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Research Article

Relationship between Particle Size Distribution of Low-Rank Pulverized Coal and Power Plant Performance

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The impact of particle size distribution (PSD) of pulverized, low rank high volatile content Alaska coal on combustion related power plant performance was studied in a series of field scale tests. Performance was gauged through efficiency (ratio of megawatt generated to energy consumed as coal), emissions (SO_2, NO_x, CO), and carbon content of ash (fly ash and bottom ash). The study revealed that the tested coal could be burned at a grind as coarse as 50% passing 76 microns, with no deleterious impact on power generation and emissions. The PSD's tested in this study were in the range of 41 to 81 percent passing 76 microns. There was negligible correlation between PSD and the followings factors: efficiency, SO_2, NO_x, and CO. Additionally, two tests where stack mercury (Hg) data was collected, did not demonstrate any real difference in Hg emissions with PSD. The results from the field tests positively impacts pulverized coal power plants that burn low rank high volatile content coals (such as Powder River Basin coal). These plants can potentially reduce in-plant load by grinding the coal less (without impacting plant performance on emissions and efficiency) and thereby, increasing their marketability.

1. Introduction

Despite containing an estimated 5 trillion tons of a variety of coal [1], Alaska has only one operating coal mine, the Usibelli Coal Mine. The low-rank, high-volatile content coal produced by the mine has a low grindability, as indicated by its hardgrove grindability index (HGI). This can be an issue for the salability of the coal since power plants prefer coals that are easy to grind. A possible mitigation for the low grindability is less grinding, if the coal could be burned at a coarser grind without impacting power plant performance.

The rank and volatility of the coal are key to combustion. As many researchers agree, the lower the rank of coal, the more reactive it is [2–4]. The authors in [5] also found that rank influenced combustion properties of pulverized coal more than the maceral composition. In addition to the rank, [6] found that the quantity of volatile matter also impacted the ignition of the volatile matter, though there was no correlation between the actual content of the volatile matter and the ignition behavior [4, 7]. Additionally and directly relevant to this paper are the findings by [8, 9], who studied pulverized coal combustion of the low-rank high-volatile UCM coal to explore if it could be burned at a coarser particle size distribution (PSD) than the industry standard of 65–70% passing 76 microns (200 mesh). Both reported encouraging results. In this paper, the PSD is quoted in percentage passing 76 microns (200 mesh), similar to what is done in the power industry.

The preliminary study by [9] preceded the more detailed tests conducted for this paper. His study consisted of two tests, one at an average PSD of 42% and the other at an average PSD of 49%. Each test in the preliminary study resulted in 24 samples (six samples per pipe—description in the next section); thus, the reported PSDs were averages of 24 samples. Multiple PSD samples were taken (according to the ASTM D-197 method) in each of the 3 hr long tests. The test (major details from [9] are reproduced below for helping the reader) showed that there was no difference in electricity generation (in megawatts or MW). Following the proof of concept that the coal could be burned at coarser PSD without loss in power generation, a detailed study was undertaken to include important aspects such as repeatability of results,

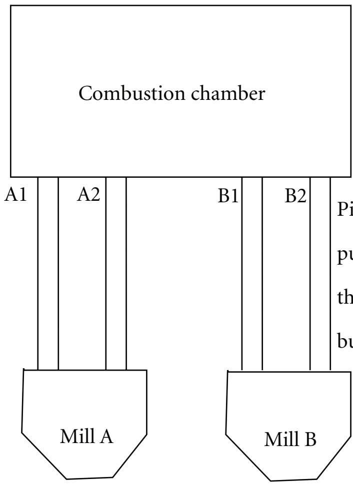

Figure 1: Mill (pulverizer) and combustion chamber layout (after [2]).

impact of quality of feed coal, impact on emissions, and carbon content of fly ash and bottom ash. This paper presents the results of the detailed tests. Note that additional information and data from the tests can be obtained from a publicly available report [10]. The implications of the study are important; though Alaska low-rank coal is burnt in very few plants, similar coals (such as those burning coals Powder River Basin in the United States) are burned in a significant number of plants worldwide.

