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Combustion Efficiency and Emissions Analysis for a School Wood Energy System in Interior Alaska

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Cover photo: building that houses the wood energy system at Delta Junction High School, Delta Junction, Alaska. Photo by David Nicholls.

Abstract

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A recent expansion in wood energy use at schools in Alaska has resulted in more than a dozen wood energy systems in operation. However, few have been evaluated for fuel efficiency and pollution impacts, both of which can be examined via combustion gas analysis. In this research, we monitored the wood energy system at a public school during winter heating conditions. Wood energy parameters were sampled on three occasions during early, mid, and late winter in northern Alaska. Combustion gas was sampled for a range of parameters that indicated boiler performance, including gas emmissions of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), excess air, combustion efficiency, and stack temperature, which were monitored over 6 days. We observed differences in combustion gas composition between seasons as well as the response of combustion efficiency to gas concentrations. Combustion efficiency most strongly correlated with excess air ($R^2 = 0.693$), but poorly correlated with stack temperature ($R^2 = 0.005$). The primary combustion gases (O_2, CO_2, and CO) were moderately correlated with combustion efficiency (with R^2 values of 0.40, 0.56, and 0.55, respectively). Seasonal differences were found between early, mid, and late winter, with generally less variation in combustion gas contents occurring during late winter. Mean combustion gas concentrations also varied with heating season. In all cases, mid-winter means were significantly different than early and late winter values. This research found that more efficient combustion of wood fuels should lead to cost savings, especially during early and late heating seasons. The findings should also be relevant to those of other wood-energy-using schools (in Alaska and elsewhere) that experience severe mid-winter conditions coupled with milder shoulder seasons.

Keywords: Wood energy, schools, Alaska, chip-fired, combustion, sawmill residue, biomass, thermal energy.

Summary

We monitored the wood energy system at a public school during winter heating conditions. Wood energy combustion parameters were sampled on three occasions during early, mid, and late winter in northern Alaska. We observed differences in combustion gas composition between seasons as well as the response of combustion efficiency to gas concentrations. Seasonal differences were found between early, mid, and late winter, with generally less variation in combustion gas contents occurring during late winter. This research found that more efficient combustion of wood fuels should lead to cost savings, especially during early and late heating seasons.

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Introduction

Wood has been used as a source of heat for centuries, and recent advances such as gasification technologies, automated fuel handling systems, emissions control devices, and the use of hydronic heating systems have led to cleaner burning and higher efficiencies. All these advances are changing the way wood energy users interact with forest environments—this is especially true in rural areas. School-size systems often have outputs of between about 1 and 5 million British thermal units (MMBTUs) per hour, a scale that is considerably larger than the scale used for residential systems, but smaller than that of most industrial systems. In Alaska, recent adoption of wood energy has been significant and growing, with close to 25 small-scale industrial systems currently in use.[1] As recently as a decade ago, there were only about 10 operating systems (Nicholls 2009). One reason for this growth is that Alaska lends itself well to wood energy. It has high winter heating loads (especially in interior locations), vast forests, and a low population density. Renewable energy adoption has created many economic benefits for rural Alaska, including fuel cost savings, increased employment, and reduced reliance on imported fossil fuels.

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There is greater environmental risk associated with transporting fossil fuels than there is with wood fuels. For example, in Alaska, three recent fuel spills worth noting occurred in 2018: up to 3,000 gal of fuel oil spilled north of Kodiak Island (Andrews 2018); more than 20,000 gal spilled in Savoonga, (Grueskin 2018); and about 800 gal spilled from a tanker truck in interior Alaska (Granger 2018).

A disadvantage associated with using wood energy systems in interior Alaska, however, is the high cost of wood fuel. Temperatures can drop as low as -50 °F, necessitating extensive use of wood fuel. Costs associated with transporting wood fuel can be rather high as some facilities in Alaska are quite remote, making it sometimes necessary to transport wood fuel over long distances. In addition, high-quality wood residues are in limited supply. All of these factors make it important to maximize the utility of this fuel to provide maximum economic benefit to users. Often, wood energy users in interior Alaska communities are school districts, government agencies, and other facilities that previously used heating oil or other fossil fuels. Nonetheless, wood energy often offers less volatile pricing than fossil fuels and can allow for greater control of fuel costs. One Alaska school that uses a wood energy system reported that their cost savings allowed them to add a full-time teacher (Tressel 2016).

