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Four Years of Operating Experience with DryFining^{TM} Fuel Enhancement Process at Coal Creek Generating Station

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Abstract: Lignite and sub-bituminous coals from western U.S. contain high amounts of moisture (sub-bituminous: 15%-30%, lignites: 25%-40%). German and Australian lignites (brown coals) have even higher moisture content, 50% and 60%, respectively. The high moisture content causes a reduction in plant performance and higher emissions, compared to the bituminous (hard) coals. Despite their high-moisture content, lignite and sub-bituminous coals from the western U.S. and worldwide are attractive due to their abundance, low cost, low NO_x and SO_x emissions, and high reactivity. A novel low-temperature coal drying process employing a fluidized bed dryer and waste heat was developed in the U.S. by a team led by GRE (Great River Energy). Demonstration of the technology was conducted with the U.S. Department of Energy and GRE funding at Coal Creek Station Unit 1. Following the successful demonstration, the low-temperature coal drying technology was commercialized by GRE under the trade name DryFining^{TM} fuel enhancement process and implemented at both units at Coal Creek Station. The coal drying system at Coal Creek has been in a continuous commercial operation since December 2009. By implementing DryFining at Coal Creek, GRE avoided $366 million in capital expenditures, which would otherwise be needed to comply with emission regulations. Four years of operating experience is described in this paper.

Key words: Power generation, pulverized coal combustion, high-moisture coals, coal beneficiation, efficiency improvement, emissions reduction.

1. Introduction

The low-rank, high-moisture coals constitute about 50% of the U.S. and world coal reserves. Given the abundance of these low-cost coals, the use of high-moisture coal for power generation is common and growing. Despite their high-moisture content, lignite and sub-bituminous coals from the western U.S. and low-rank coals worldwide are attractive due to their low NO_x and SO_x emissions and high reactivity, compared to bituminous (hard) coals. In the U.S. alone, 279 power facilities burn high moisture coals such as lignite and PRB (Powder River Basin) sub-bituminous coal. These plants produce nearly a third of the coal fired electric generation in the U.S. [1].

When high-moisture coals, such as lignite, are burned in utility boilers, about 7% of the fuel heat input is used to evaporate and superheat fuel moisture. As presented in Fig. 1, most of this loss is associated with latent heat of evaporation of fuel moisture. The use of high-moisture, low HHV (higher heating value) coals, results in higher fuel and flue gas flow rates, auxiliary power use, net unit heat rate, and mill, coal pipe and burner maintenance requirements compared to bituminous (hard) coals.

To improve unit efficiency, plant operation and economics, and reduce CO_2 emissions from the existing and future-built power plants firing low-rank coals, countries with large resources of high-moisture

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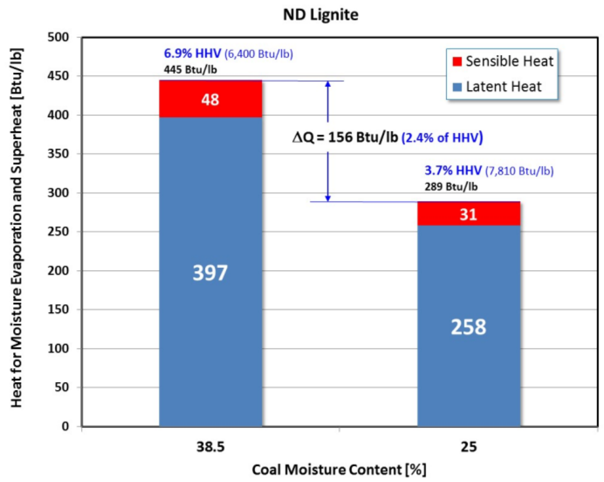

Fig. 1 Losses due to evaporation of coal moisture (raw and dried North Dakota lignite).

low-quality coals are developing coal dewatering and drying processes. This is particularly important for advanced PCC (pulverized coal combustion) technology operating at high steam parameters.

However, many thermal processes developed thus far are either quite complex or require costly primary energy or steam to remove moisture from the coal. This significantly increases process cost, which represents a main barrier to industry acceptance of this technology. A comprehensive review of coal drying technologies is provided in Ref. [2].

2. DryFining™: A-Low Temperature Coal Drying Process

A novel low-temperature coal drying process employing a moving bed FBD (fluidized bed dryer) and using waste heat to decrease moisture content of low-rank coals was developed in the U.S. by a team led by GRE (Great River Energy).

2.1 DryFining Development

During the 1990's, the engineering staff at Coal Creek Station began investigating alternative approaches to dealing with future emission regulations. Conventional approaches included changing fuels and/or adding environmental control equipment and, often, resulted in lowering emissions at the expense of increases in unit heat rate and operating and maintenance costs. Higher heat rate results in higher required fuel heat input, higher CO_2 emissions and higher flow rate of flue gas leaving the boiler, and lower plant capacity due to higher station service power requirements or limited equipment capacity. Increased flue gas flow rate requires a larger size of environmental control equipment, higher equipment cost and station service power.

The alternative to traditional approaches involves improvement in coal quality, which in case of the high-moisture coals, may be achieved by removing a portion of coal moisture.

A systematic phased approach to development of a coal drying technology was initiated by GRE in 1997 by performing analyses to quantify benefits of coal drying, small-scale experiments, and large-scale burn tests where dried coal was burned in Unit 1 boiler in 2002 to verify theoretical findings [3].

