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Wood and Coal Cofiring in Alaska—Operational Considerations and Combustion Gas Effects for a Grate-Fired Power Plant

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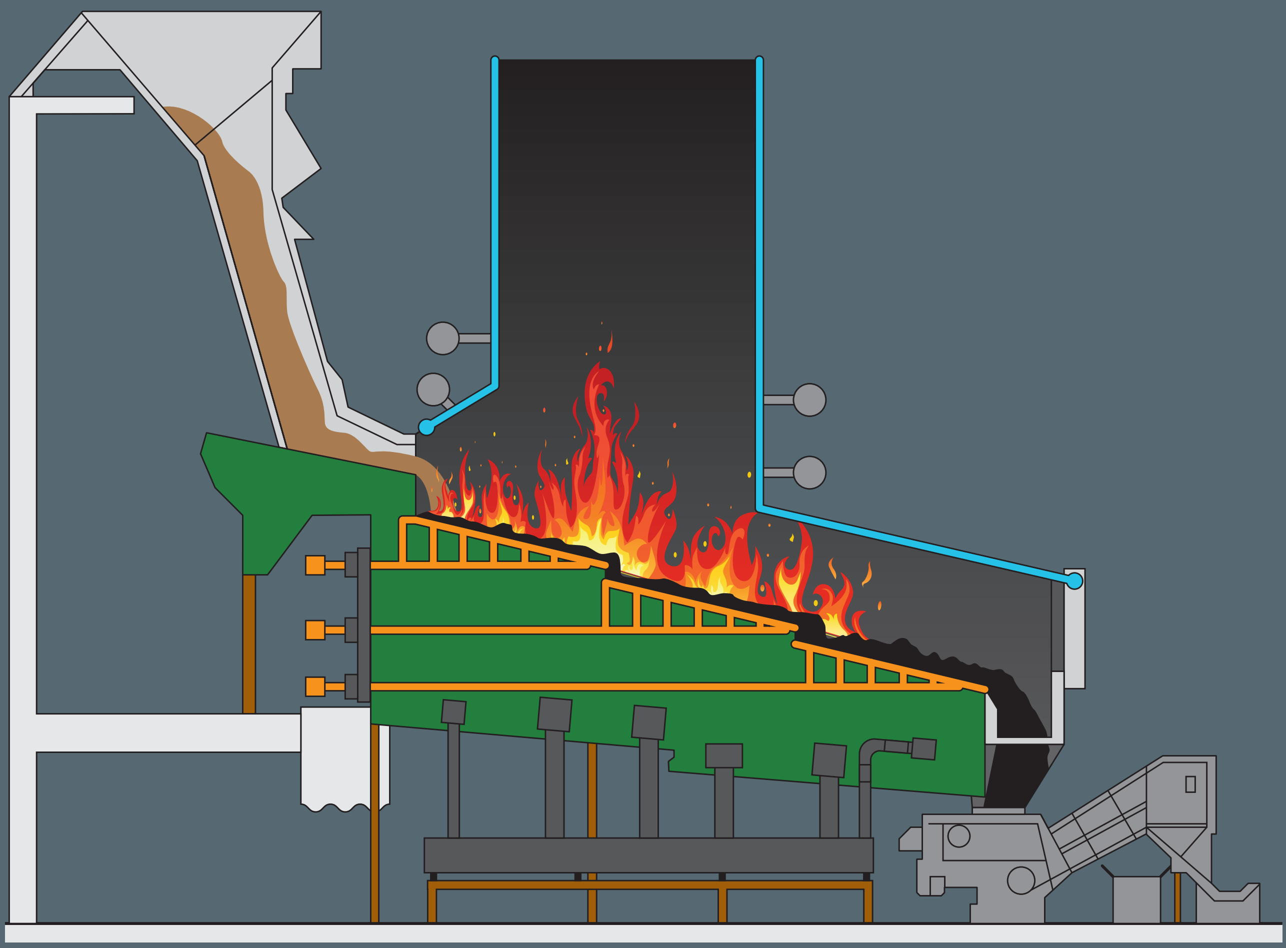

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Cover illustration: Gravity-fed stoker grate combustion system.

Abstract

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Coal is the primary fuel source for electrical power generation in interior Alaska, with more than 600,000 tons burned annually at five different power plants. Woody biomass could be used as part of this fuel mix, offering potential environmental and economic benefits. In this research, debarked chips were cofired with locally mined coal at the Aurora Power Plant facility in downtown Fairbanks, Alaska. During two days of testing, aspen chips were successfully cofired with coal at average rates of 2.4 percent and 4.8 percent of total energy value. Combustion gases were analyzed during combustion of 100- percent coal, as well as at two different blends with aspen chips, for levels of carbon dioxide, carbon monoxide, oxygen, and nitrogen compounds. Carbon monoxide was suggested as the combustion gas most influenced by changes in woody biomass blend rate. The potential logistic and operational challenges when cofiring were also observed. Cofiring biomass at low levels in grate-combustion systems could be performed with relative ease, with only minor impacts on plant operations, including fuel storage, handling, and performance.

Keywords: Coal, electrical power, cofire, combustion gases, biomass, Alaska, wood chips.

Contents

Introduction and Alaska Context

Cofiring Potential in Alaska

Coal is the primary fuel used to generate electricity in interior Alaska. Power is provided by five small interior Alaska power plants, each of which features a grate system of up to about 30 megawatts (MW) in generating capacity. About 600,000 tons of coal are combusted for power annually in Alaska (Nicholls et al. 2006), with significant economic impacts associated with the mining, transporting, and sale of this resource (McDowell Group 2013). The Usibelli Coal Mine near Healy, Alaska, is the state's only operating surface coal mine, and it produces about 1.5 million tons of coal per year (USEIA 2014).

Cofiring is the combustion of two different materials at the same time; usually coal and a biomass fuel. Cofiring of biomass with coal has been observed and documented to reduce emissions of sulfur, nitrogen, and mercury from coal-fired plants, and also could play a significant role in reducing life-cycle carbon dioxide (CO_2) emissions. Typically, biomass is cofired between 5 and 20 percent by mass of the coal (FEMP 2004). Interior Alaska has shown great potential to use a wide variety of biomass sources in cofiring operations (Nicholls et al. 2006, Sampson et al. 1991). The coal power plants in interior Alaska serve a university, a municipality, and two military bases.

In interior Alaska, power generation is achieved using relatively small-scale grate system power plants. For systems of this size, the mechanics of cofiring are relatively simple. Here, fuel particles fall onto a travelling grate and are combusted with airflow from below as well as secondary air above the combustion bed (figs. 1 and 2). In travelling grate systems, a metal grate moves across the combustion chamber and drops any unburned ash and particles into a collection chamber. Often the grate is at an incline to facilitate complete combustion of fuel and the removal of ash after fuel has traversed the length of the grate, in part aided by gravity. One advantage of grate-fired systems is that, when cofiring at low levels, existing equipment can be used without significant modifications (FEMP 2004).

Numerous cofiring tests have been completed using pulverized coal systems (Amos 2002, Boylan 1996, Tillman 2001), many of which are much larger than the Aurora Power Plant described in this report. However, these power generation facilities pulverize the coal to very fine particle sizes to ensure that particles burn completely during short residence times in the combustion chamber. This creates another step in the process because both coal and biomass must be ground to an adequate particle size. Grate systems bypass this extra step because larger fuel particles of both coal and biomass can rest on the grate, while any fine particles that are included in the fuel mix will burn in suspension above the grate.