[1] Daniel Parrent. Personal communication. Natural resource specialist (retired), USDA Forest Service, State and Private Forestry, Utilization and Forest Stewardship, 161 East 1st Avenue, Door 8, Anchorage, AK 99501.

Although combustion gas composition and operating efficiencies can reveal a great deal about wood energy operating conditions, very few studies have evaluated these parameters at larger than residential scales.

Although combustion gas composition and operating efficiencies can reveal a great deal about wood energy operating conditions, very few studies have evaluated these parameters at larger than residential scales. In larger systems (schools, businesses, etc.), volatile gases released from the fuel are combusted along with the fuel, often with the assistance of fans, resulting in increased efficiency. Thus, there is a strong need to provide detailed operating information for larger scale wood energy systems that often use bulk wood chips. Although wood chips are often the preferred fuel for heating schools (in systems that produce from 1 to 5 MMBTUs per hour), cordwood burners can be used for smaller installations. This report adds to past research by also evaluating three different parts of the heating season—early, mid, and late season, which encompass a period from about mid-November through mid-April. We focused on combustion efficiency and emissions of the primary combustion gases (oxygen [O_2], carbon monoxide [CO], and carbon dioxide [CO_2]). Our research objectives included (1) a comparison of combustion gas differences for three parts of the heating season (early, mid, and late) and (2) an evaluation of combustion efficiency as influenced by combustion gas concentrations. Both of these factors can have direct implications on fuel cost, which is often a leading operational expence for school districts. For example, high levels of CO are an indicator of incomplete combustion (which in turn indicates inefficient use of wood fuel). Thus, the findings of this research may enable facility managers to operate their wood fuel systems in the most efficient manner and to better monitor their combustion procedures, resulting in cost savings for their school districts.

Review of Literature

Much past research has focused on combustion emissions of residential wood energy systems that included evaluations of CO, CO_2, and nitrogen oxides (NO_x), as well as other gases. Many other additional studies have evaluated particulate emissions, a prime concern for residential wood energy use in many environments (Buchmayr et al. 2015, Hedberg et al. 2002, Johansson et al. 2003). Methods to reduce particulate emissions have also been investigated (Hukkanen et al. 2012).

Combustion efficiency of wood burning systems has also been studied, mostly at smaller scales. Eskilsson et al. (2004) optimized the efficiency of pellet burners at commercial and prototype scales by recognizing the tradeoffs between NO_x and CO emissions at different excess air levels. Serrano et al. (2013) evaluated combustion efficiency of pine chips and pine pellets, finding similar efficiency and gaseous emissions for both types of wood fuels. Other research has considered wood pellets (Dias et al. 2004), focusing on the particulate emissions from wood pellet systems (Garcia-Maraver et al. 2014) and the range of technologies available for wood pellet

burners (Míguez et al. 2012). Roy et al. (2013) measured combustion efficiency in wood pellet stoves, evaluating four types of biomass fuels.

Combustion of agricultural residues has also been evaluated under numerous conditions. Fournel et al. (2015) predicted emissions from combustion of short-rotation crops such as willow, reed canary grass, switchgrass and miscanthus, and used these findings to suggest optimum harvesting seasons. Still other researchers (Krugly et al. 2014) considered wood, agricultural fuels, and sewage sludge. Koyuncu and Pinar (2007) evaluated 11 separate types of biomass for CO, NO_x, and sulfur dioxide emissions, while Pilusa et al. (2013) considered emissions from briquettes composed of four biomass types. Similarly, Dias et al. (2004) tested four types of pellets, evaluating CO, O_2, and NO_x emissions.

