	540
Frequent	21	300	465	480
Upper Elkhorn Chemical Coal, 9.2 μm MMD, 0.53% A-23, No Flocon				
No Remixing	0	200	580	765
Infrequent	1	185	550	740
Frequent	8	130	540	720
Illinois No. 6 HMS Coal, 13.0 μm MMD, 0.72% A-23, No Flocon				
No Remixing	0	480	440	450
Infrequent	1	480	435	440
Frequent	8	400	395	410
Upper Elkhorn Flotation Coal, 13.0 μm MMD, 0.466% A-23, No Flocon				
No Remixing	0	290	400	430
Infrequent	1	290	380	400
Frequent	8	290	385	410

Figure 2.14 Average Viscosities of Four Sample Slurries Which Did Not Contain Flocon

Figure 2.15 Average Viscosities of Four Samples Which Did Contain Flocon

The flat bottom and cone bottom tanks both had the same kind of ship-propeller-type mixer. Two types of slurry were used for the Part 2 comparisons - one prepared from HMS cleaned Upper Elkhorn coal and the other from chemically cleaned Upper Elkhorn coal. These slurries were selected because they were known to settle rather rapidly so testing could be accomplished in the shortest time.

The resuspension tests were made after the slurries had settled either overnight or over a weekend, and depending on the type of slurry and the settling time, the cake thickness of the sediments ranged between 0.9 and 5.5 inches. This amount of hard-pack or very hard-pack cake filled between 4 and 23 percent of the total depth of the slurry in the tank. The primary measured response was the length of time required for the mixer to fully resuspend the cake. The observed times ranged between 3.5 and 51 minutes. The current drawn by the mixer motors was also recorded so estimates could be made of the power draft and the amount of energy required to resuspend the sediment. These data are presented in Table 2.9.

The data in Table 2.9 were evaluated by averaging all test results for a specific condition. For example, all of the test results for sedimentation in a flat bottom tank were averaged, and the average compared to the average for all of the results for sedimentation in the cone bottom tank. The averages are presented in Table 2.10.

The summarized data in Table 2.10 show that both slurries, one with a poor stability rating and the other with a fair stability rating, required about the same amount of power for remixing. A much longer mixing time was needed, though, to resuspend the thicker cake from the slurry with the poor stability rating, so the energy consumption was much greater, even after adjustment for the differing thickness of the cake. On the other hand, increasing the speed of the mixer increased the power draft significantly, but the mixing time was reduced, so the energy consumption per inch of cake was little changed. Similarly, the data in Table 2.9 show that baffling and a flat bottom improved the effectiveness of the remixing.

The observations described above indicate that a flat bottom tank with four baffles is the preferred configuration when following a periodic remixing strategy. The mixer speed is relatively unimportant except that it might be less expensive to install a lower horsepower medium-speed mixer rather than a higher speed mixer.

Continuous slow-speed mixing was also investigated as a method for dealing with the natural tendency of coal slurries to separate. The same slurries, tanks, and mixers were used as for the periodic resuspension work described above.

TABLE 2.9
RESULTS OF MIXING TESTS FOR RESUSPENSION OF SEDIMENT

Slurry ^a	Configuration				Standing Time, Hours	Sediment Depth, Inches	Remixing			
	Tank ^b	No. of Baffles	Mixer ^c	Mixer, rpm			Estimated hp	Time, Minutes	Hp-hr/1,000 Gallons	Hp-hr/1,000 Gallons/Inch Sediment
A	F	0	1	245	17.5	2.0	0.123	35.00	1.844	0.92
A	F	0	1	445	17.5	2.0	0.361	14.25	2.196	1.10
A	F	2	1	245	17.5	2.0	0.132	10.00	0.566	0.28
A	F	2	1	445	17.5	2.0	0.361	10.00	1.541	0.77
A	F	4	1	245	17.5	2.0	0.132	9.50	0.538	0.27
A	F	4	1	445	17.5	2.0	0.370	8.00	1.264	0.63
A	F	4	1	445	65.5	4.5	0.370	11.50	1.818	0.40
B	C	0	2	245	17.5	0.9	0.121	10.00	0.575	0.66
B	C	0	2	445	17.5	0.9	0.372	5.25	0.930	1.06
B	C	2	2	245	17.5	0.9	0.130	5.75	0.357	0.41
B	C	2	2	445	17.5	0.9	0.382	4.50	0.818	0.93
B	C	4	2	245	17.5	0.9	0.130	4.25	0.264	0.30
B	C	4	2	445	17.5	0.9	0.391	3.50	0.652	0.75
B	C	4	2	245	65.5	2.5	0.130	9.25	0.574	0.23
A	C	0	1	245	17.5	2.0	0.205	51.00	4.478	2.24
A	C	0	1	410	17.5	2.0	0.370	19.00	3.003	1.50
A	C	2	1	245	17.5	2.0	0.205	25.00	2.195	1.10
A	C	2	1	410	17.5	2.0	0.370	15.50	2.450	1.23
A	C	4	1	245	17.5	2.0	0.215	26.50	2.430	1.22
A	C	4	1	410	17.5	2.0	0.370	15.00	2.371	1.19
A	C	4	1	410	65.5	5.5	0.205	27.00	2.371	0.43
A	C	4	1	410	65.5	5.5	0.370	18.00	2.845	0.52
B	F	0	2	245	17.5	0.9	0.217	6.75	0.699	0.80
B	F	0	2	410	17.5	0.9	0.391	4.75	0.885	1.01
B	F	2	2	245	17.5	0.9	0.217	4.50	0.466	0.53
B	F	2	2	410	17.5	0.9	0.391	2.00	0.372	0.43
B	F	4	2	245	17.5	0.9	0.237	3.00	0.338	0.39
B	F	4	2	410	17.5	0.9	0.391	1.75	0.326	0.37
B	F	4	2	245	65.5	1.5	0.227	5.50	0.595	0.40
B	F	4	2	410	65.5	1.5	0.391	2.25	0.419	0.28

^aType A Slurry = HMS cleaned Upper Elkhorn Coal, 16.3 μ m MMD, 55.0% coal, 250 cP at 100 s⁻¹, stability rating 0.5 at 65.5 hours.
 Type B Slurry = Chemically cleaned Upper Elkhorn Coal, 23.6 μ m MMD, 53.8% coal, 190 cP at 100 s⁻¹, stability rating 2.0 at 65.5 hours.