The next project phase involved coal drying tests conducted at a pilot-scale (2 t/h) fluidized bed coal dryer located at Coal Creek Station (2 × 600 MW_{gross} subcritical) located in Underwood, ND, and laboratory-scale coal drying tests conducted at Lehigh University to determine drying kinetics and create analytical model of the coal drying process in a FBD.

A moving bed FBD was selected due to its high heat and mass transfer coefficients which produce a compact dryer design. The air is employed as a fluidization medium instead of commonly used steam[1]. Potential devolatization of coal is avoided by performing drying with plant low-grade waste heat.

Following successful testing and operation of the pilot-scale dryer, a prototype-scale (75 t/h) FBD was designed, built, tested, and operated at Coal Creek Station during the time period from 2005 to 2007. A series of controlled tests was performed to establish performance characteristics of the dryer and gain operating experience. Test results are described in Refs. [4-6].

[1]Inert fluids, other than steam, may be used for fluidization to achieve deep reductions in coal moisture content.

Based on a successful operation of the prototype drier, and considering co-benefits of coal cleaning, GRE decided to implement the full-scale coal drying and cleaning system at Units 1 and 2 at Coal Creek Station in 2007. The system design allowed tie in with the plant equipment while both units were on line, requiring no down time.

The coal drying and cleaning technology was commercialized by GRE in 2009, and is available under trade name DryFining™ fuel enhancement process. The DryFining system has been in continuous commercial operation at Coal Creek Station since December 2009.

2.2 Process Description

A two-stage moving bed FBD is the heart of the DryFining system. A schematic representation of a dryer is presented in Fig. 2.

The FBD, developed by GRE, accomplishes two important functions. It cleans the coal by removing a significant portion of sulfur (S) and mercury (Hg) from the raw coal in the first stage, and dries the coal in the second stage. The cleaning function distinguishes this coal drying technology and provides a very important co-benefit of emissions reduction.

Crushed coal is fed to the first FBD stage where non-fluidizable material such as rocks and other higher-density fractions ("jetsam") are segregated at the bottom of the dryer, while less dense and smaller particles ("floatsam") are floating. Therefore, the segregated stream, discharged from the dryer, has higher mineral matter content (including pyrite), in comparison to the dried coal (product stream). Because most of the inorganically associated S is contained in pyrite forms, as well as a considerable fraction of Hg, in case of the ND lignite, about 30% of S and Hg from coal are segregated out in the first stage of the FBD [7].

The segregation tests performed with other lignites and sub-bituminous coals have demonstrated similar levels of S and Hg removal. The amount of segregated

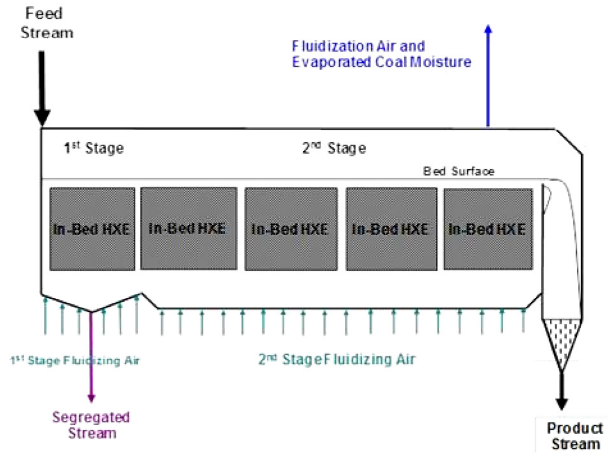

Fig. 2 Schematic representation of a moving bed FBD.

sulfur and mercury depends on many factors, such as percentage of inorganically associated sulfur in coal, the presence or absence of clays, and other factors related to coal morphology.

The fluidizable material next enters the second stage of the dryer, where the surface and inherent coal moisture are evaporated by the heat supplied by the fluidizing air and the in-bed HXE (heat exchanger). The in-bed heat exchanger increases the temperature of the fluidizing (drying) air and fluidized coal bed, improving drying kinetics (the rate of coal drying). The drying process affects the microstructure of coal particles that disintegrate during drying. This reduction in coal particle size has a significant positive effect on mill power. The drier and finer coal is discharged from the FBD as the product stream. The bed residence time and temperature are the main parameters affecting the residual moisture content.

2.3 DryFining Applications

DryFining may be retrofitted to the existing PCC plants, integrated into the new-build PCC plants, as well as coal gasification IGCC (integrated gasification combined cycle) and CTL (coal-to-liquids), and low rank coal-fired oxyfuel power plants employing dry feed oxygen-blown gasifiers.

For existing units, depending on site specifics, DryFining is capable of reducing coal moisture content by 10% to 20%-points, with higher value corresponding to the supercritical units. Higher moisture reductions are possible for newly built units where DryFining is integrated with a power plant, and boiler is designed to burn dried coal.

Thermal integration of DryFining with an existing power plant is site-specific and depends on the available heat sources, space constraints, and general layout of the plant. The benefits of coal drying, such as heat rate improvement, increase as moisture content of the raw coal and reduction in coal moisture increase. For North American lignites containing approximately 40% moisture, the heat rate improvement is in the 3%-5% range[2], while for the sub-bituminous coals with lower moisture content (15%-30%), the heat rate improvement is in the 2%-3% range.