2. Description of Tests and Sampling

The detailed tests were similar to what was done in [9], except that in these tests a lot more data was collected. The data collected in the 24 detailed tests, also conducted in Golden Valley Electric Association's Healy 28 MW Unit no. 1 as in [9], included (in addition to MW generated) raw feed coal quality, pulverized feed coal quality and PSD, fly ash and bottom ash characteristics, and emissions measurements. Figure 1 shows a schematic of the power plant.

Two Foster Wheeler MBF 19.5 mills, A and B, ground the raw feed coal into pulverized coal. The mills are air swept; that is, the pulverized coal is carried by air at 65.6°C (150 F) to the combustion chamber through the four pipes A1, A2, B1, and B2. The grind size is altered by increasing or decreasing the air flow through the mill or by opening/closing the mill "classifiers." Each of the four pipes has a sampling port that was used for sampling pulverized coal. While most of the pulverized coal samples were collected by ASTM D-197 method, some samples were collected using ISO 9931 by a contractor. The reason for the change was that the research team damaged its sampling probe and had to hire a third party to collect the pulverized coal samples. Multiple pulverized coal samples were collected from each pipe during a test (typically 3 hours long) so that the PSD was representative of the duration of the test. As in [8], validity of PSD sampling was verified using the Rosin-Ramler (RR) plots. The particle size, at which 36.8% of the flow is retained on the screen, or the k value was estimated from the plots. The k values for Tests 3 to 20 averaged about 100 microns, while those of Tests 21–26 averaged 56 microns. Tests 1 and 2 are from the preliminary study [9].

The raw coal samples were collected from the feed stream of the two mills A and B. The data collected from the raw coal feed included proximate analysis and HGI. The data collected from the pulverized coal included PSD and proximate analysis. The fly ash and bottom ash were sampled for unburned carbon. The fly ash was sampled from fabric filters (bag houses), while the bottom ash was sampled from the bottom of the combustion chamber. Collecting representative bottom ash samples was very difficult as the bottom ash chamber was not designed for sampling. The flaming ash chamber had to be flooded, and the ash sample collected quickly as it left the chamber, while flames shot out of the open door from where the sample was collected. Additionally, the stack emissions were sampled (by a contractor) for Hg using the Ontario Hydro Method in two of the tests. Data on NO_x, SO_x, and CO were obtained using automated continuous emissions monitoring system from stack gases exiting the plant. Emissions controls in the plant consisted of fabric filters (bag houses) only. There were no wet scrubbers.

The PSD of the pulverized coal being burned is never known in real time. The plant operators manipulated the mill classifier vanes and primary air flow to increase or decrease the fineness of the grind. The vane and primary air flow were set at least two hours prior to a test to ensure stability of the grind during the test. The operating PSD for a test was only known after several weeks of the test. It was very difficult to run the plant at the settings required for some of the finer grinds. Therefore, the reader will notice very few tests at PSD finer than 65%.

3. Results and Discussion

The data from the tests are shown in Tables 1, 2, 3, 4, 5, 6, 7. Tests 1 and 2 in the tables are from [9]. The reader will notice gaps in some data. Budgetary constraints in some

Table 1: Raw coal quality data (as received).

	Ash	Moisture	Volatile	Sulfur	Fixed carbon	kJ/kg (BTU/lb)	HGI*
Test 3	11.7	27.2	34.3	0.21	26.9	16,907 (7275)	34
Test 4	10.2	28.7	34.3	0.19	26.8	16,865 (7257)	31
Test 5	11.9	25.2	35.2	0.22	27.7	17,309 (7448)	31
Test 6							32
Test 7							33
Test 8							31
Test 9	12.7	27.5	31.2	0.20	28.3	16,331 (7027)	37
Test 10	12.2	27.4	31.7	0.19	28.7	16,479 (7091)	34
Test 11	11.8	27.5	32.2	0.19	28.5	16,633 (7157)	36
Test 12	12.3	27.5	32.0	0.21	28.2	16,461 (7083)	36
Test 13	13.5	27.5	31.3	0.21	27.8	16,349 (7035)	36
Test 14	12.3	27.0	31.6	0.22	29.2	16,747 (7206)	34
Test 15	11.4	27.3	32.4	0.22	28.9	16,954 (7295)	32
Test 16	12.7	27.1	32.3	0.21	28.0	16,540 (7117)	33
Test 17	14.0	27.2	31.7	0.19	27.1		35
Test 18	13.9	27.2	32.3	0.19	26.7		35
Test 19	13.6	26.6	32.3	0.20	27.5		36
Test 20	12.3	26.1	33.1	0.18	28.5		36
Test 21	14.1	28.2	30.8	0.20	27.0		40
Test 22	12.8	28.3	31.2	0.20	27.7		40
Test 23	13.8	29.3	32.5	0.21	24.5		39
Test 24	13.3	31.3	31.8	0.20	23.6		37
Test 25	11.4	37.2	29.5	0.18	21.8		35
Test 26	13.4	29.0	33.2	0.20	24.4		36

* Hardgrove grindability index.