^bTank F = 22.5 inches in diameter, flat bottom.
 Tank F = 22.5 inches in diameter, cone bottom with 30-degree slope.

^cTwo 1/3-hp variable-speed mixer drives of the same model number.
 Both were equipped with 7-inch diameter ship-propeller-type blades set 7 inches above the bottom of the tanks.

TABLE 2.10
SUMMARIZED RESUSPENSION TEST RESULTS

Average Estimated Power Draft and Energy Consumptions				
Parameter	Operating Horsepower	Horsepower/ 1,000 Gallons	Horsepower- Hours/1,000 Gallons	Horsepower-Hours/ 1,000 Gallons/ Inch of Cake
Slurry Stability				
A. Poor	0.28	7.1	2.13	0.92
B. Fair	0.28	7.9	0.55	0.57
Mixer Speed				
245 rpm	0.17	4.7	1.14	0.70
410 – 445 rpm	0.37	9.9	1.52	0.79
Baffles				
None	0.27	7.3	1.83	1.16
2	0.27	7.4	1.10	0.71
4	0.28	7.6	1.02	0.63
Tank Bottom				
Flat	0.27	7.2	0.92	0.57
Cone	0.26	7.1	1.75	0.92

In this case, the measured response was the minimum mixer speed which prevented formation of a hard-pack sediment over a 17.5-hour period. The following observations were made:

Slurry	Tank Bottom	Baffles	Minimum rpm	Estimated Horsepower
A. Poor Stability	Cone	0	60	0.04
A. Poor Stability	Cone	4	90	0.05
B. Fair Stability	Flat	0	75	0.04
B. Fair Stability	Flat	4	90	0.05

The preferred tank configuration for a continuous agitation strategy appears to be different from the preferred configuration for periodic remixing strategy. It appears, for instance, that baffles impede the formation of vortex flow patterns which sweep sediment from the bottom of the tank during slow speed mixing. Also, a conical bottom appears to aid development of the favorable flow patterns for holding the coal in suspension. Power requirements are quite low (on the order of 1.8 hp per 1,000 gallons), but energy would be consumed around the clock rather than periodically.

Part 3

Pump recycling was next evaluated as an alternative method for preventing sedimentation. Two entry flow patterns and two flow rates were tried. The following data were obtained for the Type A poor stability slurry:

Entry Flow Pattern	Flow Rate, gpm	Turnover Ratio Tank, Volumes/Hour	Duration, Hours	Sediment, Inches
Vertical	4 to 5	6 to 8	1	0.50
Tangential	4 to 5	6 to 8	1	<0.25
Tangential	5 to 6	8 to 9	17.5	0.62
Tangential	5 to 6	8 to 9	72	2.75

It appears from these data that exceedingly high pumping rates are necessary to hold coal slurry in suspension (over at least 150 gpm per 1,000 gallons).

Recycle pumping was also attempted with the Type B fair-stability slurry, but a pump failure occurred and a portion of the slurry was lost.

Continuous and periodic air lifting and sparging were investigated as alternatives to mechanical mixers. No sediment buildup was seen during a 17.5-hour test with a continuous air flow, estimated at 60 cfm and 5 psi, from the bottom of the cone bottom tank. The change in slurry volume due to evaporation of water was monitored during this test, and the loss did not appear to be any greater than losses observed during mechanical mixing.

The time required to resuspend caked sediment by air sparging was also determined. These tests were done in the flat bottom tank using the Type B fair-stability slurry. Two configurations were used. In one configuration, the air inlet was at a fixed position through the bottom at the center line of the tank. A 1/2-inch pipe air lance was used from above in the other configuration, and the operator moved the tip as needed to break up and resuspend the cake. In both cases, the air flow was estimated to be approximately 80 cfm at 10 psi. The following data were gathered:

Configuration of Air Inlet	Settling Time, Hours	Cake, Inches	Time Needed to Resuspend	
			Minutes	Minutes/Inch Cake
Moving Lance	120	3.5	65	19
Moving Lance	17.5	1.5	21.5	14
Center Fixed	17.5	1.5	55 ^a	37 ^a
Center Fixed	17.5	1.5	85 ^b	57 ^b

^aAll but 1/4 inch of sediment at circumference of tank.

^bCake completely resuspended.

These data show the effectiveness of air lancing as a method for breaking up and resuspending coal slurry sediment. A movable lance approach is quite labor intensive, but the same effect can be obtained by multiple air entry points at the bottom of the tank. The inlets can be no farther apart than 22 inches to match the results of the center fixed inlet configuration listed above and need to be more closely spaced to match the results of the moving lance approach.

Water was added to the slurries as needed to replace the volume lost due to evaporation. Properties of the slurries were measured at the conclusion of the resuspension work for comparison with the original slurry. Unfortunately, useful

comparisons were available only for the Type A slurry because of the pump failure and loss of a portion of the Type B slurry. The comparisons are shown in Table 2.10.

2.3 RESIDENTIAL STORAGE (TASK 4)

In order to effectively store CWF's at a residential site, several issues must be addressed. They include slurry tank design, slurry stability, slurry resuspension, and effects of freeze/thaw cycles.