Integration of DryFining into the newly built power plants operating with high steam parameters is especially beneficial for units burning low-rank coals, since their efficiency is severely affected by the high coal moisture content (Fig. 3). A reduction of coal moisture is necessary to achieve the full benefits of the advanced PCC technologies.

Additionally, in arid regions, capturing and recycling the water vapor from the fuel prior to combustion can provide additional water cycle benefits.

The achievable reduction in coal moisture content may be limited by thermal performance of the boiler convection pass, the amount of available heat or by the equilibrium moisture content of coal[3]. A new plant with integrated DryFining will have a lower initial capital cost (CAPEX), compared to the plant burning raw coal, including the front-end coal drying system, and will not be limited by the convection pass performance.

[2]For German and Australian brown coals containing 55%-60% moisture, the heat rate improvement is in the 5%-7% range.

[3]Oxyfuel, and oxygen-blown gasification plants are not subject to the equilibrium moisture content limit. The studies conducted with DryFining integrated with the lignite-fired oxyfuel and CTL (coal-to-liquid) plants employing dry-feed gasifier, have demonstrated coal moisture reduction from the 40%-55% range to the target moisture level of 8%-12%.

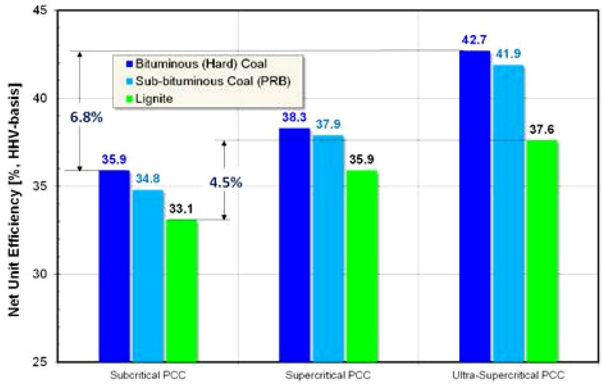

Fig. 3 Effect of coal rank and steam parameters on net unit efficiency (source: EPRI (Electric Power Research Institute)).

In addition, due to higher efficiency and lower flow rate of flue gas, the size of the CCS (carbon capture and storage) system and its adverse effect on plant efficiency and capacity will be smaller.

According to four years of operating experience at Coal Creek, DryFining also reduces operating cost (OPEX).

3. Baseline Performance and Emissions

The coal drying and cleaning system at Coal Creek is sized for 1,100 t/h of raw North Dakota lignite with moisture content in the 40% range.

Controlled performance and emissions tests were conducted on Coal Creek Unit 1 at full load (600 MW_{gross}) steady state operating conditions before (2009) and after (2010) and (2011) the implementation of DryFining, in order to establish baseline unit performance and emissions, and quantify and document the improvement. The results are reported in Refs. [8, 9].

3.1 Operating Conditions

The operating conditions corresponding to the tests performed with the wet and dried coal at Unit 1 are summarized in Table 1.

With the dried coal, the APH (air preheater) air leakage decreased due to the lower drafts and lower gas- and air-side pressure drops associated with lower flows of combustion air and flue gas (Table 2). In

Table 1 Unit 1 operating conditions with and without coal drying applied.

Test	P_G (MW)	$O_{2,\text{ APH, in}}$ (%)	APH leakage (%)	FGD inlet temp. (°F)	Stack temp. (°F)	Opacity
Raw coal	600	2.54	8.2	345	188	6.6
Dried coal	606	2.76	4.1	309	156	5.8

Table 2 The effect of DryFining on the performance of Coal Creek Unit 1.

Test	TM (%)	HHV (Btu/lb)	Coal used (klb/hr)	Flue gas (kscfm)	Mill power (kW)	ID fan power (kW)	HR_{net} (Btu/kWh)	Boiler efficiency (%)
Wet coal	37.1	6,251	946	1,557	3,989	8,767	10,246	80.34
Dried coal	32.1	6,914	856	1,467	3,596	7,251	9,890	83.06
Difference (%)	-13.5	10.6	-9.5	-5.8	-9.9	-17.3	-3.5	3.4

addition, the temperature of flue gas at the APH exit decreased, resulting in lower volumetric flow of flue gas entering the FGD (flue gas desulfurization) system, thus, allowing a larger proportion of the flue gas to be scrubbed (Coal Creek employs a FGD gas bypass to maintain dry stack conditions).

As a consequence of the lower FGD bypass flow, the stack temperature decreased, but remained well above saturation temperature. Also, with lower flue gas flow and temperature, flue gas velocity through the ESP (electrostatic precipitator) decreased, resulting in improved particulate collection efficiency and lower opacity.

3.2 Unit Performance

The effect of the DryFining process on HR_{net} (net unit heat rate) and boiler efficiency (η_B), fuel and stack flow, mill and ID (induced draft) fan power is summarized in Table 2. During the 2011 tests, the coal moisture content was reduced by 5%-points (or 13%) resulting in approximately 11% increase in coal HHV. Further reduction in coal moisture was limited by steam temperatures, which began to decrease due to lower flow rate of flue gas through the convective pass of the boiler.

As a result of the lower coal flow rate, improved grindability, and reduced size of dried coal, mill power decreased by almost 10%. This allowed unit to be operated with six mills in service, instead of customary seven (or eight). Freeing up one of the mills to be used as a spare improved plant availability, as mills can be rotated in and out of service for routine maintenance or repair without reducing fuel-processing capacity.