Several researchers have considered log (i.e., firewood) combustion in residential-scale wood stoves (Hedberg et al. 2002, Johansson et al. 2004, Lamberg et al. 2017). Related work compared the emissions of wood pellets to those from fire logs (Johansson et al. 2004). Mitchell et al. (2016) evaluated eight fuels in domestic-scale stoves, including biomass and coal mixtures. Obaidullah et al. (2014) evaluated only CO emissions from residential-scale burners, while Ozgen et al. (2014) evaluated CO emissions in addition to other compounds, and Ozil et al. (2009) considered catalytic reduction of CO in similarly sized burners. Because much of the recent research on the use of wood for heating has focused on residential uses, information is lacking on fuel storage, handling, and emissions.

Several studies considered wood chip combustion at larger than residential scales. Buchmayr et al. (2015) investigated wood chip combustion in a small-scale commercial boiler. They found that primary air ratio and fuel moisture content were important in influencing combustion products as well as particulate formation. Caposciutti and Antonelli (2018) studied excess air ratios on a small-scale (140 kW) biomass burner also fueled by wood chips. They found that levels of excess air can directly influence emissions of CO, CO_2, and NO_x. Similarly, Zhang et al. (2010) evaluated a 320-kW biomass grate system, finding that excess air influenced both bed temperatures and combustion gas composition.

These studies and others that focus on residential-scale wood energy systems reveal a significant research deficiency for larger wood energy systems typically fired with wood chips. There has also been very little research in arctic or semi-arctic conditions, where heating seasons can be longer and heating loads more severe than those at lower latitudes. Furthermore, much past research has evaluated combustion gases for just a few hours at a time (often in a laboratory setting), basing conclusions on limited testing parameters. Thus, there is a need for multiday research that evaluates combustion gases under a wide range of daily and seasonal conditions. Our current research attempts to address all three of these research gaps.

Wood Energy System Background

Overview

Wood energy systems have become an effective means of providing heat and other benefits to schools, government buildings, small businesses, and other community users. These systems typically burn wood chips, wood pellets, or cordwood to generate hot water, which is circulated via pipes to individual buildings. The Biomass Energy Resource Center maintains a database of more than 500 community-scale wood energy systems (VEIC 2017). This resource illustrates the breadth of potential wood energy applications, including those in schools, hospitals, government buildings, and small-business facilities. In Alaska, numerous wood energy systems have been installed, including at least four at schools.

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The Delta/Greely School District in Delta Junction started operating its wood energy system in September 2011 and completed its first heating season in April 2012. The thermal system burns between 1,400 and 2,000 green tons of wood chips per year at a delivered wood cost of about $63 per ton (Tressel 2016). During the first three heating seasons, nearly $300,000 was saved by burning wood instead of heating oil (Tressel 2016). The school district burns mostly clean wood processing residues containing little or no bark or needles. The delivered wood fuel moisture content is typically 30 percent green basis or drier. The wood energy system includes a Messersmith[2] burner rated at 5.5 MMBTUs per hour. The project was financed by the Alaska Renewable Energy Fund and other state funding to meet the total installed cost of about $2.8 million.

The boiler is a chip-fired system that uses chipped slab wood from a local lumber mill. The burner design is such that volatile gases released from the fuel are burned along with the fuel, increasing efficiency and decreasing incomplete combustion products. The boiler heats water, and the energy is transferred using a double-plate heat exchanger with a glycol-water mixture; this is circulated throughout the school for heat. The boiler is designed to comply with AP-42 federal emission standards (US EPA 2018).

Lessons Learned

Delta/Greely School District maintains its fuel oil system as an automatic backup in case of unexpected downtime for the wood system. However, operation has been fairly smooth during the first seven heating seasons, and there has been little need for the fuel oil backup system. One problem to note with the school district's system

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

(as well as several others in Alaska) is that softwood foliage, dirt, and contaminants can create solid slag residues within the combustion chamber, resulting in greater maintenance time.