2.3.1 Tank Design

A storage tank concept utilizing a polyurethane liner was tested. A plastic bag was placed in a 5-gallon plastic bucket. Two bulkhead fittings were installed in the bottom of the tank as the inlet and outlet. The locking nut on the fitting sandwiched the liner to the tank wall to prevent leakage. A bypass line was used to circulate the slurry and keep it in suspension. A second pump metered the slurry to the combustor. In the program to develop an Integrated Emissions Control System for Residential CWS Furnace (Contract No. DE-AC22-89PC89804) there was some difficulty with the Illinois No. 6 CWF that was used. The slurry had a tendency to form a dry skin on the top surface. It was thought that the skin was being drawn into the suction line of the pump, causing blockage problems. The liner concept was used for the storage system to alleviate the problem. Using the lined tank prevented the slurry from forming a skin even when the slurry was left in the tank for prolonged periods of time (2 days). Some other difficulties arose with the Illinois No. 6 - heavy media separated slurry used. Apparently, the work done on the slurry by recirculation created a time-dependent problem of increasing the slurry viscosity (rheopectic) to the point of preventing the slurry from being delivered to combustor in the transfer line. A larger transfer line was installed (increased from 3/8 inch diameter to 1/2 inch diameter) to the atomizer from the metering pump. The difficulty with the slurry viscosity changing with time as the slurry recirculates indicates the importance of minimizing the amount of mechanical work put into the slurry.

A handling system, shown in Figure 2.16, is being constructed. The frame, control system, and tank for the storage/handling system were fabricated/assembled. The system is divided into two areas: the storage facility and the combustor. Typically, the distance between them will be 10 to 20 feet at a residential site. Two tank configurations were considered for use in the system. One design consists of a solid tank with a flexible liner that contains the slurry. The flexible polyurethane liner collapses as the level of slurry decreases and prevents evaporation of water from the slurry, preventing the slurry from drying on

Figure 2.16 Residential Slurry Storage and Handling System

the interior surfaces. However, in the collapsible bladder tank design a recirculating pump strategy would be required to maintain the slurry in suspension since using a mechanical mixer would be difficult. Using a mechanical stirrer would necessitate sealing the rotating shaft going through the liner material. This would be a cumbersome design. Also, since pump recycling may not be a viable approach because it requires relatively high pumping rates to maintain the slurry in suspension, the second approach of humidification is being considered. The volume above the free surface of the CWF is humidified to prevent the slurry coated on surfaces from drying out.

The following gives an explanation of the handling/storage system operation. A three-way valve at the bottom of the tank diverts the flow from the slurry tank or the flushing tank to the pump. The three-way valve is utilized to eliminate dead ends that would exist if two two-way valves were used which could get plugged with slurry. When slurry is to be delivered to the combustor, the slurry flows through the strainer, pump, then through an accumulator, and then to the atomizer. The accumulator is used to dampen the flow pulsations due to the peristaltic pump. During shutdown, the pump is deactivated and a short burst of water is used to flush the atomizer, which would quickly get plugged from slurry due to residual heat in the combustor drying the slurry. The slurry in the lines can remain there for some time before the lines have to be flushed. After an allotted time, the lines are flushed. Valve 1 is diverted to bring water from the flushing tank through the pump and flush the lines through valve 4 and then back to the flushing tank. Then the pump is reversed to empty the line of water so that at startup excess amounts of water do not enter the combustor. To resuspend the slurry using a pumping strategy, valve 2 is opened and valve 3 is closed and the slurry is recirculated within the storage tank. The storage facility will be tested with valves of different materials (PVC, brass, and stainless steel) to determine their reliability when used with CWF.

2.3.2 Mechanical Resuspension

The results obtained for mechanical resuspension for bulk storage (section 2.2.2) can be applied to residential storage as well. The investigation into the use of sensors to determine the onset of settling is continuing. By continually monitoring the status of the CWF suspension, mixing will be initiated at the appropriate time. This will reduce the use of the mixing system which will minimize both the electrical power consumption and the mechanical work into the CWF. Three sensors are being tested: ultrasonic, vibrating probe, and pressure transducers.

Panametrics Inc. provided several ultrasonic transducer configurations that were tested on a barrel of batch D slurry. The sensors were attached to the outside of the 55-gallon metal drum, but there was difficulty in producing a strong enough signal for the unit to respond. Two transducers were then fitted to the end of a long U-shaped tube and directly submerged into a barrel of slurry that had settled. The transducers were four inches apart. The transducers were placed in different locations in the barrel. The speed of sound across the four-inch gap was measured. The speed of sound was higher near the bottom of the tank in the sediment than at the top, which indicated that the ultrasonic transducers do distinguish between different CWF loadings (or densities). Panametrics fabricated two transducers specifically designed to be submerged. The submersible ultrasonic transducers were mounted in a jig to maintain the transducers parallel and at the desired distance apart (5 inches). The transducers will initially be tested in water before they are tested in CWF.

The vibrating probe was mounted in the 55-gallon barrel of batch D CWF. Tests showed that the probe senses only soft-pack, an extreme condition, even though it was set at its most sensitive level. There was difficulty in making settling measurements using pressure transducers due to blockage in the tubing. The connecting lines to the transducers were modified and more tests will be conducted.

2.3.3 Climatic Assessment

Two foot-long sections of polyethylene tubing were filled with the CWFs and then frozen. They were allowed to thaw and were then connected to a pump. The CWF pushed through the tubing was of a paste-like consistency which would be unacceptable in an actual handling system. A control sample with CWF that was not frozen flowed easily. Batches A through D were tested with the same result.

2.4 RESIDENTIAL HANDLING (TASK 5)

The required piping network used in a small-scale residential CWF furnace installation has several unique requirements. The system should be able to meter a highly viscous non-Newtonian fluid (CWF) to the atomizer in the combustor and flush the atomizer to prevent clogging. The work performed in this task identifies relevant issues in slurry handling for a residential application and builds a database for the design of such a system.