The volumetric flow rate of flue gas through the stack decreased due to lower coal flow rate and lower stack temperature, resulting in lower draft losses.

With drier coal, the net unit heat rate, determined by the BTCE (boiler-turbine cycle efficiency) method, decreased by 3.5%. The boiler efficiency, determined by the ASME PTC (American Association of Mechanical Engineers, power test code) 4 method, has increased by 3.4%. The improvement in net unit heat rate is higher than the improvement in boiler efficiency because, with drier coal, the combined fan and mill power are lower, compared to the wet coal.

The change in CO_2 emissions is traditionally related to the change in net unit heat rate. That is, one percent change in heat rate results in one percent change in CO_2 emissions.

The reduction in CO_2 emissions determined by using the performance test data shown in Table 2 was 3.5%. Such a small difference is difficult to measure, considering the CEM (continuous emission monitor) measurement accuracy and precision. The CO_2 intensity was reduced by 3.0% (Table 3).

However, the heat rate reduction achieved at Coal Creek is somewhat limited by site-specific conditions, other power plants could potentially achieve greater efficiency improvements. At Coal Creek, the planned increase of the heat transfer surface in convective pass

Table 3 Effect of DryFining on emissions at Coal Creek Unit 1.

Test	NO_x (lb/MBtu)	SO_x (lb/MBtu)	Hg^T (μg/dNm^3 @3% O_2)	CO_2 intensity (lb/MWh)
Wet coal	0.284	0.578	14	2,209
Dried coal	0.200	0.346	8.5-9	2,144
Reduction (%)	30	> 40	35-40	3.0

of the boiler will allow further reductions in the coal moisture content, with a projected heat rate improvement and CO_2 emissions reduction of 4.5%.

3.3 Emissions

3.3.1 NO_x Emissions

Implementation of DryFining had a significant positive effect on NO_x, SO_2, and Hg emissions (Table 3). A reduction in NO_x emissions is attributed to the lower coal input, and lower PA (primary air) to SA (secondary air) flow ratio, compared to the wet coal operation. The lower PA flow results in lower NO_x formation at the burners, while the higher SA flow allows for deeper furnace staging, with more overfire air available for SOFAs (separated overfire airs). The resulting 30% NO_x reduction allowed Coal Creek to meet its new NO_x emission limits by boiler tuning, avoiding a costly installation of a SNCR (selective non-catalytic reduction) or SCR (selective catalytic reduction) reactor.

3.3.2 SO_x Emissions

SO_x (SO_2) emissions reduction may be attributed to three factors. First, the lower flow rate of dried coal to the boiler results in a reduction in the amount of S entering the boiler. Second, a significant portion of the inorganically bound sulfur is segregated out by the FBD. Finally, the lower volumetric flow of flue gas allows a larger proportion of flue gas to be scrubbed (with less being bypassed), further reducing SO_2 emissions (Fig. 4).

The resulting 40% reduction in SO_2 emissions allowed Coal Creek to meet its new SO_2 emissions limits without installing additional scrubber module.

3.3.3 Hg Emissions and Speciation

Flue gas Hg concentration and Hg speciation were

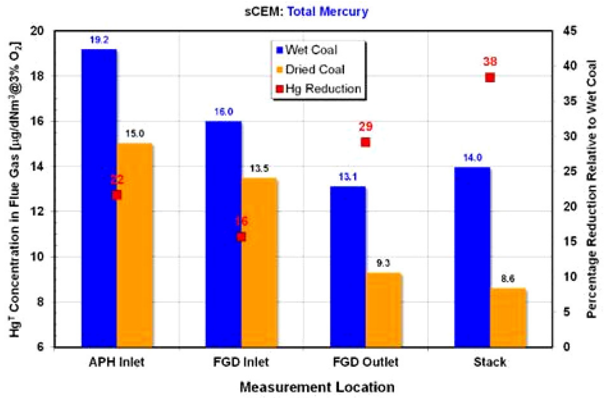

Fig. 4 SO_2 removal in the FGD before and after implementation of DryFining.

measured using wet impinger-based sCEMs (semi-continuous emissions monitors) at the APH inlet, FGD inlet and outlet, FGD bypass, and stack. Sorbent trap measurements were conducted for quality control at the FGD inlet and outlet, and FGD bypass. The plant CEM was used for continuous measurement of total mercury, Hg^T in the stack [8].

Concentration of Hg^T measured at various locations before and after implementation of DryFining, is presented in Fig. 5. With dried coal, concentration of Hg^T at the boiler outlet (APH inlet) decreased by approximately 22% (from 19.2 μg/dNm^3 to 15 μg/dNm^3 @3% O_2), relative to the wet coal baseline. As presented in Fig. 6, at that location, most of Hg is insoluble elemental mercury, Hg^0. The reduction in Hg^T at boiler exit is mainly attributed to the Hg removal in FBD which lowers mercury content in dried coal by 20%-30%. With DryFining in service, concentration of Hg^T across the FGD decreased by more than 30% (from 13.5 μg/dNm^3 to 9.3 μg/dNm^3 @3% O_2). With wet coal, the decrease in Hg^T concentration across the FGD was significantly smaller, approximately 16% (from 16 μg/dNm^3 to 13.5 μg/dNm^3 @3% O_2).

This change in native mercury removal in the FGD is mostly due to the change in mercury speciation (Fig. 6).