The neighboring community of Tok, Alaska, uses the same kind of boiler to heat its school. However, the operators added a steam turbine to the boiler to generate electricity (approximately 50-kW capacity) as well as heat. Thus, it consumes a larger quantity of fuel than does the Delta/Greely system. Another difference is that, during the first few years in operation, the Tok operators burned chips that came from low-quality black spruce that was cleared for fire remediation. The spruce trees were chipped whole and included the needles, bark, and roots. Because these materials were included, in addition to using a higher burn rate, the Tok system produced solid residues in the burn box (including slag), which needed frequent removal. The operators have since switched their fuel to clean chips, and the maintenance problems have abated. Thus, wood has become an effective energy source for both of these school systems, although their fuel sources and modes of operation are different.

Methods

Part I: Correlation of Combustion Gas With Operating Efficiency

This research was an observational study measuring combustion gases during normal operation of a 5.5-MMBTU per hour school wood heating system. Combustion gas measurements were taken with a Bacharach® PCA3 portable combustion gas analyzer inserted about 1 ft from the outlet of the combustion chamber, before the cyclone and stack (fig. 1).

Measurements were taken in real time for percentages of O_2, CO_2, excess air, and combustion efficiency as well as CO (in parts per million [ppm]), and stack temperature (°F). Combustion gases were sampled on three different occasions, representing different parts of a typical heating season in interior Alaska: late autumn (December), mid-winter (February), and early spring (April). Mean emissions data were compared for each of the three sampling dates for each parameter of interest. Data were collected at 2-minute intervals over a cumulative sampling period of more than 32 hours. Each data point was collected as a "snapshot" point in time (rather than an average value over a sampling period). A primary goal was to determine differences between mid-winter heating conditions and the two shoulder seasons. Our statistical analysis included regression analyses of combustion efficiency against independent variables of interest (including CO, O_2, CO_2, and stack temperature).

Combustion gases were sampled on three different occasions, representing different parts of a typical heating season in interior Alaska.