2.4.1 Transfer Line Evaluation

The alternative tube material testing was completed. Each length of material was tested separately. Upper Elkhorn No. 3 - heavy media separated (batch C)

CWF was pumped through each 3/8-inch-diameter tube made of different materials (copper, stainless steel, iron, Teflon, and polyethylene), and the pressure drop was measured. The viscosity of the CWF pumped into the tubes was adjusted using Flocon to obtain a viscosity of 150 cP at 80 1/s. Therefore, the use of the CWF with the same initial viscosity characteristics was assured. Figure 2.17 gives a plot of shear stress versus shear rate for each of the tube materials. In general, the points lie about the same line which describes the slurry characteristics. It can be concluded that the material does not have an effect on the shear stress (i.e., pressure drop). There was some variation in the shear rates in tubes due to slightly different inside diameters.

The pressure drop per unit length of the 3/8 inch straight line, 3/8 inch long radius elbow and 3/8 inch standard elbow versus flow rate for slurries A, C, D, and E are given in Figures 2.18, 2.19, 2.20, and 2.21, respectively. As can be seen from the plot, the pressure drop per unit length for the fittings and the straight section are about the same. As the flow rate increases, the deviation of the fitting pressure drops become larger, indicating that there may be some slight secondary flow effects. However, the entire transfer line could be treated as straight tubing.

Some transfer line measurements were retested to determine the repeatability of the data. In addition, measurements on a Brookfield viscometer were made to verify the results from the transfer line. Variations in the pressure drop from the original measurements were found. However, the viscometer measurements corresponded to the values obtained from the transfer line measurements. This showed that there had been some change in the slurry viscosity. It was determined the stabilizer (Flocon), a xanthum gum, underwent biological degradation. Xanthum is a polysaccharide gum derived by microbial fermentation. As such, this biopolymer is susceptible to biodegradation by the aerobic and anaerobic microbes commonly found in coal. Loss of stabilizer results in a loss of viscosity and stability.

The atomization quality of coal water slurry is an important factor in determining the combustion characteristics. It is well known that the viscosity of the slurry at high shear rates has a dominant effect on the size distribution of the atomized fuel droplets. The shear rates under atomization conditions are on the order of 10^5 sec^{-1} . A capillary viscometer is being constructed to measure the viscosity of the beneficiated CWFs at these high shear rates.

The experimental setup shown in Figure 2.22 consists of a cylindrical vessel 4 ft long and 2 in. in diameter. It was designed to operate at a maximum pressure of 2000 psi. One end of the vessel is connected to a nitrogen bottle which provides the pressure required to drive the CWF through the capillary tubes. The capillary

FUEL: UPPER ELKHORN, HMS

Figure 2.17 Investigation of Alternate Materials

Figure 2.18 Batch A - Pressure Drop versus Flow Rate

Figure 2.19 Batch C - Pressure Drop versus Flow Rate

Figure 2.20 Batch D - Pressure Drop versus Flow Rate

Figure 2.21 Batch E - Pressure Drop versus Flow Rate

Figure 2.22 Capillary Viscometer Setup

tubes that were used have a diameter of 0.070 inch. A pressure transducer is located upstream of the tube. The flow rate is measured using a Micro-Motion detector.

In order to determine the apparent viscosity at each shear rate, the pressure drop through two capillary tubes of different lengths will be obtained at the same flow rate. The pressure drop of the fully developed flow through the capillary tube will be determined by subtracting the pressure drop values for each tube, thereby eliminating the entrance effects. However, it would be extremely difficult to adjust the flow rate to be the same when measuring the pressure drop in each tube. Therefore, the following approach will be taken. The flow rate for various pressures will taken for each length. A curve fit will done yielding an expression for pressure as a continuous function of the flow rate. Therefore, at a single flow rate (shear rate) the pressure (shear stress) is found and the viscosity determined.

2.5 ATOMIZATION (TASK 6)

The shadowgraphs of the three atomizers were completed. Drawings of the three nozzles - Tecogen, Delavan, and Bete - are given in Figures 2.23, 2.24, and 2.25, respectively. The conditions under which the shadowgraphs were taken are given in Table 2.11.

Shadowgraphs of the Tecogen nozzle for water and for batches A, B, C, and D, are given in Figures 2.26 through 2.30, respectively. As can be seen, batch A atomizes slightly better than batches B, C, and D. These shadowgraphs were taken at a relatively high air/fuel ratio of 3. Shadowgraphs in Figures 2.31 and 2.32 show that good atomization takes place with the Tecogen nozzle at lower air/fuel ratios of 1.4 and 2.0 at the same liquid flow rate, 1.3 gph. Also, at higher liquid flow rates, 2.7 and 4.6 gph, the Tecogen nozzle gives excellent atomization with low air/fuel ratios, shown in Figures 2.33 through 2.36. The atomization at high flow rates with the Tecogen nozzle implies that it can be used for larger CWF combustors and has further upscaling possibilities.

The Tecogen nozzle did not exhibit any clogging tendencies with CWF. However, after the flow through the atomizer is terminated, a droplet is retained on the atomizer tip due the surface tension effects. In a hot combustor environment this droplet would dry out and clog the nozzle tip. However, this situation is easily alleviated by passing a small amount of water through the tip.

The Delavan nozzle shown in Figures 2.37 and 2.38 shows good atomization was achieved at reasonable air/fuel ratios. Operationally, the Delavan nozzle has some peculiarities. Since it works on an internally mixed/impingement concept,

Figure 2.23 Cutaway Drawing of Tecogen's CWF Fuel Atomizer

Figure 2.24 Cutaway of Bete's XA-EF Series

Figure 2.25 Delavan-Delta Nozzle

TABLE 2.11
CHANGES IN SLURRY PROPERTIES DURING RESUSPENSION ACTIVITIES

	Solids Loading, %	A-23, %	Viscosity, cP			Stability Rating
			100 s ⁻¹	500 s ⁻¹	1,000 s ⁻¹	
Type A						
Original	55.24	0.32	250	300	310	0.5
End of Testing	56.01	0.32	420	440	430	3.0
Add Water	55.24	0.32	300	340	345	3.0
Add A-23	55.24	0.34	200	280	310	0.0
Type B^a						
Original	53.88	0.16	190	215	215	2.0
End of Testing	51.57	0.16	190	175	175	2.0

^aSome sediment lost from Type B slurry during test program.