With dried coal, water-soluble oxidized mercury, Hg^{2+} at the FGD inlet was 41% of the total mercury, while with wet coal, Hg^{2+} was significantly lower, approximately 27% of the total (Fig. 6). This increase in Hg^{2+} may be attributed to lower flue gas

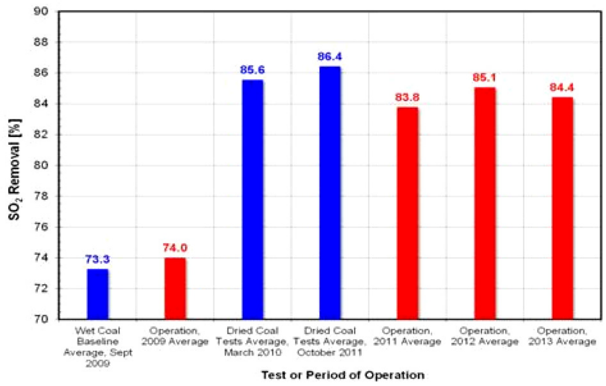

Fig. 5 Total mercury concentration at various locations measured before and after implementation of DryFining.

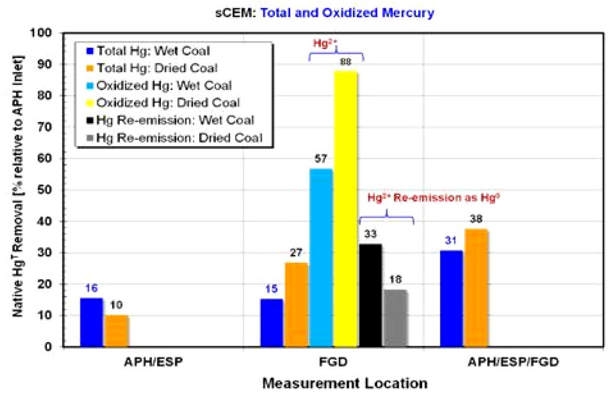

Fig. 7 Native mercury removal before and after implementation of DryFining.

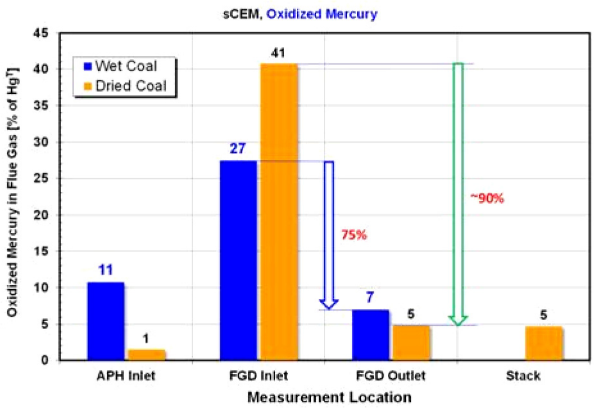

Fig. 6 Mercury speciation before and after implementation of DryFining.

temperatures leaving the APH (increased quench rate) and lower flue gas moisture content (both are promoting oxidation of Hg^0).

While, some of Hg^0 and Hg^{2+} is adsorbed on the fly ash particles and removed in the ESP, most of the water-soluble Hg^{2+} is removed in the FGD (approx. 90% and 75% with dried and wet coal, respectively).

The change in Hg speciation combined with the increase in flue gas flow rate treated by the FGD resulted in approximately 40% reduction in Hg^T emissions (from 14 µg/dNm^3 to 8.6 µg/dNm^3 @3% O_2), compared to the wet coal (Fig. 5). The concentration of Hg^T measured at the stack is higher compared to the FGD outlet because Hg^T concentration in the FGD bypass flow is about the same as at the FGD inlet.

The effect of DryFining on native Hg removal in the pollution control system at Coal Creek is presented in Fig. 7.

In addition, with dried coal, reduction of Hg^{2+} captured in the FGD and it re-emission from the scrubber liquor in form of Hg^0 was significantly reduced (Fig. 7) further contributing to the reduction in Hg^T. The emitted Hg^T at Coal Creek is 95% Hg^0 and 5% Hg^{2+}.

In summary, the 35%-40% reduction in Hg^T emissions produced by DryFining is due to the lower flow rate of dried coal into the plant, removal of the pyrite-bound mercury from the coal in the FBD, change in mercury speciation, and increased flow rate of flue gas through the FGD, where oxidized mercury (Hg^{2+}) is removed.

The reduction in Hg^T emissions has allowed Coal Creek Station to meet its Hg emission limits with FGD additives to reduce Hg^{2+} re-emission, thereby avoiding injection of powdered activated carbon.

4. Long-Term Operating Experience

DryFining has been in continuous commercial operation at Coal Creek Station for over four years, achieving availability higher than 95%, and not causing a single unit outage.

The HHV values for the AR (as-received) and DryFining product coals and their blend to the feeders are presented in Fig. 8. During the last two years of operation, on average approximately 95% of the total coal input was refined, while 5% was bypassed and blended with the refined coal. Coal bypass occurs as a result of maintenance on a coal dryer. As the results

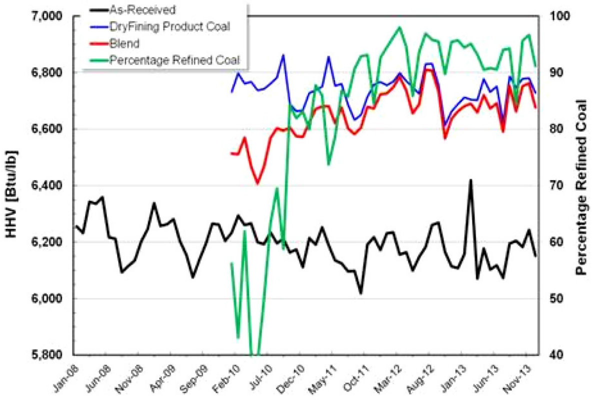

Fig. 8 Higher heating value of as-received and refined coals.

show, following the initial operating period, DryFining process has achieved projected availability of higher than 95%. To date DryFining system has refined 26 million tons of raw lignite supplied by the Falkirk mine.