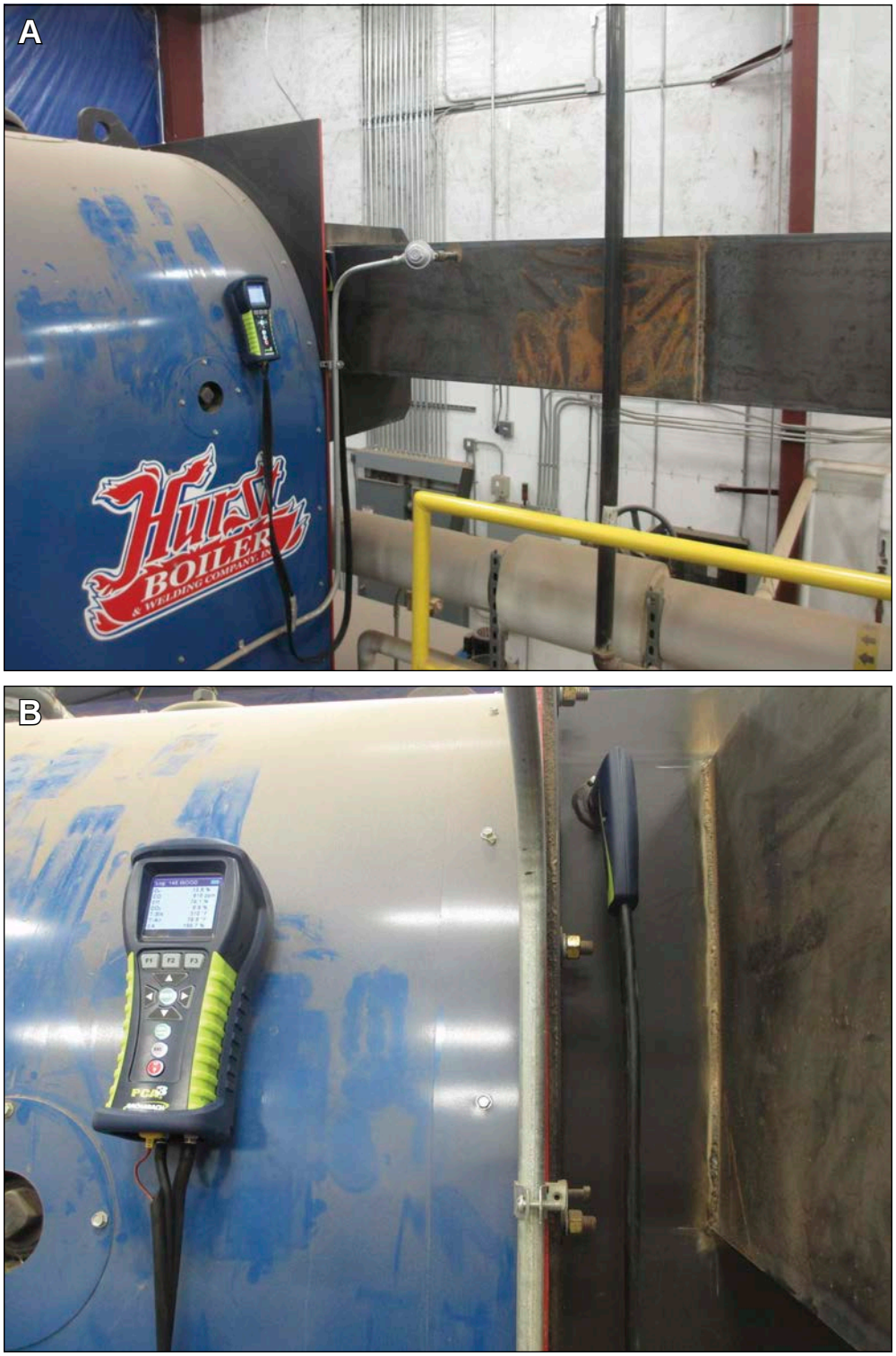

Figure 1—(A) Wood energy burner at Delta Junction High School; (B) closeup of combustion gas analyzer showing insertion point for sampling.

Part II: Seasonal Differences in Combustion Gas Emissions

We also conducted an analysis of variance on all independent variables of interest comparing early, mid, and late winter heating season. We evaluated mean differences in O_2, CO_2, CO, combustion efficiency, and stack temperature. Significant differences between treatment means were determined using Bonferroni's pairwise means comparison test, at the 0.05 significance level.

Part III: Variation of Individual Combustion Gases

We compared differences within combustion gases during combustion cycles. The burner alternated between two firing modes—a low-fire mode (in which little or no fuel was metered into the combustion chamber), and a high-fire mode (in which greater amounts of wood were actively burned to increase the heating load). As a result, there was a clear cyclic nature for several of the response variables (CO_2, CO, O_2, stack temperature). This typically lasted about 15 to 20 minutes per cycle, in response to changes in the firing mode described above. We compared the results of each heating season.

Limitations of This Study

Several limitations to this exploratory study are worth noting. Our sampling period for the three testing periods totaled 6 days; a longer period would have been ideal. The study was limited to one fuel type (sawmill waste wood chip residues). Data on additional fuel types could provide greater insights to wood energy managers. We did not evaluate fuel usage directly; therefore, we were not able to determine the direct effects of combustion efficiency on wood fuel use. Last, the study was largely observational; there was very little experimental control over system variables. Many of these limitations would have been ameliorated had the data collection site been less remote, allowing researchers to spend more time onsite.

Combustion efficiency is important in wood energy systems because of its influence on fuel use and hence fuel cost as well as air quality.

Results

Combustion Gas Analysis

Part I: correlation with combustion efficiency—
Combustion efficiency is important because of its influence on fuel use and hence fuel cost as well as air quality, which are often related to the system scale (Dornburg and Faaij 2001). The school system we evaluated burns more than 1,400 tons of wood each year at a purchase price of nearly $90,000 per year (Tressel 2016). Thus, operational changes that can enhance wood-fuel-use efficiency are desirable.

We found strong correlations between combustion efficiency and certain parameters. Correlations ranged from 0.0005 (stack temperature vs. combustion efficiency) (fig. 2) to 0.693 (excess air vs. combustion efficiency) (fig. 3), with CO vs. combustion efficiency having an intermediate correlation of 0.40 (fig. 4). Similar correlations for O_2 and for CO_2 were close to 0.55 (table 1) (figs. 5 and 6).