Figure 2.26 Tecogen Nozzle - Water
Water Flow Rate = 1.4 ml/sec
Air Pressure = 80 psia
Air/Liquid = 3.0

TF3-791

Figure 2.27 Tecogen Nozzle
Illinois No. 6 - HMS
CWF Flow Rate = 1.4 ml/sec
Air Pressure = 80 psia
Air/Fuel = 3.0

TF4-791

Figure 2.28 Tecogen Nozzle - Wyodak
CWF Flow Rate = 1.4 ml/sec
Air Pressure = 80 psia
Air/Fuel = 3.0

Figure 2.29 Tecogen Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 1.4 ml/sec
Air Pressure = 80 psia
Air/Fuel = 3.0

Figure 2.30 Tecogen Nozzle
Upper Elkhorn - HMS/Filtered
CWF Flow Rate = 1.4 ml/sec
Air Pressure = 80 psia
Air/Fuel = 3.0

TF52-691

Figure 2.31 Tecogen Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 1.4 ml/sec
Air Pressure = 65 psi
Air Fuel = 2.0

Figure 2.32 Tecogen Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 1.4 ml/sec
Air Pressure = 50 psi
Air/Fuel = 1.4

TF54-691

Figure 2.33 Tecogen Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 2.8 ml/sec
Air Pressure = 65 psi
Air/Fuel = 0.9

Figure 2.34 Tecogen Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 4.5 ml/sec
Air Pressure = 35 psi
Air/Fuel = 0.40

Figure 2.35 Tecogen Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 4.5 ml/sec
Air Pressure = 50 psi
Air/Fuel = 0.60

Figure 2.36 Tecogen Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 4.5 ml/sec
Air Pressure = 80 psi
Air/Fuel = 0.80

TF58-691

Figure 2.37 Delavan Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 1.6 ml/sec
Air Pressure = 50 psi
Air/Fuel = 0.9

Figure 2.38 Delavan Nozzle
Upper Elkhorn - HMS
Liquid Flow Rate = 2.46 ml/sec
Air Pressure = 50 psi
Air/Fuel = 0.6

the air and liquid pressures must be properly balanced with the mixing chamber. At times the nozzle that was tested underwent some transient behavior before atomization occurred in a steady fashion. Also, when the air was turned off the slurry backed up into the air inlet and caused a blockage in the passage. Therefore, when the Delavan nozzle is not in use, the nozzle should be flushed with water and a small amount of air purged through the system.

The Bete nozzle shadowgraphs are shown in Figures 2.39 and 2.40. Atomization using the Bete nozzle was good; however severe clogging problems were encountered due to the extremely small liquid passage.

Particle size measurements for the batch C CWF were taken for the Tecogen atomizer. The results are shown in Table 2.12. The mean size for water was approximately 16 μm , whereas for slurry C was under the mean size of 200 μm at a location of 7.6 cm from the nozzle tip. The Tecogen solid cone atomizer presents a flat particle size distribution, as shown in Figure 2.41.

Figure 2.39 Bete Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 2.7 ml/sec
Air Pressure = 22 psi
Air/Fuel = 0.2

Figure 2.40 Bete Nozzle
Upper Elkhorn - HMS
CWF Flow Rate = 1.4 ml/sec
Air Pressure = 14 psi
Air/Fuel = 0.4

TABLE 2.12
PARTICLE SIZE MEASUREMENTS

Nozzle	Liquid	Axial Location (cm)	Liquid Flow Rate (ml/s)	Fuel/Air Mass Ratio	Planar SMD (microns)
A	Water	7.62	1.4	0.3	11.47
A	Water	10.16	1.4	0.3	11.38
A	Slurry C	7.62	1.4	0.3	208.59
A	Slurry C	10.16	1.4	0.3	246.25
A	Slurry C	10.16	0.7	0.3	362.05

Figure 2.41 Droplet Size Distribution of Water from Nozzle A
Water Flow Rate = 1.4 ml/s, $F/A = 0.3$

3. SUMMARY STATUS ASSESSMENT AND FORECAST

Ash fusion temperatures and properties of the CWFs were determined. Bulk storage (chemical stabilization and mechanical resuspension) testing and interpretation of results were completed. Mechanical resuspension included periodic and continuous agitation for maintaining slurry fuels, effects of storage tank configurations, and pump recycling. Testing with different tube materials exhibited similar pressure drop characteristics. Two residential tank designs, collapsible liner and humidification, were tested and showed positive results in preventing the CWF from drying on coated surfaces. Results from investigations into the effects of freeze/thaw cycles in tubes showed that the CWFs should not be allowed to freeze. Several were tested to determine the onset of slurry settling: ultrasonic, vibrating probe, and pressure transducers. The ultrasonic sensor showed the best results in determining CWF settling. Atomization testing was completed. Further print processing and interpretation of the atomization results will be done. A capillary viscometer was constructed to measure the viscosity characteristics at high shear rates comparable to those experienced in CWF atomizers. Construction of a demonstration handling/storage system was initiated.

Remaining work includes the following.

- Cost analysis of a residential handling/storage system.
- Burning the seven beneficiated CWFs in the residential combustor developed under contract DE-AC22-87PC79650.
- Testing of the demonstration handling/storage system.
- Capillary viscometer measurements.