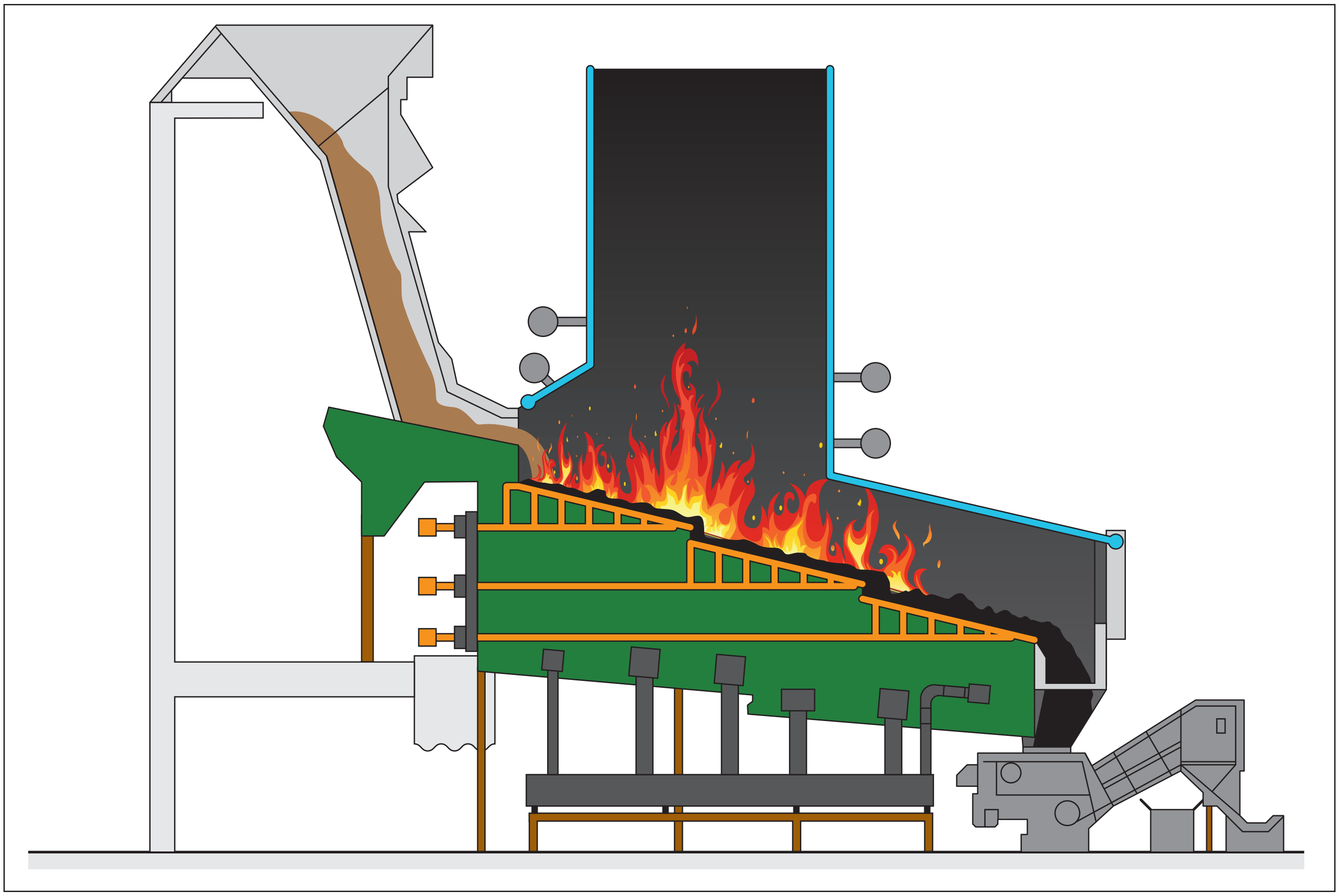

Figure 1—Gravity-fed stoker grate combustion system. Adapted from Loo and Koppejan 2008.

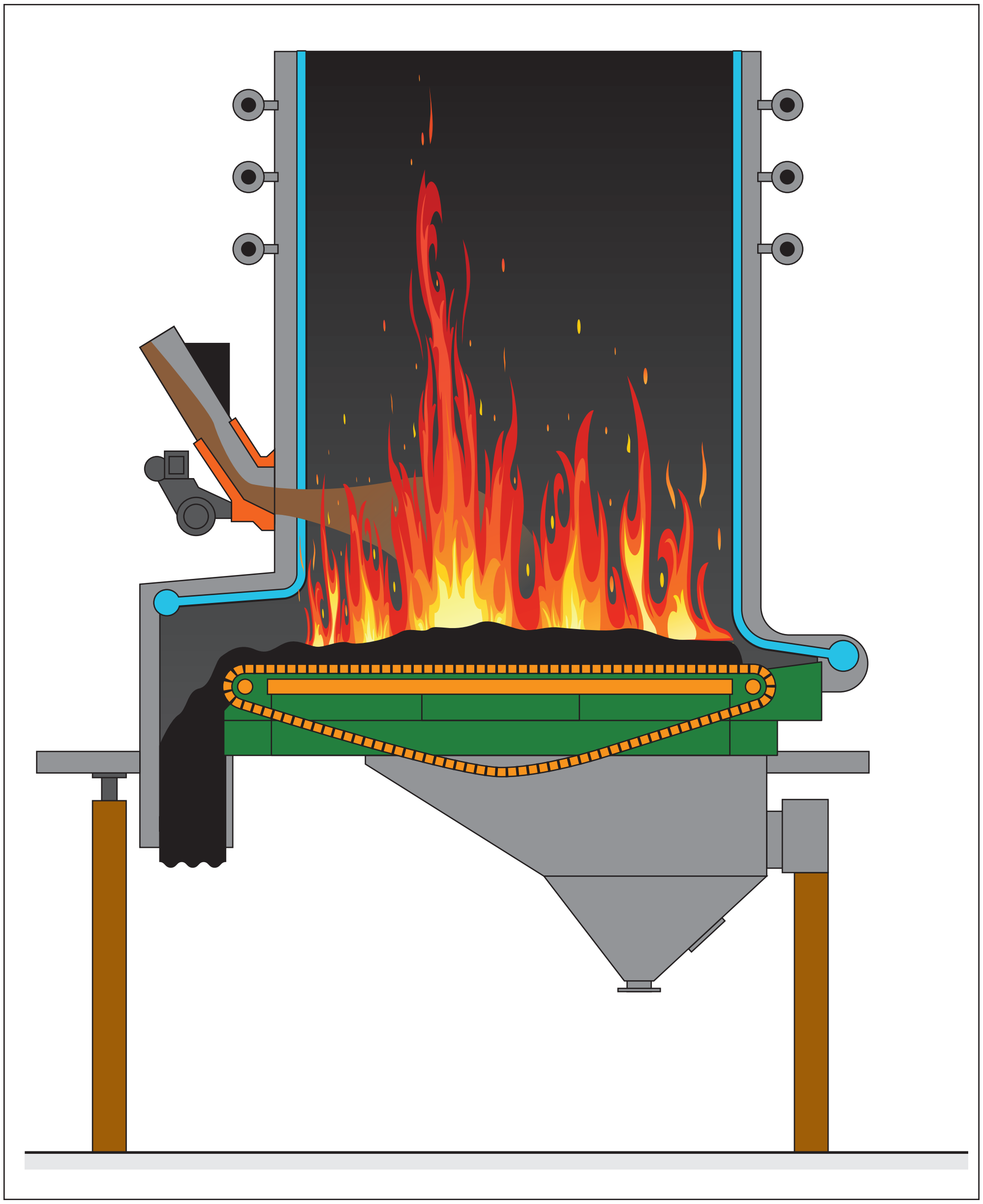

Figure 2—Rotor-fed travelling grate system, showing mechanical transport of fuel particles into the flaming combustion chamber. Adapted from Loo and Koppejan 2008.

Benefits of cofiring—

Miles (1980) articulated several benefits from burning wood with coal on a grate surface, rather than pulverizing the coal and burning it in suspension. Wet wood can carry moisture to the fuel on the grate, reducing peak temperatures and reducing slagging of the ash. Alkali compounds in the wood ash can capture sulfur from the fuel, which can then be removed as flyash.

Wood has a high content of volatile compounds, which means that most of its mass converts to gaseous form before burning above the grate. The more volatile flame of the wood oxidizes unburned hydrocarbons, improving combustion efficiency. However, wood requires more overfire air than coal because of its higher volatility, which can limit the amount of wood that can be burned in most coal boilers. Finally, coal has a high fixed-carbon content, which means that most of the solid burns on the grate in direct contact with air (creating high temperatures at the grate, complementing the wood combustion above).

Power generation in Fairbanks, Alaska—

Fairbanks, Alaska, has great potential to use biomass cofiring, because four power plants in the area consume about 600,000 tons of coal per year, and the city is located near extensive biomass resources (Nicholls et al. 2006). Fairbanks's power comes mostly from stoker-fired grate systems, which are the easiest to convert to cofiring. This is especially true when cofiring wood with coal at small percentages or with similar particle sizes; for example, wood chips and pea coal (FEMP 2004). Also, Fairbanks is within economical transportation distance of considerable timber and biomass resources within the Tanana River Valley (Richmond et al. 1987). Some of these resources are being used as feedstock for a pellet mill in North Pole, Alaska, about 10 mi from downtown Fairbanks. Pellet storage at the site of manufacture is sufficient to buffer both residential and commercial demand as well as potential demand from cofiring. However, because the plant can use raw chips or pellets, a variety of tradeoffs are likely to be associated with the two fuels. Above all, the decision to use either is likely to hinge on the operational and combustion characteristics of the resultant fuel mix.

Aurora Power Plant

Test burns were performed at a power plant owned and operated by Aurora Energy LLC, located in downtown Fairbanks, Alaska (hereafter referred to as Aurora Power Plant). The plant has a nameplate power capacity of 32 MW, and sells up to 25 MW to a local utility, the Golden Valley Electric Association (GVEA). GVEA serves a portion of the Alaska rail belt, which is the largest (and arguably the only) electrical grid system in Alaska (figs. 3 and 4). This grid stretches from Fairbanks to Anchorage, then south to Seward, a distance of about 480 mi. The Aurora Power Plant