Moisture removal hovered around the targeted rates. Tiered targets were established for the first six years, reaching the ultimate target of 11.25%[4] in the seventh year.

The coal cleaning part of DryFining system worked well and required little maintenance. Reductions in sulfur concentration in the coal feed to the boiler have been measured and demonstrated on a daily basis.

No or very little thinning of the in-bed HXE walls was detected. Wall thickness measurements were conducted during each major outage. The NDE (non-destructive) readings approximated the OEM (original equipment manufacturer) wall thicknesses. This confirmed that a proper design of the in-bed HXE has a major effect on wear intensity.

In addition, inspection and wall thickness measurements of the low-temperature HXEs, operating partially below the acid dewpoint temperature did not indicate corrosion or wall thinning. This is because of the low sulfur content of the coal and high alkaline content of the ash. The alkaline ash, coating the tubes, is neutralizing deposited sulfuric acid and protecting HXE from the gas-side corrosion.

The particulate control system, a baghouse, performed above expectations. Due to the high humidity of the fluidizing air leaving the dryers, it was expected that, useful life of the bags in the bag houses would be approximately three years. Bag house inspection and bag testing, conducted during each outage, have demonstrated that the bag life is decreasing by only about 15%/year of operation. If this trend continues, the expected bag life will be significantly longer than expected.

4.1 Unit and Station Performance

The performance of both units at Coal Creek continued to improve since commercial operation of DryFining began in December 2009. Fig. 9 offers a comparison of monthly average net unit heat rate values, determined by the input/output method. The average annual improvement in net unit heat rate for Unit 1 is 3.4%—virtually the same as measured during the baseline tests. The heat rate improvement for Unit 2 of 5.8% is higher because it also includes the effect of a steam turbine upgrade.

The station net generation has increased since implementing DryFining since the auxiliary power use by each unit has decreased 5 MW.

In addition, it can be noted that, implementation of DryFining has significantly reduced seasonal variations

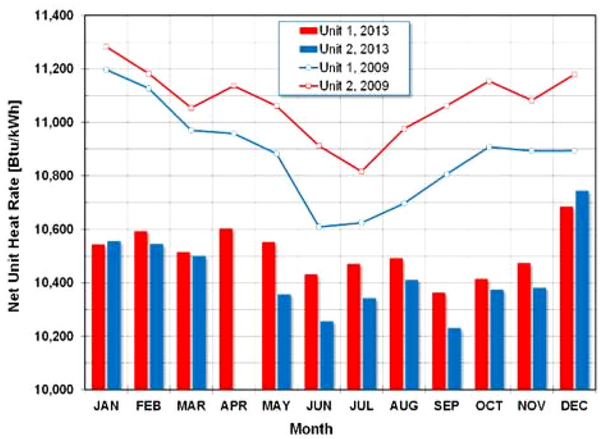

Fig. 9 Monthly average net unit heat rate for refined (2013) and wet (2009) coals.

[4]The target level of coal moisture removal was set based on the analysis of the boiler convection pass performance, performed by an OEM. It represents the maximum moisture reduction at which steam temperature set points can be maintained.

in unit performance. This is because the coal and combustion air are entering the boiler envelope at nearly constant temperature year around. Prior to the implementation of DryFining, temperature of inlet coal and air varied significantly from winter to summer. Therefore, as expected, with DryFining, the heat rate improvement is more pronounced in the winter, compared to the summer. The values of net unit heat rate for April, May and December 2013 are a little higher for Unit 1 due to extended outages during these time periods.

4.2 Unit Emissions

Annual averages of NO_x and SO_x emissions (measured by the plant CEMs) for the Coal Creek Station are presented in Fig. 10 for the 2005-2013 time period.

Following implementation of DryFining, the SO_x emissions were reduced by 44%-46%, while the NO_x emissions were reduced by 24%-25%, compared to the 2005-2009 average. The long-term reduction in NO_x was smaller compared to the test results presented in Table 3, because changes in unit load and combustion settings, experienced in regular operation, increase NO_x.

4.3 Effect of Coal Drying on Major Plant Equipment

Implementation of DryFining coal drying and refining system had positively affected performance of all components in the gas path, from the boiler to the stack. Changes in operation of APHs, mills, and PA fans are summarized in Table 4.