Table 2: Data on pulverized coal (as received).

	PSD76	Pulverized coal					
		Ash	Moisture	Volatile	kJ/kg (BTU/lb)	Fixed carbon	Sulfur
Test 1	49	15.8	14.1	38.7	19,094 (8216)	31.4	
Test 2	42	14.1	12.9	39.2	20,026 (8617)	33.9	
Test 3	46	13.8	15.6	40	19,329 (8317)	30.5	0.26
Test 4	48	12.9	16.7	40	19,324 (8315)	30.4	0.24
Test 5	48	13	16	40.4	19,552 (8413)	30.7	0.25
Test 6	50	11.1	19.9	37.6	18,838 (8106)	31.4	0.23
Test 7	52	11.6	18.4	37.7	19,096 (8217)	32.7	0.24
Test 8	46	10.3	18.5	37.9	19,296 (8303)	33.3	0.23
Test 9	55	13.6	17.5	36.3	18,564 (7988)	32.6	0.24
Test 10	54	14.3	13.3	38.8	19,640 (8451)	33.9	0.24
Test 11	52	14.1	13.1	38	19,856 (8544)	34.9	0.24
Test 12	46	14.2	12.5	38.2	20,038 (8622)	35.2	0.24
Test 13	51	15.5	15.5	36.7	18,941 (8150)	32.3	0.25
Test 14	52	14.9	15.3	37.4	19,236 (8277)	32.5	0.27
Test 15	52	14.5	15	37.6	19,310 (8309)	32.9	0.26
Test 16	51	16.1	15.2	37	18,766 (8075)	31.7	0.24
Test 17	46	15.6	15.1	39.9	19,868 (8162)	29.4	
Test 18	49	16.2	13.4	39	19,154 (8242)	31.4	
Test 19	48	15.6	12.9	39.3	19,459 (8373)	32.2	
Test 20	50	15.8	13.1	38.9	19,347 (8325)	32.2	
Test 21	66	15.1	17.9	37.4	18,357 (7899)	29.6	
Test 22	70	16.5	14.9	36.7	18,917 (8140)	31.9	
Test 23	75	13.9	17.9	39	19,029 (8188)	29.2	
Test 24	67	13.2	18.5	40.3	18,957 (8157)	28.1	
Test 25	78	14.9	18	38.1	18,671 (8034)	29.1	
Test 26	81	16.3	16.9	37.8	18,713 (8052)	29	

Table 3: Carbon content (dry basis) of fly ash and bottom ash.

	Carbon in fly ash (%)	Carbon in bottom ash (%)
Test 3	3.6	18.1
Test 4	3.1	4.6
Test 5	4.1	22.6
Test 6	3.1	17.4
Test 7	2.6	22.3
Test 8	2.7	25.4
Test 9	3.6	5
Test 10	3.7	5.9
Test 11	3.7	3.5
Test 12	4.2	4.3
Test 13	2.8	6.9
Test 14	3	—
Test 15	3.4	3.4
Test 16	3.2	4.4
Test 17	1.9	3.6
Test 18	1.9	3.6
Test 19	2.6	5.8
Test 20	2.6	5.8
Test 21	2.4	1.9
Test 22	2.5	0.9
Test 23	1.2	4.3
Test 24	1.3	7.1
Test 25	1	3.2
Test 26	0.8	5.2

Table 4: Stack gas emissions data.