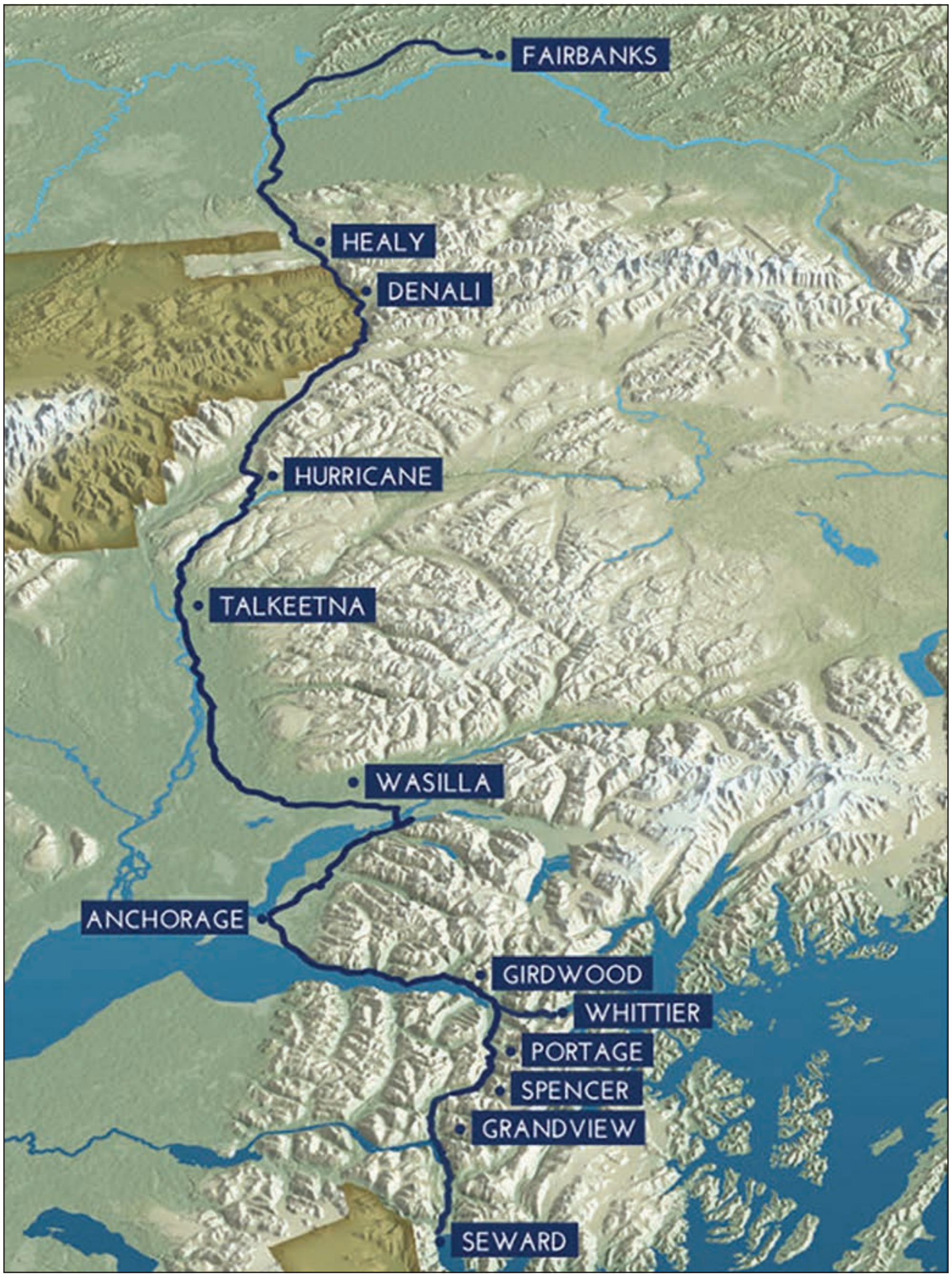

Figure 3—Map of the Alaska Railbelt within the state of Alaska. Source: Alaska Railroad 2016.

burns about 210,000 tons of coal per year, acquired via railroad from the Usibelli Coal Mine. Net electrical generation is close to 180,000 megawatt-hours (MWh) per year. In addition to electricity, the plant provides steam and hot water to a district heating system serving downtown Fairbanks. This network includes approximately 15 mi of buried pipeline and reaches about 50 buildings (Wright 2011).

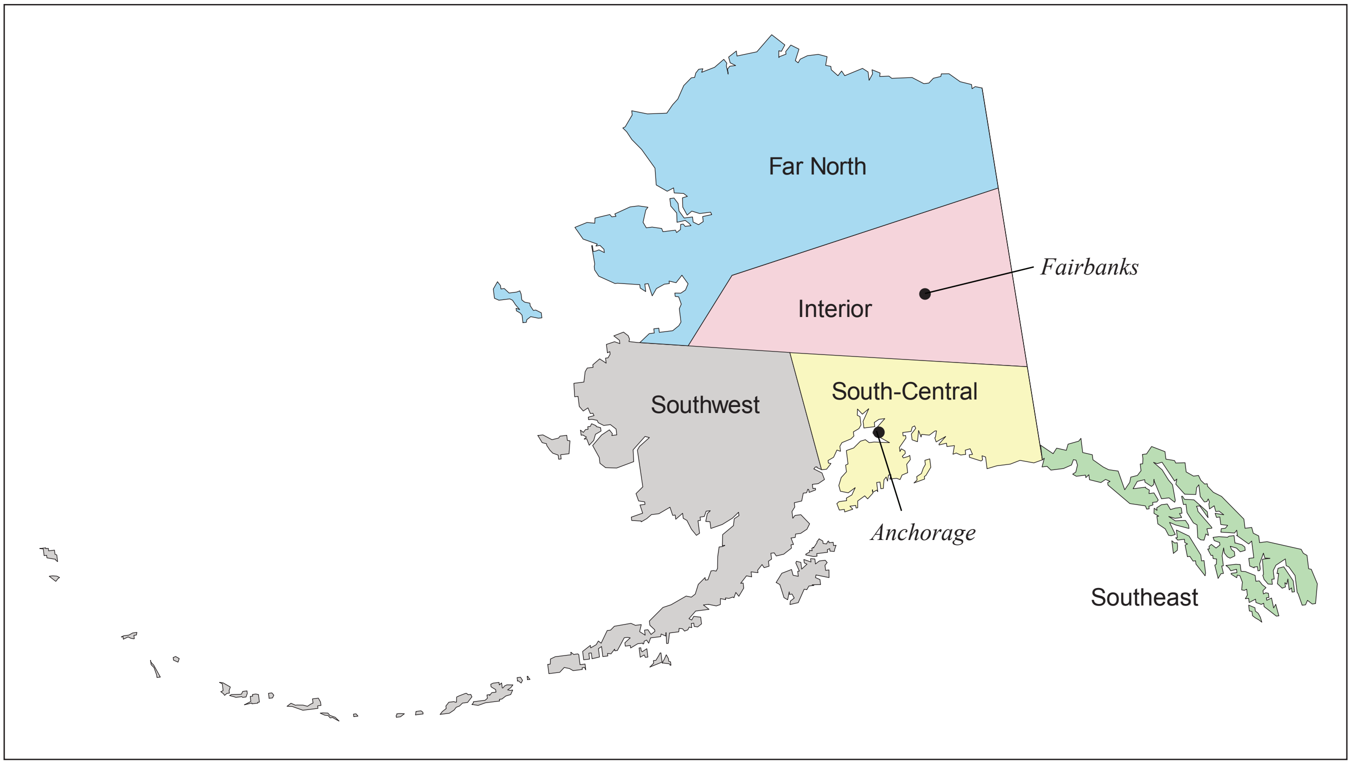

Figure 4—Map of Alaska regions.

The Aurora Power Plant has a series of 11 baghouse filters, used to trap particulate emissions in a device somewhat resembling a large vacuum cleaner. All our combustion gas sampling occurred "upstream" of the baghouse (thus the measurement probe was placed into a gas stream containing particulates). From a practical standpoint, this did not influence our results because we did not measure particulates and do not expect particulates to have had a significant effect on gas constituents, but it did require frequent changing of our filter.

The Aurora Power Plant presently has limited outdoor storage area for wood fuel. Additional storage and handling equipment and procedures would need to be installed and implemented if they were to perform cofiring on a regular basis. However, wood could potentially be delivered efficiently from the nearby wood pellet mill as required, on a scheduled basis resembling "just in time" delivery, reducing the need for the additional storage area. Other options could include construction of storage bins or silos onsite, to hold limited volumes of wood fuel.

Research Objectives

The primary objective of this research was to measure the combustion gases in stack emissions when cofiring quaking aspen (*Populus tremuloides* Michx.) (hereafter aspen) wood chips and coal, under two different cofiring rates. A secondary objective was to identify any problems or challenges in plant operations at the Aurora Power Plant associated with cofiring.

Literature Review

International cofiring—

Coal-fired power plants are one of the leading emitters of CO_2 worldwide, as well as other compounds, including nitrogen oxides (NO_X) and sulfur dioxide (SO_2) (USEIA 2015). Numerous empirical research and modelling studies have demonstrated that cofiring coal with biomass can mitigate these emissions. Internationally, more than 100 coal plants have conducted cofire test burns, most of them in the European Union (EU), North America, and Australia (Koppejan, n.d.). Much of this work has been conducted in pulverized coal systems, and many of the tests have been short-term trials lasting up to a few days. Almost all tests have demonstrated a high degree of technical feasibility for cofiring biomass and coal over a wide range of cofire ratios, biomass types, and operating conditions.

Cofiring studies conducted in the EU include work in Germany (Luschen and Madlener 2013); Italy (Aresta et al. 1997); Poland (Berggren et al. 2008, Ericsson 2007); Serbia (Miljkovic et al. 2013); and Bosnia-Herzegovina (Kazagic and Smajevic 2009). Syntheses of the issue have included overviews of cofiring, including current status and opportunities within the EU (Al-Mansour and Zuwala 2010, Hansson et al. 2009); North America (Agbor et al. 2014, Nicholls and Zerbe 2012); and the United States (Baxter 2005, Hughes 2000). Commercial cofiring systems have also been established in Denmark (mostly in the period 1990–2005), and some of these burn wood pellets with coal.

In addition to wood cofiring, a number of other biomass feedstocks have been investigated, including switchgrass (Amos 2002, Boylan et al. 2000, Tillman 2000); straw (Kær 2004, 2005; Miljkovic et al. 2013; Yin et al. 2012; Yu et al. 2010); rice husks (Kwong et al. 2007); and sugar cane bagasse (Turn et al. 2006). Dong Energy, a large energy company based in Denmark, has cofired both straw and wood pellets at several facilities. It is increasing renewable energy use to the extent that it plans to be coal-free at all seven of its Denmark power plants by 2023 (Kotrba 2017).