APPENDIX A

DATA ON PERIODIC REMIXING ON STABILITY

TABLE A.1

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type A: Upper Eikhorn HMS Coal, 13.0 μ m MMD, 0.34% A-23, 0.04% Flocon

Storage Time	Mixing Configuration	Cake Thickness, Inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	5-3/16	0	5/16	1/8
2 Weeks	0	4-13/16	3/16	1/4	3/8
3 Weeks	0	4-3/8	5/16	3/8	9/16
4 Weeks	0	4-1/16	1/2	3/8	11/16
1 Month	0	3-13/16	11/16	3/8	3/4
5 Weeks	0	3-7/8	7/16	5/16	1
6 Weeks	0	3-1/8	3/4	7/16	1-5/16
7 Weeks	0	2-5/8	13/16	9/16	1-5/8
8 Weeks	0	2-9/16	11/16	7/16	1-15/16
2 Months	0	2-11/16	3/8	9/16	2
Remix 5 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-9/16	0	0	1/16
5 Weeks	1	5-9/16	0	0	1/16
6 Weeks	1	5-1/2	0	0	1/8
7 Weeks	1	5-1/2	0	0	1/8
8 Weeks	1	5-1/2	0	0	1/8
2 Months	1	5-1/2	0	0	1/8
Remix 2 Times per Week					
1 Week	1	5-9/16	0	0	1/16
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-9/16	0	0	1/16
5 Weeks	1	5-1/2	0	0	1/8
6 Weeks	1	5-7/16	0	0	3/16
7 Weeks	1	5-7/16	0	0	3/16
8 Weeks	1	5-7/16	0	0	3/16
2 Months	1	5-3/8	0	0	1/4
Remix 1 Time per Week					
1 Week	1	5-9/16	0	0	1/16
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-1/2	0	0	1/8
4 Weeks	1	5-1/2	0	0	1/8
5 Weeks	1	5-1/2	0	0	1/8
6 Weeks	1	5-7/16	0	0	3/16
7 Weeks	1	5-7/16	0	0	3/16
8 Weeks	1	5-3/8	0	0	1/4
Remix Every 2 Weeks					
2 Weeks	4	5-5/8	0	0	0
4 Weeks	4	5-1/2	0	0	1/8
6 Weeks	4	5-1/2	0	0	1/8
8 Weeks	4	5-3/8	0	0	1/4

TABLE A.2

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type B: Upper Elkhorn HMS Coal, 9.0 μ m MMD, 0.42% A-23, No Flocon

Storage Time	Mixing Configuration	Cake Thickness, Inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	5-3/8	1/8	1/8	0
2 Weeks	0	4-5/8	1/2	3/8	1/8
3 Weeks	0	4-3/8	5/8	1/2	1/8
4 Weeks	0	3-1/2	1	1/2	5/8
1 Month	0	3-5/16	15/16	3/4	5/8
5 Weeks	0	3-1/16	13/16	11/16	1-1/16
6 Weeks	0	2-3/8	9/16	5/8	2-1/16
7 Weeks	0	2-1/8	0	15/16	2-9/16
8 Weeks	0	1-7/16	0	1-3/16	3
2 Months	0	1-1/8	0	1-3/16	3-5/16
Remix 2 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-9/16	0	0	1/16
5 Weeks	1	5-9/16	0	0	1/16
6 Weeks	1	5-9/16	0	0	1/16
7 Weeks	1	5-1/2	0	0	1/8
8 Weeks	1	5-1/2	0	0	1/8
2 Months	1	5-1/2	0	0	1/8
Remix 1 Time per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
5 Weeks	1	5-1/2	0	0	1/8
6 Weeks	1	5-9/16	0	0	1/16
7 Weeks	1	5-1/2	0	0	1/8
8 Weeks	1	5-1/2	0	0	1/8
Remix Every 2 Weeks					
2 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-9/16	0	0	1/16
6 Weeks	1	5-1/2	0	0	1/8
8 Weeks	1	5-1/2	0	0	1/8
Remix 1 Time per Month					
1 Month	5	5-1/2	0	0	1/8
2 Months	5	5-1/4	0	0	3/8

TABLE A.3

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type A: Upper Eikhorn HMS/Filtered Coal, 13.0 μ m MMD, 0.405% A-23, 0.04% Floccon

Storage Time	Mixing Configuration	Cake Thickness, Inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	5-1/4	1/8	3/16	1/16
2 Weeks	0	4-7/8	5/16	1/8	5/16
3 Weeks	0	4-9/16	1/4	3/8	7/16
4 Weeks	0	4-3/16	1/2	5/16	5/8
1 Month	0	4-3/16	7/16	5/16	11/16
5 Weeks	0	3-7/8	9/16	7/16	3/4
6 Weeks	0	3-9/16	9/16	3/8	1-1/8
7 Weeks	0	3-3/16	7/16	11/16	1-5/16
8 Weeks	0	2-7/8	5/8	7/16	1-11/16
2 Months	0	2-7/8	9/16	1/2	1-11/16
Remix 5 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-9/16	0	0	1/16
5 Weeks	1	5-1/2	0	0	1/8
6 Weeks	1	5-9/16	0	0	1/16
7 Weeks	1	5-9/16	0	0	1/16
8 Weeks	1	5-1/2	0	0	1/8
2 Months	1	5-1/2	0	0	1/8
Remix 2 Times per Week					
1 Week	1	5-9/16	0	0	1/16
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-9/16	0	0	1/16
5 Weeks	1	5-9/16	0	0	1/16
6 Weeks	1	5-9/16	0	0	1/16
7 Weeks	1	5-7/16	0	0	3/16
8 Weeks	1	5-3/8	0	0	1/4
2 Months	1	5-7/16	0	0	3/16
Remix 1 Time per Week					
1 Week	1	5-9/16	0	0	1/16
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-1/2	0	0	1/8
4 Weeks	1	5-1/2	0	0	1/8
5 Weeks	1	5-7/16	0	0	3/16
6 Weeks	1	5-1/2	0	0	1/8
7 Weeks	1	5-7/16	0	0	3/16
8 Weeks	1	5-7/16	0	0	3/16
Remix Every 2 Weeks					
2 Weeks	3	5-5/8	0	0	0
4 Weeks	3	5-1/2	0	0	1/8
6 Weeks	3	5-7/16	0	0	3/16
8 Weeks	3	5-3/8	0	0	1/4