	SO_2 (ppm)	NO_x (ppm)	CO (ppm)	CO_2 (%)
Test 3	113	164	817	11.3
Test 4	104	158	1423	11.2
Test 5	113	175	1474	10.6
Test 6	120	151	937	11.9
Test 7	119	150	918	11.9
Test 8	131	157	797	11.8
Test 9	121	147	1654	11.6
Test 10	107	145	2708	11.7
Test 11	115	149	1779	11.3
Test 12	121	150	1725	11.4
Test 13	120	153	1300	11.8
Test 14	129	156	2715	11.8
Test 15	107	165	561	11.3
Test 16	119	168	1990	11.7
Test 17	114	165	363	11.2
Test 18	115	166	411	11.3
Test 19	107	161	483	11.4
Test 20	144	164	549	11.5
Test 21	137	159	321	12.9
Test 22	135	153	718	12.5
Test 23	112	134	1096	12.3
Test 24	123	136	1489	12.4
Test 25	133	154	221	12.4
Test 26	136	156	201	12.5

years determined what data was collected, with only data that was central to the project being always collected.

Figure 2 (same data as Table 5) shows the relationship between the PSD and efficiency. The efficiency was computed as the ratio of energy generated (from MW data in Table 6) to energy burned (computed from pulverized coal data, Table 2, and coal mass flow data, Table 6). The plot, which includes data from the two tests from [9], shows a negligible correlation between PSD and efficiency. However, it also shows clustering in the data due the formation of two clusters that could be named the *coarser grind* tests and the *finer grind* tests, depending on whether they were coarser than a PSD of 60 or not. This is quite convenient for the purpose of this research since it allows the two clusters to be compared. The coarse grind group consisted of 20 tests (Tests 1–20), with an average (and statistically different from the fine group) PSD of 50% compared to only 6 tests (Tests 21–26) with an average PSD of 73% for the fine group. Table 8 summarizes the difference between the major results of the two groups of tests, while Table 9 summarizes the difference between the feed coal quality for the two groups. Note that the t-test was used to test significance when the data was normally distributed. Otherwise, the Mann-Whitney test was used. Sometimes these statistical tests were not possible if the data did not meet the criteria for the tests. The data shown in Tables 1, 2, 3, 4, 5, 6, 7 were used for the various statistics. For example, the efficiencies for the coarse group (Tests 1–20 in Table 5) average 23.05%, while the fine group (Tests 21–26 in Table 5) average 23.75%. The difference in efficiency is statistically significant as reported in Table 8.

The results show a difference in efficiency between the two groups of tests. However, it is very small and could simply be due to the small number of samples in the finer grind group. The test with the highest efficiency (0.244 at a PSD of 66) was in this group. Additionally, 7 out of the 20 tests in the coarse group had efficiencies that could be in the finer grind group. The coal quality in the two groups does not provide a clear explanation for this difference. However, that is to be expected since coal quality and combustion are typically not directly related [12].

The difference in the carbon content in fly ash and bottom ash between the two groups would normally be explained as higher loss of carbon from coarse grind combustion. However, [8] reported that low-rank high-volatile content Alaska coal results in complete burn out even for very coarse grinds. Therefore, given the small magnitude of difference, the higher carbon content in fly ash and bottom is explained by the higher fixed carbon content of coals in the coarse grind group. This is because the difference in fixed carbon content of feed coal applies to the entire tons burned, whereas the difference in carbon content of ash applies to only 15% of the tons burned (since ash constitutes about 15% of the weight in both groups). Note that conclusions on bottom ash should be made with a caveat: bottom ash sampling conditions were very challenging and could have

Table 5: Efficiencies for the various tests.

	PSD76	Efficiency
Test 1	49	0.2299
Test 2	42	0.2305
Test 3	46	0.231
Test 4	48	0.222
Test 5	48	0.225
Test 6	50	0.238
Test 7	52	0.224
Test 8	46	0.236
Test 9	55	0.240
Test 10	54	0.230
Test 11	52	0.229
Test 12	46	0.226
Test 13	51	0.228
Test 14	52	0.228
Test 15	52	0.230
Test 16	51	0.229
Test 17	46	0.236
Test 18	49	0.232
Test 19	48	0.232
Test 20	50	0.233
Test 21	66	0.244
Test 22	70	0.236
Test 23	75	0.2323
Test 24	67	0.2342
Test 25	78	0.2406
Test 26	81	0.2377