Wood pellet cofiring and power generation has also been explored as a means of mitigating CO_2 emissions (Ehrig and Behrendt 2013), and has been adopted by the United Kingdom (UK) as a major greenhouse gas emissions reduction strategy, for example, at the Drax power plant in North Yorkshire, UK.

Grate-fired systems have been studied extensively for both modelling and experimental research (Bauer et al. 2010, Ji et al. 2008, Lin et al. 2009, Rezeau et al. 2012, Sefidari et al. 2014, Sudbrock et al. 2010, Van der Lans et al. 2000, van Kessel et al. 2004, Yin et al. 2008, Zhang et al. 2010,). Several studies on grate-fired systems have focused on combustion gas emissions (Miles 1979, Rogaume et al. 2009, Ross et al. 2002), the subject of the current research.

Numerous studies have also evaluated coal and biomass cofiring on grate systems; however, much of this work has considered nonwoody biomass. For example, the Institute of Energy Technology in Denmark has produced a literature review with a top-down overview of the challenges and effects of cofiring with grate-fired systems (Yin et al. 2008). Also in the EU, considerable research has been conducted on straw biomass on grate systems. This has included two-dimensional mathematical modelling of straw combustion in grate systems (Miljkovic et al. 2013). In general, these studies can be very useful in evaluating temperature profiles, fuel consumption, combustion gas composition, and other variables.

Cofiring is also gaining importance in Asia. China has successfully cofired coal and biomass at the utility scale (Li et al. 2009), accurately measuring flue gas compositions and boiler efficiency. Other tests have been accomplished monitoring specifically the fine ash and trace element emissions of cofiring (Lind et al. 2007). This test was done with circulating fluidized beds and with municipal waste as the cofiring fuel. Other test burns attempting to simulate travelling grates with stationary grates burning waste product have been successful in laboratory settings (Rogaume et al. 2009). This work observed the effects of excess air on grate systems and discovered that excess air in secondary zones of combustion can create additional NO_x production.

Cofiring in the United States—

Much of the cofiring research has occurred at large-scale pulverized coal power plants (Agbor et al. 2014, Al-Mansour and Zuwala 2010, Boylan 1996, Nicholls and Zerbe 2012). Tillman (2001) conducted test burns at more than a dozen different coal facilities throughout the Eastern United States and found that cofiring can be feasible over a wide variety of power plant technologies, biomass feedstocks, and geographic locations. Only minor reductions in efficiency were observed at cofiring ratios of up to 15- percent biomass by energy value Tillman (2001). This work evaluated a number of operational aspects of cofiring as well as combustion gas characteristics. Still other studies have considered life cycle analysis of cofiring, and the potential benefits of including biomass (Mann and Spath 2001, Sebastián et al. 2011). Agricultural residues, including switchgrass, have also been cofired, including at a 600-MW power plant in Iowa (Miles et al. 2005).

Modelling of biomass with pulverized coal systems has also been considered (Backreedy et al. 2005). Pulverized coal systems have also been studied extensively in full-scale cofiring tests. A significant body of work was conducted in the late 1990s in the United States as part of a cooperative agreement between the Electrical Power Research Institute and the U.S. Department of Energy. This research considered mostly pulverized coal systems in the Southern and Midwestern United States, exploring a range of feedstocks and operating conditions (Boylan 1996, Boylan et al. 2000, Prinzing and Hunt 1998, Tillman 2001).

Alaska cofiring—

Relatively little cofiring research has been conducted in Alaska. Sampson et al. (1991) evaluated cofiring and found a strong potential to use wood at ratios of up to about 22 percent of the total fuel load. The authors also found that wood chips could be economically hauled up to 60 mi to an energy facility. In general, cofiring was regarded as technically feasible but not economically viable without financial incentives, when compared to coal alone. Other Alaska cofiring research considered the use of forest thinnings from within Fairbanks' wildland-urban interface as potential cofiring feedstock (Nicholls et al. 2006). Whole-tree biomass had been harvested and piled in windrows to reduce wildfire risk near Fairbanks. This material represents a viable short-term biomass source for cofiring (although none was used for this purpose).

In Alaska, all the coal power plants use Usibelli coal, a subbituminous coal with a relatively low energy value (McDowell Group 2013). This is significant when cofiring with low-moisture wood fuel because, in this case, the energy contents of wood and coal are comparable. Many other coal varieties, including those in other parts of the United States, have considerably higher energy value than wood, sometimes twice as much or higher, depending on the moisture content of the wood fuel. Usibelli coal is also noted for its very low sulfur content. Therefore, the benefits of sulfur emission reductions would likely be less when cofiring biomass in interior Alaska, versus other regions of the country that burn higher sulfur coal. However, we did not measure sulfur emissions in the current research at the Aurora Power Plant.

In summary, considerable cofiring research has been conducted on grate-fired systems globally over the past several decades; much of this within the EU. A wide range of biomass types and operating conditions have been considered, and a consistent finding has been that cofiring at low energy ratios (i.e., between about 5 and 20 percent of total energy) generally poses very few operational problems in these systems. It is also worth noting that much of the stimulus for cofiring in the EU has come through legislative mandates related to greenhouse gas emissions. The United States, which does not have such mandates in place, is not presently incentivized to cofire by economics alone. Thus, although the operational feasibility of cofiring has been well established, the economic feasibility is still unproven in many power markets.

Grate Systems Overview and Challenges

In grate-fired systems (as opposed to pulverized coal systems), the grate provides four main functions: (1) provide a platform for fuel drying, (2) burn the fuel, (3) distribute combustion air, and (4) dispose of ashes (Nicholls 2014). Grate systems, where fuel rests on either a stationary or travelling grate, are most common for small-scale (i.e., less than about 50 MW) energy production facilities that combust solid fuels.

There are two general types of systems. The first is a spreader stoker (fig. 2). This type of facility has fuel that is fed into an overthrow rotor, where the fuel is thrown (i.e., “spread”) toward the opposite side of the chamber, and the fuel then travels back toward the spreader before exiting into an ash chamber. Specially designed stokers capable of handling two fuel types are also available from some manufacturers. A second type of fuel spreader is known as the conical spreader (fig. 1) and features a cone-shaped chamber located adjacent to the combustion chamber. The conical chamber receives fuel until a certain predetermined level is reached, then dumps fuel by gravity into the combustion chamber. An advantage of gravity-fed conicals is their reduced likelihood of jamming, a problem sometimes encountered when the mechanical paddles in spreader stokers attempt to pass oversized or stringy pieces of wood. However, a disadvantage of conicals is their tendency to distribute particles of uneven size or density unevenly in the combustion chamber.

The Aurora Power Plant employs one spreader-stoker and two gravity-feed systems at their three combustion units. Our research was conducted on one of the gravity-feed burners, which consisted primarily of a conical to distribute fuel across the width of the combustion chamber. With gravity-feed systems, fine fuels are burned in suspension and larger particles come to rest on the grate, being combusted as they travel with the grate toward the ash pit. This illustrates the importance of fuel size when firing grate systems—if the fuel mix contains too many fines, particles will be swept upwards in the air stream and may experience incomplete combustion. If particles are too large, they may remain partially uncombusted during the entire residence time on the grate, and fall into the ash pit, containing unburned carbon.

When cofiring biomass with coal, each system has its own set of challenges, depending on size, year of manufacture, design of combustion chamber, and density and size of fuel particles, among other variables. With spreader-stokers (fig. 2), oversized fuel can potentially jam the rotors, rendering them ineffective. Variable-sized biomass (and oversized pieces in particular) could adversely affect the rotor operation or cause clogging. This makes it critical that screening systems effectively remove oversized pieces during the chipping process. With conicals, there is often a diminished ability to distribute fuel uniformly across the grate (because fuel distribution is based primarily on gravity rather than mechanical action).

Wood Fuel Quality for Cofiring

Many fuel-related variables can influence cofiring operations. Some of these include the moisture content (MC) of the fuels; percentage of biomass (relative to coal); relative energy content of the fuels; average wood particle size (relative to coal particle size); range of fuel particle sizes; and fuel quality (including presence of bark, needles, and dirt). Fuel characteristics can also influence many operational aspects of cofiring, including fuel storage, conveying, fuel mixing, distribution on the combustion grate, combustion gas generation, opacity of emissions, heat transfer for steam generation, and ash generation. In the current study, the wood and fuel particles were approximately the same size, facilitating mixing and conveying (fig. 5). Because grate systems operate most effectively with a small amount of open air space (typically about 3 percent of grate area) (Nicholls 2014), differential

Figure 5—Wood and coal sample taken for moisture content and cofire ratio tests.

burn rates can influence the amount of this open space, which can in turn influence air velocity and other combustion chamber parameters. Having particles of varying fuel MC, sizes, and composition (i.e., wood, bark, foliage) can also lead to differential burn rates. Coal boilers have limited overfire air so that only a limited amount of turbulent mixing occurs, needed to burn the volatile gases from wood combustion. Thus, higher carbon monoxide (CO) levels and particulate carryover can occur when cofiring wood and coal (versus burning coal only).