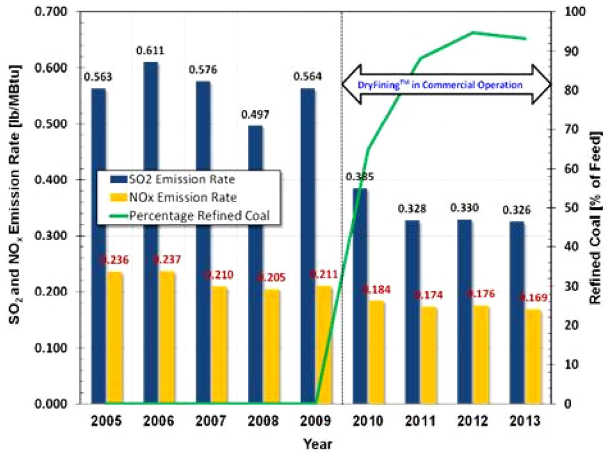

Fig. 10 NO_x and SO_2 emissions before and after implementation of DryFining.

Table 4 Operating parameters: air preheaters, mills and primary air fans.

Parameter	Units	Prior to DryFining	With DryFining
Air preheater (APH)			
APH gas outlet temp.	°F	340-380	290-320
APH gas-side pressure drop	inches w.g.	10-15	5-8
APH primary air pressure drop	inches w.g.	8-12	2-3
APH air leakage	%	8-15	5-6
	klb/hr	840	396
Primary air (PA) fan			
PA Fan discharge pressure	inches w.g.	48-52	40-42
PA flow to mills	klb/hr	2,840-2,920	1,860
Reduction in PA flow	%	NA	~ 30
Mills			
Number of mills at full load		7-8	6
Primary air flow	klb/hr-mill	360	310
Mill capacity	klb/hr	156	165
Inlet coal temperature	°F	35-65	100
Mill power	kWh/ton	9	8
Coal flow at full load	klb/hr	945-1,000	840-900
Bowl pressure drop	inches w.g.	8-11	7-10
Total mill coal flow between overhauls	10^6 tons	2.4	3.3

4.3.1 Boiler

The lower flow rate of refined coal and its lower moisture content have reduced the convective path flue gas flow, heat capacity of the flue gas, and convection heat transfer coefficient. To maintain the reheat steam temperature setpoints, the combustion control system has increased main burner tilts and closed attemperator valves. Total sootblowing steam flow has remained constant, although the usage split changed. The frequency of cleaning furnace waterwalls decreased while cleaning frequency for the convective path increased to improve steam temperatures.

4.3.2 APH

Each unit at Coal Creek is equipped with two Ljungstrom trisector APHs. Prior to the implementation of DryFining, the APHs experienced high differential pressure (ΔP) across the primary air and flue gas sectors. This was a result of high flows and fouling of the heat transfer passages in the APH CE (cold end) layer. The high moisture content of the flue gas along with seasonal variations in the air inlet temperatures were major culprits of fouling and corrosion of the APH CE layer heat transfer surfaces, which needed replacement every three years. The high ΔPs also resulted in high levels of air to gas-side leakage. DryFining virtually eliminated those problems, reducing the ID fan power and the PA airflow.

4.3.2 Mills and Coal Pipes

Each unit at Coal Creek is equipped with eight CE roller mills which feed eight corners of a dual furnace CE boiler (64 burners). Prior to the implementation of DryFining, seven mills were normally run (eight were required for full load in cold weather). Feeder trips, caused by large pieces of coal, rocks, and tramp iron stalling the feeder, were frequent occurrences resulting in load derate and numerous feeder belt replacements. High PA flows, required to maintain mill exit temperatures, resulted in high velocities in the coal pipes and increased erosion. Also, due to the high PA flow, the mill classifiers were set to low to increase internal mill circulation and maintain coal fineness resulting in increased mill power requirements.

DryFining has allowed each unit at Coal Creek to operate at full load with six mills and reduced PA flow. With lower PA flow, the mill classifier settings were increased, causing a decrease in the internal mill recirculation, increase in the mill capacity, reduction in mill power, and reduction of mill wear and mill maintenance. Mill feeder trips have been eliminated, and plant availability has improved.

4.3.3 PA Fans

Each unit at Coal Creek is equipped with two primary air fans employing IGV (inlet guide vane) to control pressure at the APH outlet. The reduction in the APH ΔP, APH leakage and PA flow to the mills had a large positive impact on the PA power and spare capacity.

4.3.4 ID Fans

Each unit at Coal Creek is equipped with four ID centrifugal fans with VFD (variable frequency drive) flow control. After implementation of DryFining, the ID fan power has been reduced between 2-4 MW per unit due to lower flow rate of the flue gas, lower drafts, higher flue gas density, and reduced APH fouling.

4.3.5 FGD System (Scrubber)

Each unit at CCS is equipped with a four-module WFGD (wet flue gas desulphurization) system that was initially designed to scrub 60% of the flue gas from the unit. Modification to the scrubber in the late 90 s allowed scrubbed flow to be increased to 75%. Implementation of DryFining allowed scrubbed flow to be increased to 85%. The short-terms tests performed in 2013 indicated that, 100% scrubbing may be achieved without the need to install a fifth scrubber module.

4.3.6 ESP

The reduction in the flue gas temperature (Table 2) has decreased resistivity of the fly ash which, for the low-rank coals is on a high side, thereby improving ESP performance. The reduced volume of the flue gas decreased its velocity and increased the specific collection area. These effects combined with reduced particulate loading helped to improve the ESP collection efficiency over the past four years.

5. Avoided Capital Expenditures

As previously stated, in 1990, GRE compared a conventional approach (compliance options) to meeting new mercury emission regulations and regional haze limits which would have required installation of the air pollution control equipment to reduce NO_x and SO_x emissions and meet mercury emission limits, to the coal beneficiation alternative. The conventional approach assumed installation of the fifth scrubber module, COHPAC (compact hybrid particulate collector), and SNCR on both units, and second generation of SOFA on Unit 1 (Unit 2 was already equipped with second generation of SOFA.