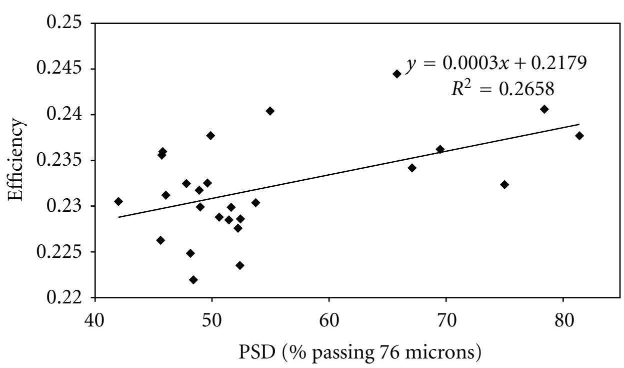

Figure 2: Negligible correlation between PSD and efficiency.

impacted bottom ash values. This may explain why bottom ash carbon values are significantly higher than fly ash carbon values in Table 3 for some tests.

NO_x and CO do not appear to be impacted by PSD (Table 1, and Figures 3 and 4). Both demonstrate significant variability within each test condition. NO_x formation originates with the production of NO, which is formed when the nitrogen in coal or air reacts with oxygen. The authors in [13, 14] have identified three mechanisms for the initial formation of NO, thermal NO, prompt NO, and fuel NO. Thermal NO occurs at very high temperatures when molecular nitrogen combines with oxygen. When the coal contains very little nitrogen, the NO created by this mechanism becomes a significant proportion of the total NO created. Prompt NO occurs when molecular nitrogen combines with hydrocarbons. It, however, forms only a small portion of the total NO formed. Fuel NO, as the name implies, is formed from the nitrogen in the coal and constitutes most of the NO formed. Therefore, the amount of fuel NO formed is highly dependent on the amount of nitrogen in the coal. Thus, since the factors that impact NO generation do not change between the two test groups, there should be no difference in the NO_x generation. Hence, the obtained results are in line with NO_x generation fundamentals.

Table 6: Coal flow rate and MW generated.

	Coal flow rate kg/hr	Mean MW generated
Test 3	22,615	28.12
Test 4	23,709	28.29
Test 5	22,828	27.92
Test 6	22,850	28.47
Test 7	23,780	28.24
Test 8	22,460	28.45
Test 9	22,778	28.28
Test 10	22,505	28.33
Test 11	22,377	28.26
Test 12	22,429	28.29
Test 13	23,346	28.11
Test 14	23,084	28.11
Test 15	22,729	28.07
Test 16	23,466	28.03
Test 17	22,635	28.14
Test 18	22,719	28.05
Test 19	22,279	28.04
Test 20	22,365	27.99
Test 21	22,761	28.41
Test 22	22,967	28.55
Test 23	22,663	27.88
Test 24	22,721	28.06
Test 25	22,465	28.07
Test 26	22,688	28.05

Table 7: Hg emissions through the stack.

	Hg, kg/hr (lb/hr)	Hg type (percent of total)		
		Particle bound	Oxidized	Elemental
Test 23 (PSD = 75)	0.000408 (0.000760)	0.19	34.03	65.78
Test 24 (PSD = 67)	0.000300 (0.000663)	0.66	14.02	85.31

CO generation in pulverized coal plants is usually not an issue because of thorough mixture of coal particles and oxygen [12]. Coal reactivity, however, can be a factor in CO generation [15], as can excess air be [12]. Neither the

Table 8: Difference in results between the two groups of tests.

	Average		t-statistic	Significant difference?
	Coarser	Finer		
Efficiency	0.2305	0.2375	3.44	Yes
Unburned carbon (fly ash)	3.1	1.53	4.6	Yes
Unburned carbon (bottom ash)	9.6	3.8	N/A	N/A
SO_2	118	129	2.5	Yes
NO_x	158	149	1.9	No
CO	1256	674	2.1	No

Table 9: Difference between the feed coal (pulverized, as received) quality for the two groups of tests.

	Average		t-statistic	Significant* difference?
	Coarser	Finer		
Ash (%)	14.15	14.98	1.28	No
Volatile content (%)	38.43	38.22	0.37	No
Volatile content^{RC} (%)	32.5	31.5	1.66	No
Moisture (%)	15.2	17.35	N/A	N/A
Moisture^{RC} (%)	27.1	30.6	MWT	Yes
Heat Val, kJ/kg (BTU)	19,337 (8320)	18,774 (8078)	4.1	Yes
Fixed carbon content	32.3	29.5	N/A	N/A
HGI	34	37.8	3.8	Yes

* At 95% confidence, RC: raw coal, MWT: Mann-Whitney test [11].