The quality of the fuel also affects all aspects of the fuel-burning process (Rogaume et al. 2009). Transporting fuels of inconsistent types make it more challenging to handle, load, and unload them. Non-uniform wood, such as oversize pieces, chunks, and stringy bark, could potentially clog grates, get stuck in conveyor belts, and adversely affect the mixture of fuel. Several strategies can be employed for oversized fuel. A rotating disk “scalping” screen can be used to remove oversized fuel. Also, hammermills can be used to reduce the dimensions of oversized fuel, which can then be recombined with properly sized fuel before it is transported to the combustion chamber.

Fuel that has wide MC variation will create inconsistencies in the combustion chamber. In turn, some fuel may fully combust much more rapidly than other fuel. This could potentially lead to variance in plant operation parameters (including steam production), thus making the plant less efficient and creating an additional challenge for operators.

Whole-tree chips from fuel treatments, including timber harvests, brush removal, and land clearing, could all be used for cofiring (Nicholls et al. 2006). Regarding fuel quality, these biomass sources are likely to be less uniform than the premium aspen chips used in the current study, and more likely to contain bark, dirt, and other contaminants, resulting in higher ash content and lower heat content. Further, land clearings often represent a sporadic “one-time” source of biomass. Thus, mill residues from an ongoing wood products facility are a preferred source for reliability and consistency, especially if available at low cost.

Wood-Coal Mixing and Conveying

Mixing a consistent fuel blend can be a challenging aspect of small-scale grate system cofiring; however, the degree of success depends greatly on the methods used. The greatest degree of control would be realized when there is a separate metering bin for the wood. Here, wood and coal are independently metered and combined just before entering the boiler. However, if there is only one common fuel feed mechanism, it is challenging to determine the rate at which wood is being added to the blend. In some cases, wood and coal are mixed together by a front-end loader on an asphalt pad (Tillman et al. 2001); in other cases, they can be added directly to a conveyor containing coal.

For small-scale grate systems, the easiest way to get an acceptable mixture of wood is generally to mix the biomass and coal as they are transported inside the facility, which was the method used at the Aurora Power Plant. This would more than likely be completed while moving the fuel to the bunker that will directly feed into the combustion chamber. The fuel must travel from its storage location, on conveyor belts, to the final bunker. In this scenario, wood and coal are transported on separate conveyors, with each belt being set to a certain speed to create the desired mix. The bulk density of the fuels would be very important in getting accurate measures of the cofire percentage, either by energy content or by mass. One problem that may be encountered with this approach is that fuel may settle while it is in bunkers or while it is being moved around. This could, again, cause inconsistent mixing in the fuel blend, but would be an unavoidable consequence of this blending method. Despite these potential challenges, the wood and coal mixing procedures resulted in very uniform fuel blends during our test burns at the Aurora Power Plant (figs. 5 and 6).

Figure 6—Fully mixed wood chips (white) and coal (black) mixture travelling on a conveyor belt before entering the combustion chamber.

Methods

Overview—

Cofiring tests were conducted over a 2-day period in March 2015 at the Aurora Power Plant in downtown Fairbanks, Alaska. Wood chips were provided by Superior Pellet Fuels in North Pole, Alaska, less than 10 mi from the power plant. About 40 tons of clean, uniformly sized aspen chips were purchased for $70 per ton. This price is well above the market price for woody biomass residues in interior Alaska because they were chipped specifically for this test. They were high-quality (clean, uniform-sized) chips to minimize the likelihood of fuel-related problems in blending, conveying, or combustion. Chips were approximately 1.5 inches maximum dimension and smaller (fig. 7). They were trucked directly from the pellet mill to the power plant (about 8 mi). Once at the Aurora Power Plant, wood chips were stored in an area of about 800 ft^2 (fig. 8). A front-end loader was used to transport the chips to the fuel feed system. Once fuel was inside the plant, a conveyer belt system was used to create a uniform fuel mix of wood and coal at the desired ratio (fig. 6).

The bulk density and particle geometry of the wood and coal can influence the mixing properties of the blend. In the combustion chamber, wood fuel can potentially burn more rapidly than the coal. In some cases, this can result in a “swiss cheese” pattern of fuel on the grate and affects the dynamics of the air being fed through the grate (although this was not observed in our work at the Aurora Power Plant).

Figure 7—Aspen wood chips used for cofiring, showing uniform size and composition as well as lack of bark, foliage, or contaminants.

Figure 8—Outdoor wood storage of aspen chips at Aurora Power Plant.

Cofiring rates—

We investigated two cofiring rates: (1) 2.4 percent by energy value with an original target of 5 percent by energy value for the low-level testing (day 1), and (2) 4.8 percent of energy value with an original target of 10 percent for the high-level testing (day 2). We measured the composition of combustion gases through the exhaust stack from a point on the roof of the power plant (fig. 9).

Baseline data representing the power plant's standard procedure (i.e., coal-only combustion) was collected for about 1 hour each morning. Afterward, blended fuel (coal with biomass) was introduced at target cofire rates of 5 percent for the low cofire day (day 1) and 10 percent for the high cofire day (day 2). Actual rates were lower than the target rates (table 1) owing to the difficulty of weighing and calculating large volumes of wood and coal fuel in real time. We determined actual cofiring rates by collecting fuel samples at the accessible point closest to the combustion chamber (immediately before fuel was introduced into the conical (fig. 5). We then separated wood from coal, weighing each separately. The coal energy content was provided by the plant, and wood energy content was determined by oven-drying samples, then running them through a calorimeter. The actual cofire rates, based on total energy value, were then calculated. Although our target cofire rate was 5 percent of total energy value, the true cofire rate was calculated to be between 2 and 3 percent (day 1 testing).

Figure 9—Bacharach PCA3 probe inserted into combustion flue gas stack (with red cloth, center); Testo probe inserted into the stack at the left side of photo.

Table 1—Actual cofire rates for cofiring tests conducted at Aurora Power Plant, March 2015

Cofiring rate	Sample collection time	Cumulative time	Wood fuel by mass	Wood chips by energy content	Average co-fire rate, by energy content
		Hours	- - - - - - - - - - - *Percent*	- - - - - - - - - - - -	
	9:45 a.m. (start)	0	—	—	
Low	11:19 a.m.	1.5	6.60	4.47	2.40
	12:45 p.m.	3.0	2.37	1.58	
	14:00 p.m.	4.25	1.75	1.16	
	15:00 p.m.	5.25	3.51	2.35	
	16:00 p.m.	6.25	3.62	2.42	
High	11:00 a.m. (start)	0	—	—	
	12:30 p.m.	1.5	8.06	5.78	4.81
	13:30 p.m.	2.5	6.14	4.38	
	14:30 p.m.	3.5	9.24	6.65	
	15:30 p.m.	4.5	6.53	4.66	
	16:30 p.m.	5.5	3.66	2.59	
	17:30 p.m.	6.5	2.05	1.45	
	18:30 p.m.	7.5	0.47	0.33	

Baseline data (coal only) was collected for 1 hour, followed by approximately 4.5 hours of wood and coal cofiring (table 2). Because of the difficulty of mixing the fuel stream in real time to precise levels, the high cofiring rate was estimated to be between 4 and 5 percent of total energy value. Baseline data were collected for 1 hour, using 100 percent coal. Over the next 2 hours, the wood and coal mixture started filling the bunker, after which cofiring was started.

Table 2—Daily schedules for low cofire and high cofire test dates

Event	Time of day	Cumulative time (hours)
Day 1 (March 17, 2015)—low cofire rate:		
Baseline data collection start	8:15 a.m.	0
Baseline data collection finish	9:15 a.m.	1.0
Bunker begins filling with wood/coal mixture	10:15 a.m.	2.0
Wood reaches grate (approximate)	11:15 a.m.	3.0
Cofire data collection start	11:30 a.m.	3.25
Final cofire data collection	16:00 p.m.	7.75
Day 2 (March 18, 2015)—high cofire rate:		
Baseline data collection start	8:45 a.m.	0
Baseline data collection finish	9:45 a.m.	1.0
Bunker begins filling with wood/coal mixture	11:15 a.m.	2.5
Wood reaches grate (approximate)	12:30 p.m.	3.75
Cofire data collection start	12:45 p.m.	4.0
Final cofire data collection	18:00 p.m.	9.25

Combustion gas monitoring—

Combustion gas measurements were taken with a combination of three devices: a Bacharach PCA3 portable combustion gas analyzer[1] (inserted into the stack), a more sophisticated Testo analyzer (also inserted into the stack), and in-plant monitoring equipment. The Bacharach analyzer was used to collect data, including oxygen (O_2) (percentage), CO (parts per million [ppm]), CO with respect to O_2 (ppm), combustion efficiency (percentage), and excess air (percentage). This probe was inserted directly into the stack to its full length, and was well sealed to allow minimal outside air to enter through the sampling hole (fig. 9).

A Testo combustion analyzer was also used, and had a 28-inch probe to reach the center of the flue, which was estimated to be close to 4 ft in diameter (fig. 9).

[1] The use of trade or firm names in this publication are for reader information and do not imply endorsement of the U.S. Department of Agriculture of any product or service.

The entry point for the probe was also very well sealed to prevent outside air from reaching the sampling point. This unit was used to measure nitric oxide (NO) and nitrogen dioxide (NO_2) (ppm) along with the same parameters as the PCA3. Opacity was measured using sensors that were part of the power plant's fixed equipment. The PCA3 device was set to take readings every 2 minutes for the duration of the test burns. The Testo took measurements in 30-second increments and is visible in the background of figure 9. The measurements of CO were collected with the portable PCA3 unit, while the NO and NO_2 was measured by the Testo unit. Opacity was measured by the Aurora Power Plant's in-house monitoring equipment.