The cumulative costs of the considered options are compared in Fig. 11 as functions of time.

The DryFining™ fuel enhancement system pays for itself with lower capital costs, higher plant efficiency, and ability to remove a portion of the sulfur and mercury in the coal prior to combustion, and having numerous positive effects on operation and performance of the plant air pollution control system. The combination of all the effects allowed Coal Creek to meet current emission limits without installing additional pollution control systems and equipment.

By implementing DryFining at Coal Creek, GRE avoided \$366 million in capital expenditures, which

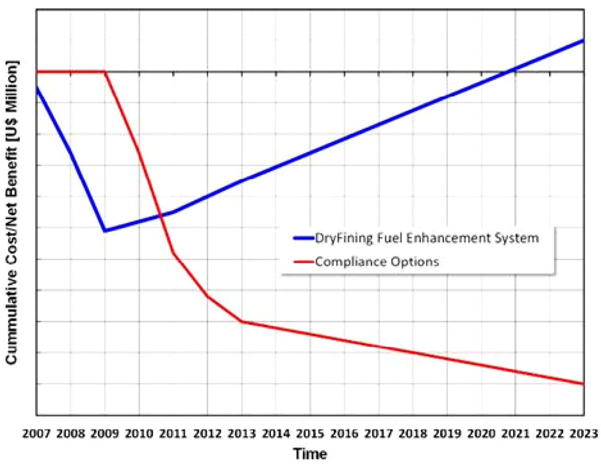

Fig. 11 Cost comparison of DryFining and emission compliance options at Coal Creek.

would otherwise be needed to comply with emission regulations.

6. International and Domestic Markets

There has been significant interest in coal drying over the past several years, especially in overseas markets experiencing high electrical load growth combined with large local resources of low-rank coals. Various lignites and sub-bituminous coals have been analyzed and tested by GRE through the pilot dryer in Underwood, North Dakota. Drying kinetics of tested coal samples was similar, starting with the removal of surface moisture, followed by progressive removal of intrinsic moisture. The segregation of coal impurities was more fuel-specific, depending upon whether and how much of the sulfur was organically bound and the amount of clays. For most of the coals, segregation of S and Hg was of the similar magnitude, as for the Falkirk lignite.

Thermal integration analyses have been conducted for a variety of plants and applications including: sub-critical retrofits along with new supercritical, oxy-fired [10] and dry-feed gasification platforms, including CTL (coal-to-liquid) plant [11], requiring constant moisture content in the gasifier feed. The results show that the DryFining™ fuel enhancement system can be integrated into all analyzed power generation systems to improve their performance and operation.

Up to recently, retrofit opportunities in North America have been limited due to uncertainty in emissions regulations. The clean power regulations to be promulgated under Section 111(d) of CAA (clean air act), and "Building Blocks" for the states expect 6% reduction in CO_2 emissions from existing coal-fired power plants. This is a formidable goal for the power generation industry. DryFining provides an option for significant heat rate improvement and CO_2 emission reduction to power plants burning lignite and sub-bituminous coals.

GRE continues to actively support the commercial development of new plant opportunities in Southeast Asia and Eastern Europe, and retrofit to existing power plants in the U.S.

7. Conclusions

A novel low-temperature coal drying and cleaning process employing a moving bed fluidized bed dryer and using waste heat to decrease moisture content of high-moisture coals was developed in the U.S. by a team led by GRE. The technology was commercialized by GRE in 2009, and is available under trade name DryFining^{TM} fuel enhancement process. DryFining has been in continuous commercial operation at GRE's Coal Creek Station since December 2009. To date DryFining has refined 26 million tons of raw lignite supplied by the Falkirk mine.

In addition to improving net unit heat rate by 3.5%, implementation of DryFining at Coal Creek has resulted in substantial reductions in NO_x emissions (25%), SO_2 emissions (> 40%), and Hg (35%-40%), thus avoiding installation of an SNCR or SCR, additional scrubber module, and injection of powdered activated carbon.

By implementing DryFining at Coal Creek, GRE avoided \$366 million in capital expenditures, would otherwise be needed to comply with emission regulations.

DryFining may be retrofitted to the existing PCC plants, integrated into the newly build PCC plants, and coal gasification (IGCC and CLT) and low rank coal-fired oxyfuel power plants employing dry feed oxygen-blown gasifiers.

Implementation of DryFining into the newly built power plants operating with high steam parameters is especially beneficial for units burning the low rank coals, since their efficiency is severely affected by the high coal moisture content. A reduction of coal moisture is necessary to achieve the full benefits of the advanced PCC technologies.

Thermal integration of DryFining with an existing power plant is site-specific and depends on the available heat sources, space constraints, and general layout of the plant.

DryFining may also be very effectively used to improve quality of washed coals, and improve efficiency and capacity of the plants that have switched from bituminous to sub-bituminous (PRB) coals to reduce SO_2 emissions.

The benefits of coal drying, such as heat rate improvement, increase as moisture content of the raw coal and reduction in coal moisture increase.

In summary, the DryFining^{TM} process at Coal Creek has met or exceeded expectations in terms of availability, plant performance improvement, emissions reduction, maintenance, and positive effect on almost all aspects of unit operation including improvement in availability.

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