TABLE A.4

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type B: Upper Elkhorn HMS/Filtered Coal, 13.0 μ m MMD, 0.47% A-23, 0.08% Flocon

Storage Time	Mixing Configuration	Cake Thickness, Inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	5-3/8	3/16	0	1/16
2 Weeks	0	5-1/16	3/8	1/8	1/16
3 Weeks	0	4-15/16	7/16	1/8	<1/8
4 Weeks	0	4-15/16	3/8	1/8	3/16
1 Month	0	4-15/16	3/8	1/8	3/16
5 Weeks	0	4-3/4	7/16	3/16	1/4
6 Weeks	0	3-3/4	1-1/8	3/8	3/8
7 Weeks	0	4-7/16	7/16	5/16	7/16
8 Weeks	0	4-3/16	5/8	1/4	9/16
2 Months	0	3-15/16	9/16	9/16	9/16
Remix 2 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-1/2	0	0	<1/8
5 Weeks	1	5-1/2	0	0	<1/8
6 Weeks	1	5-7/16	0	0	3/16
7 Weeks	1	5-7/16	0	0	3/16
8 Weeks	1	5-7/16	0	0	3/16
2 Months	1	5-7/16	0	0	3/16
Remix 1 Time per Week					
1 Week	1	5-9/16	0	0	1/16
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-1/2	0	0	1/8
4 Weeks	1	5-1/2	0	0	1/8
5 Weeks	1	5-7/16	0	0	3/16
6 Weeks	1	5-7/16	0	0	3/16
7 Weeks	1	5-3/8	0	0	1/4
8 Weeks	1	5-3/8	0	0	1/4
Remix Every 2 Weeks					
2 Weeks	1	5-9/16	0	0	1/16
4 Weeks	2	5-7/16	0	0	3/16
6 Weeks	2	5-5/16	0	0	5/16
8 Weeks	2	5-1/16	0	0	9/16
Remix 1 Time per Month					
1 Month	2	5-3/16	0	0	7/16
2 Months	2	4-5/8	0	0	1

TABLE A.5

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type A: Upper Eikhorn Chemical Coal, 13.0 μ m MMD, 0.34% A-23, 0.02% Flocon

Storage Time	Mixing Configuration	Cake Thickness, Inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	4-13/16	5/16	3/8	1/8
2 Weeks	0	4-1/4	3/8	7/16	9/16
3 Weeks	0	3-7/16	11/16	9/16	15/16
4 Weeks	0	2-3/4	1-5/16	3/4	1-3/16
1 Month	0	2-15/16	9/16	11/16	1-7/16
5 Weeks	0	2-3/8	3/4	13/16	1-11/16
6 Weeks	0	1-5/8	13/16	9/16	2-5/8
7 Weeks	0	1-5/8	0	13/16	3-3/16
8 Weeks	0	1-11/16	0	1/2	3-7/16
2 Months	0	1-5/8	0	1/4	3-3/4
Remix 5 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-9/16	0	0	1/16
5 Weeks	1	5-9/16	0	0	1/16
6 Weeks	1	5-1/2	0	0	1/8
7 Weeks	1	5-1/2	0	0	1/8
8 Weeks	1	5-1/2	0	0	1/8
2 Months	1	5-1/2	0	0	1/8
Remix 2 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-1/2	0	0	1/8
5 Weeks	1	5-1/2	0	0	1/8
6 Weeks	1	5-7/16	0	0	3/16
7 Weeks	1	5-7/16	0	0	3/16
8 Weeks	1	5-7/16	0	0	3/16
2 Months	1	5-7/16	0	0	3/16
Remix 1 Time per Week					
1 Week	2	5-5/8	0	0	0
2 Weeks	3	5-5/8	0	0	0
3 Weeks	3	5-9/16	0	0	1/16
4 Weeks	3	5-1/2	0	0	1/8
5 Weeks	3	5-7/16	0	0	3/16
6 Weeks	3	5-7/16	0	0	3/16
7 Weeks	3	5-1/2	0	0	1/8
8 Weeks	3	5-7/16	0	0	3/16
Remix Every 2 Weeks					
2 Weeks	5	5-5/8	0	0	0
4 Weeks	5	5-9/16	0	0	1/16
6 Weeks	5	5-3/8	0	0	1/4
8 Weeks	5	5-1/2	0	0	1/8

TABLE A.6

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type B: Upper Elkhorn Chemical Coal, 9.2 μ m MMD, 0.53% A-23, No Flocon

Storage Time	Mixing Configuration	Cake Thickness, Inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	5-7/16	0	1/8	1/16
2 Weeks	0	4-7/8	3/8	5/16	1/16
3 Weeks	0	4-7/16	5/8	5/16	1/4
4 Weeks	0	4-5/16	3/8	7/16	1/2
1 Month	0	4-3/16	1/2	3/8	9/16
5 Weeks	0	3-3/16	1/2	5/16	1
6 Weeks	0	3	13/16	9/16	1-1/4
7 Weeks	0	2-13/16	11/16	1/2	1-5/8
8 Weeks	0	2-5/8	3/4	1/2	1-3/4
2 Months	0	2-7/16	3/4	1/2	1-15/16
Remix 2 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
1 Month	1	5-9/16	0	0	1/16
5 Weeks	1	5-9/16	0	0	1/16
6 Weeks	1	5-1/2	0	0	1/8
7 Weeks	1	5-1/2	0	0	1/8
8 Weeks	1	5-1/2	0	0	1/8
2 Months	1	5-1/2	0	0	1/8
Remix 1 Time per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-9/16	0	0	1/16
3 Weeks	1	5-9/16	0	0	1/16
4 Weeks	1	5-9/16	0	0	1/16
5 Weeks	1	5-1/2	0	0	1/8
6 Weeks	1	5-1/2	0	0	1/8
7 Weeks	1	5-1/2	0	0	1/8
8 Weeks	2	5-7/16	0	0	3/16
Remix Every 2 Weeks					
2 Weeks	1	5-5/8	0	0	0
4 Weeks	2	5-9/16	0	0	1/16
6 Weeks	2	5-7/16	0	0	3/16
8 Weeks	3	5-3/8	0	0	1/4
Remix 1 Time per Month					
1 Month	3	5-7/16	0	0	3/16
2 Months	3	5-5/16	0	0	5/16