Discussion and Results

Low-Level Cofiring Tests

"Low" cofiring testing was performed on day 1 of testing (March 17, 2015) for a total of about 5 hours. Average flue gas concentrations for CO increased markedly (by 82.4 percent) when comparing baseline to cofiring conditions (fig. 10A; table 3). Day 1 NO decreased by 20.32 ppm or 17.7 percent (fig. 11A); and NO_2 increased by 2.27 ppm or 13.3 percent (all for cofiring versus baseline levels) (fig. 12A). Other cofiring research (Tillman et al. 2001) has indicated a greater than 1 percent reduction in NO_x compounds for each 1 percent level of cofiring. Also during the low cofire test, opacity increased slightly from an average of 5.7 to 5.9 percent (cofiring versus baseline) (fig. 13A); however, it is not known whether this is within the normal operating variation of the plant.

High-Level Cofiring Tests

The high cofire level was tested on day 2 (March 18, 2015), and lasted close to 5 hours. Average combustion gas CO content increased by 74 percent, from 125 to 220 ppm, for cofiring tests versus baseline conditions of coal only (fig. 10B; table 3). Higher CO levels were likely the result of either higher MC of wood (and the need to vaporize this moisture) or insufficient overfire air, which limited complete combustion. At the high cofiring level, NO increased slightly from 100.33 ppm to 101.16 ppm (fig. 11B), and NO_2 decreased from 20.38 ppm to 18.42 ppm, compared to coal only (fig. 12B). Also for the high cofiring level, opacity increased slightly (from 6.0 to 6.1 percent) as a result of cofiring (fig. 13B); however; it is not known whether this is within the normal operating variation of the plant.

Several similarities between low and high cofire tests were observed. The first major similarity is that the observed flue gas CO increased substantially with the addition of biomass to the fuel mix. Mean opacity increased, although only slightly, on both days when wood fuel was introduced, and 100 percent coal was no longer being burned. Although these levels showed very little difference, opacity could become an important future consideration because of air quality concerns in Fairbanks (particularly during winter months). Similarly to CO levels, opacity could also be influenced by optimizing the overfire air ratios.

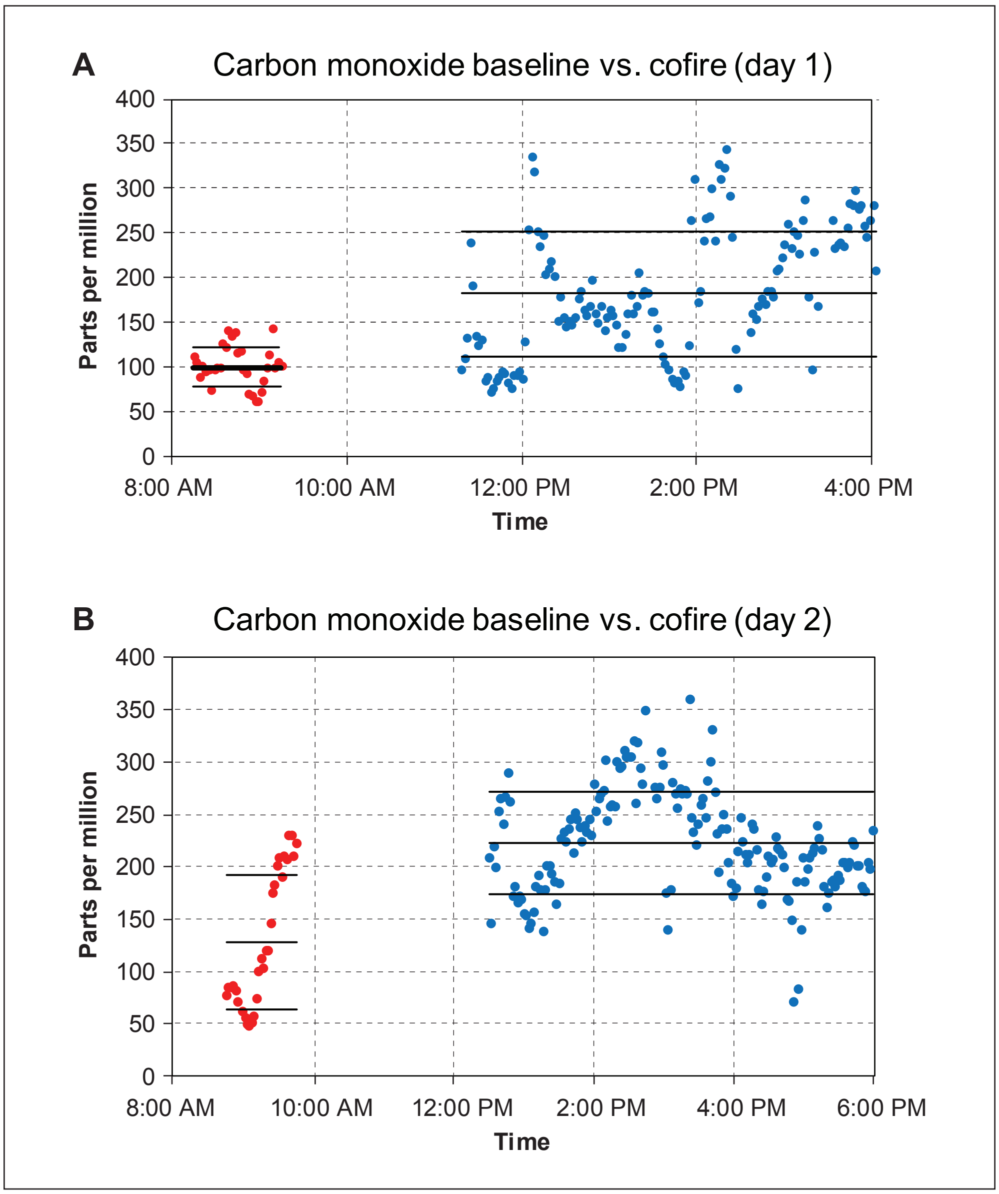

Figure 10—(A) Carbon monoxide measurements versus time from day 1 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation); (B) carbon monoxide measurements versus time from day 2 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation).

Table 3—Combustion gas comparisons between low cofire rate (2.4 percent of heat value, day 1) and high cofire rate (4.8 percent of heat value, day 2) for the Aurora Power Plant in Fairbanks, Alaska

		Low cofire rate (day 1)			High cofire rate (day 2)		
		Coal only	Wood and coal	Percent change	Coal only	Wood and coal	Percent change
		Mean values					
Carbon monoxide	Parts per million	99.97	182.34	+82.40	127.87	222.47	+73.99
Carbon dioxide	Percent	10.04	9.29	-7.53	8.51	10.34	+21.56
Nitric oxide	Parts per million	112.93	92.61	-18.00	100.33	101.16	+0.82
Nitrogen dioxide	Parts per million	14.36	16.63	+15.84	20.38	18.42	-9.58
Opacity	Percent	5.73	5.90	+2.92	6.02	6.08	+1.00