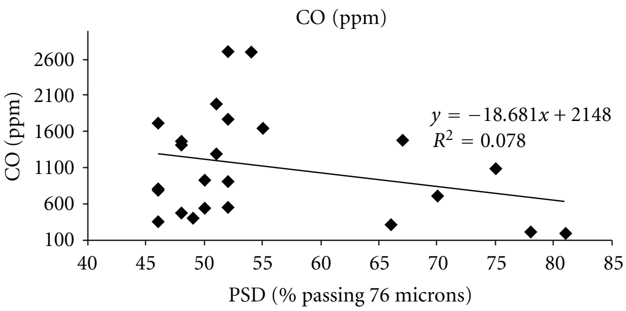

Figure 3: PSD versus CO.

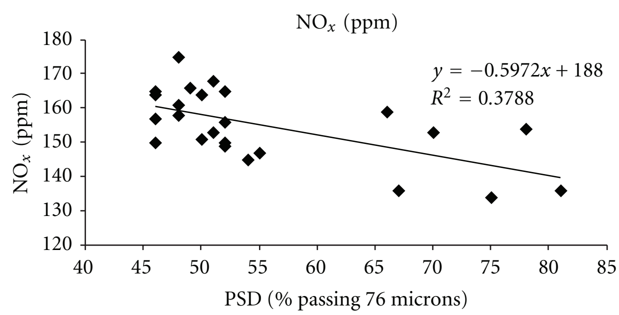

Figure 4: PSD versus NO_x.

reactivity (indicated by volatile content) nor the nature of combustion (including operational factors such as oxygen supply [10]) has changed between the two groups of tests, providing no reason for a difference in CO generation.

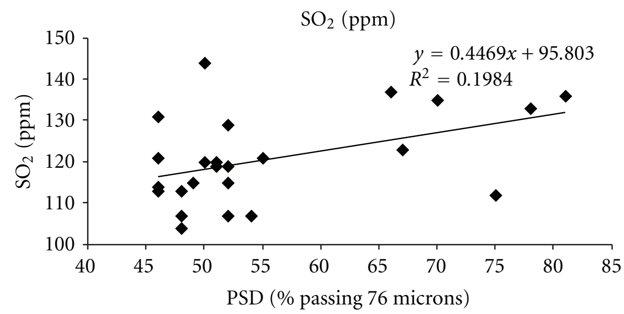

Figure 5: PSD versus SO_2 (ppm).

SO_2 varied somewhat significantly under both test conditions. It seems to be higher for the finer group (Table 8) even though it is not correlated with PSD (Figure 5). The authors in [16] suggested that oxygen concentration, sulfur content, and temperature impacted SO_2 production. The sulfur content of feed coal was not the reason for the difference between the SO_2 contents of the two groups (see Table 1 for sulfur data) since both groups had an average sulfur content of 0.2. Moisture was explored as a potential reason (since it can contribute oxygen), but it was not found to be correlated to the SO_2 content (Figure 5). The higher SO_2 content of the finer ground tests could also be explained as due to the low number of samples in that group, though that argument is tenuous given that 4 of the 6 tests had a SO_2 concentration above 130, while only 2 out of the 20 tests in the coarse group met that criterion.

The Hg emissions from stack were also studied, though, due to budgetary constraints, Hg data was collected in only two tests. These two tests were conducted one after the other to minimize variance in feed coal quality. Just based on those two tests, it did not seem that the PSD had any impact on Hg emissions. Hg emissions were very low (close to detection limits) in both tests.

4. Conclusions

The broad conclusions from the 26 field tests (including the two in [9]) are as follows.

(1) The plant efficiency was about the same (between 23 and 24%) across the particle size distributions.

(2) SO_2, CO, and NO_x levels were essentially the same between the groups, though they varied significantly within each test group. The range was higher for CO for the coarse group.

(3) Hg emissions were too low to differentiate between the two groups.

Many pulverized coal plants around the world burn low-rank high-volatile coals, either wholly or in blends. Given the field tested conclusions, these plants could experiment with coarser grinds to extract benefits of coarse grinding-reduced in-plant power consumption and increased coal throughput. For the coal producer, it improves the marketability of their coal.

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