TABLE A.7

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type B: Illinois No. 6 HMS Coal, 13.0 μ m MMD, 0.72% A-23, No Flocon

Storage Time	Mixing Configuration	Cake Thickness, Inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	5-9/16	1/16	0	0
2 Weeks	0	5-1/2	1/8	0	0
3 Weeks	0	5-3/16	7/16	0	0
4 Weeks	0	4-7/8	5/16	7/16	0
1 Month	0	4-11/16	1/4	11/16	0
5 Weeks	0	3-3/4	1	3/4	1/8
6 Weeks	0	1	3-5/16	1/2	13/16
7 Weeks	0	1-11/16	2-1/2	1/2	15/16
8 Weeks	0	2-7/8	1-1/4	1/2	1
2 Months	0	3	13/16	5/8	1-3/16
Remix 2 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-9/16	0	1/16	0
1 Month	1	5-9/16	0	1/16	0
5 Weeks	1	5-1/2	0	1/8	0
6 Weeks	1	5-1/2	0	1/8	0
7 Weeks	1	5-9/16	0	0	1/16
8 Weeks	1	5-7/16	0	3/16	0
2 Months	1	5-7/16	0	3/16	0
Remix 1 Time per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-9/16	0	1/16	0
5 Weeks	1	5-1/2	0	1/8	0
6 Weeks	1	5-1/2	0	1/8	0
7 Weeks	1	5-1/2	0	1/8	0
8 Weeks	1	5-1/2	0	0	1/8
Remix Every 2 Weeks					
2 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-9/16	0	1/16	0
6 Weeks	1	5-1/2	0	1/8	0
8 Weeks	1	5-7/16	0	1/8	1/16
Remix 1 Time per Month					
1 Month	1	5-5/8	0	0	0
2 Months	1	5-1/16	0	9/16	0

TABLE A.8

EFFECTS OF PERIODIC REMIXING ON STABILITY OF SLURRY FUEL
 Type B: Upper Elkhorn Flotation Coal, 13.0 μ m MMD, 0.466% A-23, No Flocon

Storage Time	Mixing Configuration	Cake Thickness, inches			
		Soft Pack	Medium Pack	Hard Pack	Very Hard Pack
No Remixing					
1 Week	0	5-5/8	0	0	0
2 Weeks	0	5-3/8	1/4	0	0
3 Weeks	0	5-3/16	7/16	0	0
4 Weeks	0	3-7/8	1-3/4	0	0
1 Month	0	3-7/8	1-3/4	0	0
5 Weeks	0	1/2	5-1/8	0	0
6 Weeks	0	1/2	4-1/4	7/8	0
7 Weeks	0	1-1/4	2	2-3/8	0
8 Weeks	0	15/16	3	15/16	3/4
2 Months	0	7/8	2-1/8	1-3/16	1-7/16
Remix 2 Times per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-5/8	0	0	0
1 Month	1	5-1/2	1/8	0	0
5 Weeks	1	5-1/2	1/8	0	0
6 Weeks	1	5-7/16	3/16	0	0
7 Weeks	1	5	5/8	0	0
8 Weeks	1	5-7/16	0	3/16	0
2 Months	1	5-5/16	0	5/16	0
Remix 1 Time per Week					
1 Week	1	5-5/8	0	0	0
2 Weeks	1	5-5/8	0	0	0
3 Weeks	1	5-5/8	0	0	0
4 Weeks	1	5-5/8	0	0	0
5 Weeks	1	5-7/16	3/16	0	0
6 Weeks	1	5-3/8	1/4	0	0
7 Weeks	1	5-1/2	0	1/8	0
8 Weeks	1	5-7/16	3/16	0	0
Remix Every 2 Weeks					
2 Weeks	1	5-5/8	0	0	0
4 Weeks	5	5-1/8	1/2	0	0
6 Weeks	5	5-1/2	1/8	0	0
8 Weeks	5	5-5/8	0	0	0
Remix 1 Time per Month					
1 Month	5	5-5/8	0	0	0
2 Months	5	5-5/8	0	0	0

APPENDIX B

PLOTS OF HARD-PACK DEPTHS FOR VARIOUS REMIXING FREQUENCIES

Figure B.1 Type A Upper Elkhorn HMS Slurry Residual Hard Pack and Very Hard Pack Cake Depths

Figure B.2 Type B Upper Elkhorn HMS Slurry Residual Hard Pack and Very Hard Pack Cake Depths

Figure B.3 Type A Upper Elkhorn HMS/Filtration Slurry Residual Hard Pack and Very Hard Pack Cake Depths

Figure B.4 Type B Upper Elkhorn HMS/Filtration Slurry Residual Hard Pack and Very Hard Pack Cake Depths

Figure B.5 Type A Upper Elkhorn Chemical Slurry Residual Hard Pack and Very Hard Pack Cake Depths

Figure B.6 Type B Upper Elkhorn Chemical Slurry Residual Hard Pack and Very Hard Pack Cake Depths

Figure B.7 Type B Illinois No. 6 HMS Slurry Residual Hard Pack and Very Hard Pack Cake Depths

Figure B.8 Type B Upper Elkhorn Flotation Slurry Residual Hard Pack and Very Hard Pack Cake Depths

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