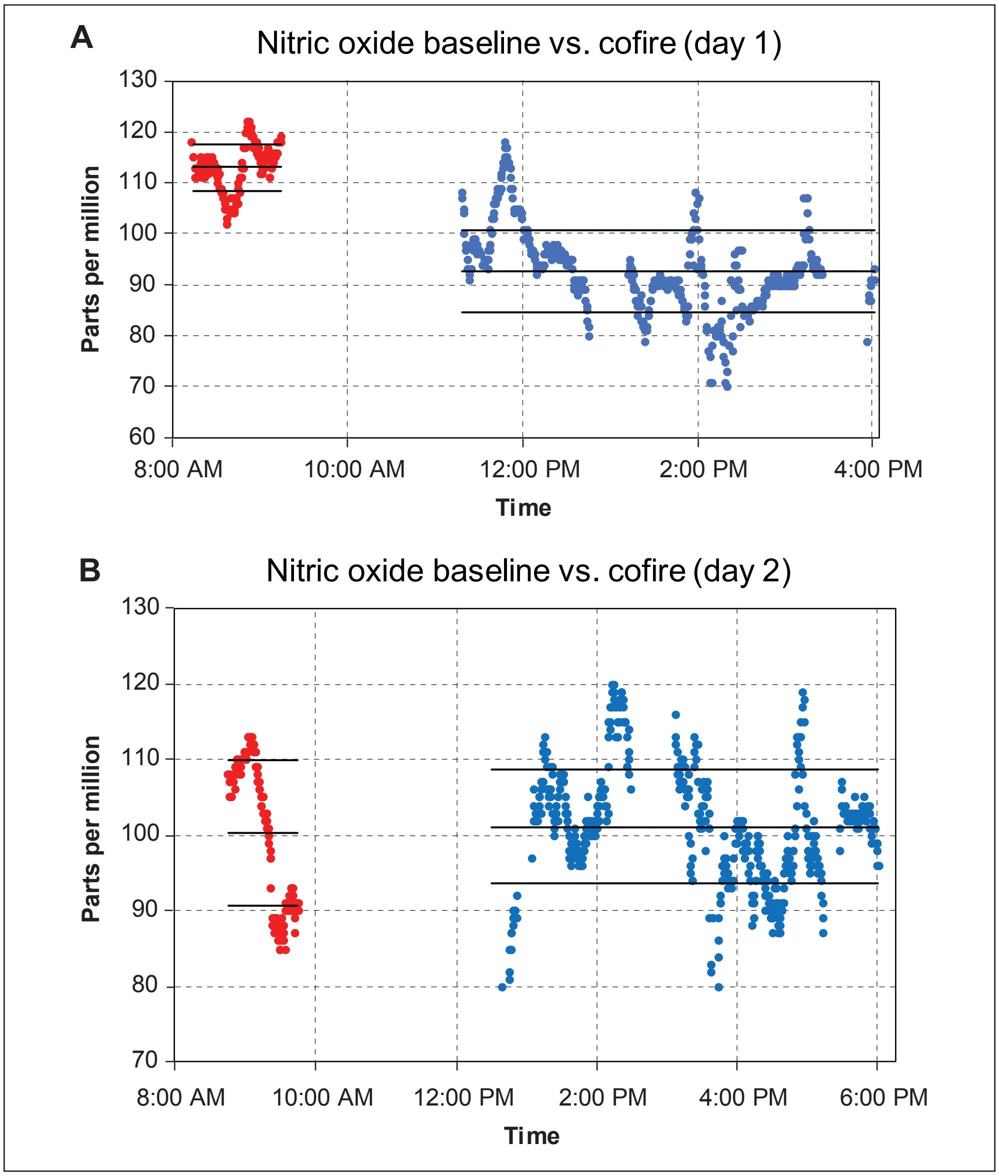

Figure 11—(A) Nitrogen oxide measurements versus time from day 1 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation); (B) nitrogen oxide measurements versus time from day 2 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation).

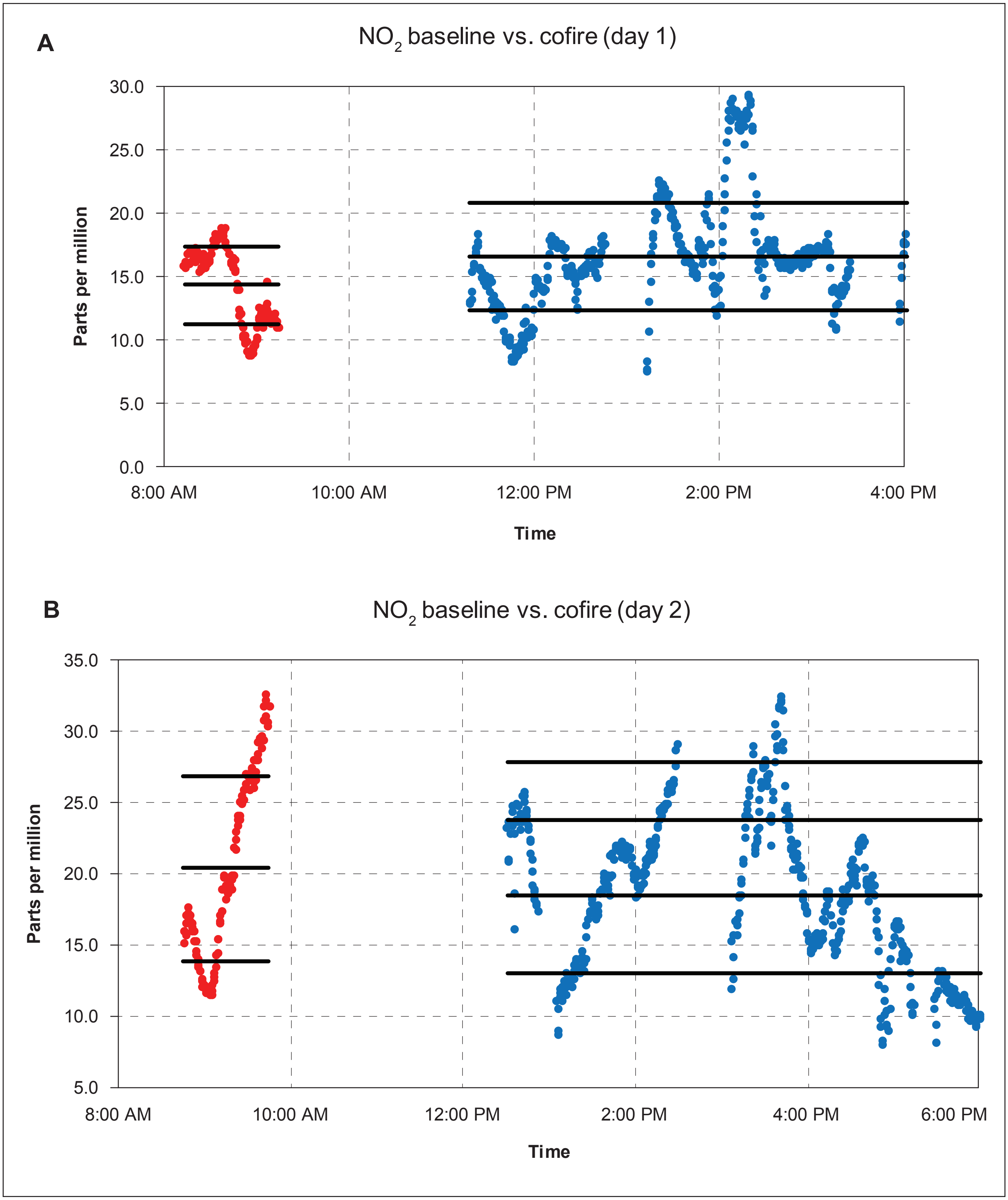

Figure 12—(A) Nitrogen dioxide measurements versus time from day 1 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation); (B) nitrogen dioxide measurements versus time from day 2 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation).

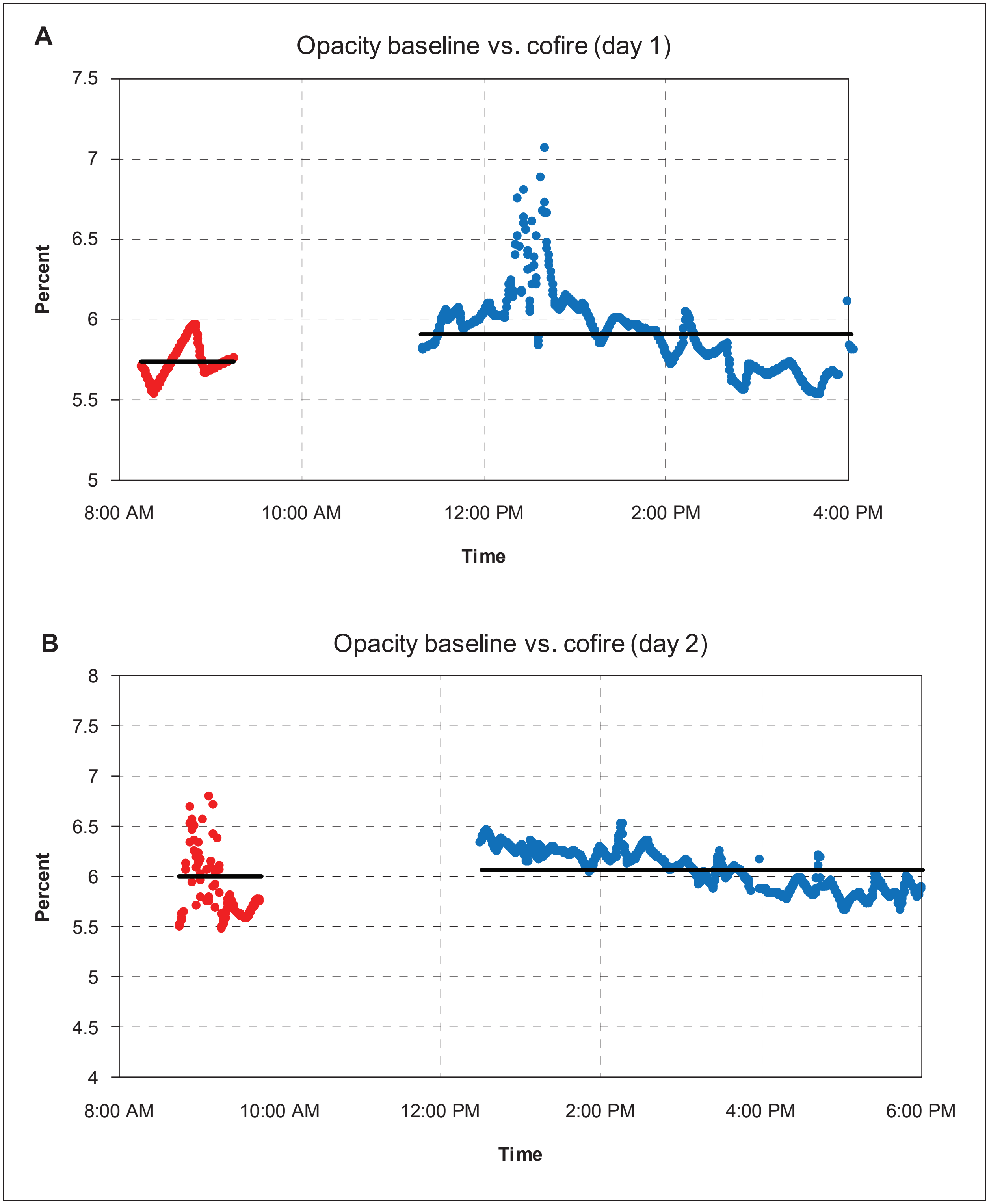

Figure 13—(A) Opacity measurements versus time from day 1 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation); (B) opacity measurements versus time from day 2 (solid horizontal lines denote observation means; dashed lines denote ± 1 standard deviation).

Power plant operations—

Overall, plant operation was not noticeably affected by the introduction of biomass to the fuel mixture throughout the test burn. The operator noted that, for the low-cofire rate (day 1), the mixed fuel burned well with no issues and no major adjustments. However, for the high-cofire rate (day 2), he noticed that combusting the fuel was somewhat more challenging, requiring careful observation and management of feed rates to maintain uniform combustion conditions across the grate and also to maintain constant steam loads.

The high wood MC, estimated to be close to 40 percent (green basis), was likely a factor influencing combustion during the high-cofire tests (day 2). Dry biomass fuels, like wood pellets, would presumably reduce this difficulty. High moisture also requires more turbulent mixing in the flame zone to evaporate the moisture and burn out the volatile gases.

Because the wood fuel was well screened, individual particles were uniformly sized and were only slightly larger than most coal particles. This could be a primary reason that there was so little differential settling, and the wood and coal mixture remaining uniform throughout conveying and combustion. As part of this process, the gravity-fed conical did a good job of distributing fuel uniformly across the grate. We think that this can also be attributed to the very uniform size and MC of the wood chips (fig. 7).

During the cofiring tests, plant operators made only minor adjustments to conditions within the combustion chamber. Note that the Aurora Power Plant arranged to have an experienced boiler operator present during the cofiring tests. This operator was able to respond quickly to changes in burning conditions and steam loads brought about by the presence of wood fuel having high MC, greater surface area, and a higher volatile content than the coal. A less experienced operator might have been less responsive and less effective in adjusting conditions to account for the effects of the mixed fuel.

It is generally accepted that wood has a lower overall ash content than coal (Demirbaş 2003, Sahu et al. 2014). Therefore, when cofiring, the reduction in ash content would be expected in proportion to the ratio of biomass included. Although we did not evaluate ash production as part of the current study, we would expect a modest reduction in ash generation rates if cofiring were conducted on an ongoing basis.

One issue that could influence long-term biomass cofiring is the potential for fouling and slagging (Pronobis 2006). Fouling and slagging are the result of deposits on boiler surfaces, which is an issue with biomass feedstocks given their high alkali, silica, or chlorine content (Vega-Nieva et al. 2015). Miles (1980) found that firing wet wood with coal reduced slagging at the grate. Although there was no way for us to evaluate the effects of biomass on slagging during this 2-day study, it could become a concern when cofiring for longer periods of time at higher energy ratios.

The following specific comments were offered by the plant operator who monitored cofiring testing:

- **Cofiring rates**—In general, aspen chips burned very well when cofiring Chena 3 at the low cofiring rate.
- **Cofiring rates**—For the higher cofiring rate, there was some minor segregation of aspen chips from coal. Combustion was also somewhat more difficult to maintain owing to greater level of moisture in the combustion chamber (NO_x and CO were therefore influenced).
- **Moisture content**—If chips had been at a lower MC, rather than fresh green, they might have burned more uniformly with more consistent steam load, even at the higher cofire rate.
- **Spatial distribution of wood and coal**—In general, the spatial distribution of wood and coal in the combustion chamber was quite uniform (no problems noted).
- **Particle size range**—If wood chips are too big or too stringy, they could get caught in the "under bunker" part of the fuel conveying system, causing problems. Chips or hog fuel in the 2-inch maximum dimension range could work well for the plant's current fuel handling capability. However, 3-inch and larger particles could potentially cause problems. Sawdust size should work well as long as it can be conveyed satisfactorily.
- **Contaminants**—Dirt, small rocks, and other contaminants could be a problem, but not a cofiring barrier. However, any rocks in bottom ash would need to be run through a crusher, creating an additional processing step.

Practical Limitations of the Study

A practical limitation of this research was that our test period was limited to 2 days (a total of 10 hours of cofiring). This was due to budget restrictions as well as the large amount of wood needed to conduct the test, even at relatively low blend ratios. An estimated 30 tons of wood was burned. However, it would have been preferable to collect data for several weeks or longer to establish baselines and trends. Our test lengths paralleled those of other researchers who were not able to collect data for more lengthy trials (Qiu 2013, Sefidari et al. 2014). Longer term cofiring studies, when feasible, would allow observation of the effects of biomass on corrosion, fouling and slagging, ash generation, and other long-term operating metrics.

Note also that, given the size of this power plant (with more than 600 tons of coal typically being burned each day), it was difficult to conduct a controlled experiment in which all variables were precisely regulated. Rather, this was an empirical study that focused on the operational feasibility of cofiring.

Another limitation was that baseline data (for coal-only combustion) was collected for only about 1 hour each day. These data turned out to be more variable than expected (figs. 10 through 13), and, in retrospect, we would have been better served to sample baseline data for a longer period (perhaps 6 to 12 hours or longer). However, despite these limitations, we believed that that the study provided valuable insights into plant operations, in particular fuel storage and handling—as well as combustion gas composition when cofiring. These findings could strengthen future work.

Further, no attempt was made to compare morning versus afternoon weather conditions, and the potential influence on cofiring conditions. Outdoor air temperatures were warmer each afternoon versus morning, and this could have influence heat requirements, steam loads, and possibly other conditions. Longer scale cofiring tests would also offer the advantage of closer examination of conditions such as "slagging and fouling, potential corrosion issues, and variations in ash content," as other researchers have explored (Pronobis 2006). By cofiring a range of wood fuel types, MCs, and cofiring ratios, it could be possible to determine those fuel blends that would minimize some of the problems sometimes associated with longer term cofiring. Alternatively, combustion systems could be designed to minimize these problems.

Conclusions

The tests at the Aurora Power Plant demonstrated that cofiring small amounts of biomass with coal is technically feasible with no equipment modifications needed and essentially no impacts on plant operation or personnel. An important consideration was that the cofire tests were done under ideal conditions using high-quality wood chips, even if they were more expensive than "run of the mill" local biomass. This material could be procured more cheaply but would likely have higher bark content and soil contamination and potentially higher variability in other characteristics like moisture. Ultimately, this study corroborated what many past studies have shown—that cofiring is very feasible at low wood ratios. In our study, we also demonstrated the feasibility of site-specific factors in interior Alaska, including fuel transportation, storage, and fuel mixing. Given this outcome, we expect that cofiring low wood ratios would also be feasible at other Fairbanks area plants because they are all of similar size to the Aurora Power Plant, all have grate systems, and all use the same Usibelli coal.

Perhaps our most important finding was that CO levels increased 82.4 percent and 73.9 percent on day 1 (low cofiring rate) and day 2 (high cofiring rate), respectively, when compared to coal-only combustion. This was likely due to the high MC of the aspen chips, which resulted in less efficient combustion. However, this could also be explained by less than optimal air distribution often found in older systems designed to accommodate coal combustion with undergrate air.

The modestly high CO levels resulting from the use of green chips could be viewed as an incentive to use dry feedstock such as pellets. However, the price difference between chips (less than $50 per delivered ton) and pellets (more than $200 per delivered ton) could probably not be justified. If cofiring were pursued on an ongoing basis, wood fuel drying strategies (especially during summer months) could be considered as a way to reduce CO emissions. Other strategies could include using waste heat from the coal power facility to dry wood chips. Also, waste wood residues (costing considerably less than the aspen chips used in this study) could be explored as a fuel source. These factors point to the strong feasibility of cofiring green chips at levels up to about 10 percent of energy value (as was done in this study).

However, combustion gas opacity changed very little when comparing cofiring to coal-only combustion. This preliminary finding could potentially be useful for power plants, if future air quality regulations regarding opacity become implemented. Moreover, plant operations such as modifying the combustion air system and fuel feed rates could be fine-tuned so that CO and opacity are at desired levels. Also, systems could be designed to efficiently blend biomass fuels of different quality if cofiring were conducted on an ongoing basis.

This research was significant for Fairbanks and interior Alaska for several reasons. First, it was the first documented cofiring study in the area in nearly 30 years, providing an updated look at the use of local wood species for cofiring. Second, it is timely in that air quality concerns are prevalent in the Fairbanks area, and are likely to continue because air inversions occur frequently during winter months. Third, cofiring is a potential economic development driver. This is especially true for local wood products facilities that generate large volumes of low-value wood waste. If cofiring were adopted on an ongoing basis, not only would mills have a reliable market for their residues, but there would be potential to draw from local treatments in the wildland-urban interface and more distant "wood baskets," including those near Delta Junction, Alaska—approximately 100 mi from Fairbanks.

The current study serves the dual purpose of being an exploratory effort to observe cofiring at the utility scale in Fairbanks, and to reacquaint energy managers and natural resource professionals with its importance. From this standpoint, it helps corroborate the results of numerous other studies demonstrating that cofiring is feasible, and that the biomass component can lead to net reductions in greenhouse gas emissions (versus burning coal alone).

Future cofiring work is planned in two areas: (1) test burns of wood and coal, using low-value waste residue from a wood products manufacturing facility; and (2) economic evaluations on a delivered cost per British thermal unit basis for woody biomass versus coal. As new knowledge becomes available to both energy producers and biomass producers, such studies will help inform the conditions under which cofiring biomass with coal successfully meets both economic and environmental objectives in Alaska.

Metric Equivalents

When you have:	Multiply by:	To find:
Inches	2.54	Centimeters
Feet (ft)	0.3048	Meters
Miles (mi)	1.609	Kilometers
Square feet (ft^2)	0.0929	Square meters
Pounds (lbs)	0.454	Kilograms
Tons	0.907	Tonnes or megagrams

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