Combustion efficiency has been found to have strong correlations to level of excess air, and in the Delta/Greely School District wood energy system, this was influenced by time spent in low-fire mode. Although relating combustion efficiency to firing mode was outside the scope of our study, it likely played a role. A practical outcome of this study would be to monitor the time spent in pilot standby mode, in which relatively little air would flow through the combustion chamber. This would be in contrast to low-fire mode, where substantially more air would be forced through the combustion chamber.

Part II: seasonal differences in combustion gas emissions—
There were seasonal differences for all variables of interest. For mean O_2, mean CO, and mean stack temperature, all three seasons were statistically different from each other (0.05 level of significance) (table 2). For CO_2 and combustion efficiency, mid-winter conditions were statistically different from early or late winter conditions. Seasonal differences were found between early, mid, and late winter, with generally less variation in combustion gas contents occurring during late winter. Mean combustion gas concentrations also varied with heating season. In all cases, mid-winter means were significantly different than early and late winter values. We could find no other studies that evaluated chip-fired systems over three heating regimes, and therefore we are not able to make comparisons to past research.

Part III: variation of individual combustion gases—
During our testing, the combustion system automatically alternated between two distinct modes of operation: a low-fire mode and a pilot standby mode. Typically, these modes lasted between 10 and 30 minutes. Therefore, certain combustion gas concentrations alternated over a wide range. For example, O_2 varied from about 20.9 percent (the maximum possible) to as low as about 11 percent (fig. 7). CO varied over an even wider range, from about 100 to 1,800 ppm (fig. 8). Likewise, stack temperatures varied over a wide range during a single cycle—more than 100 °F in some cases (fig. 9). It appears that the magnitude of cycling between low-fire and high-fire mode was less pronounced during the late winter sampling for CO, O_2, and stack temperatures.

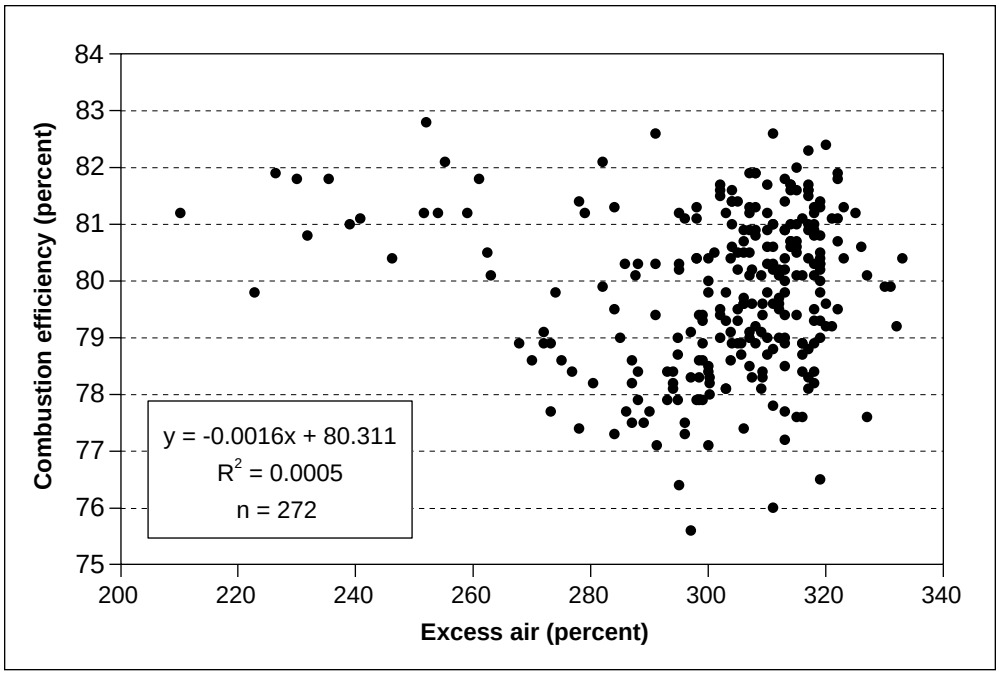

Figure 2—Stack temperature versus combustion efficiency for Delta/Greely School District wood energy system (all observations).

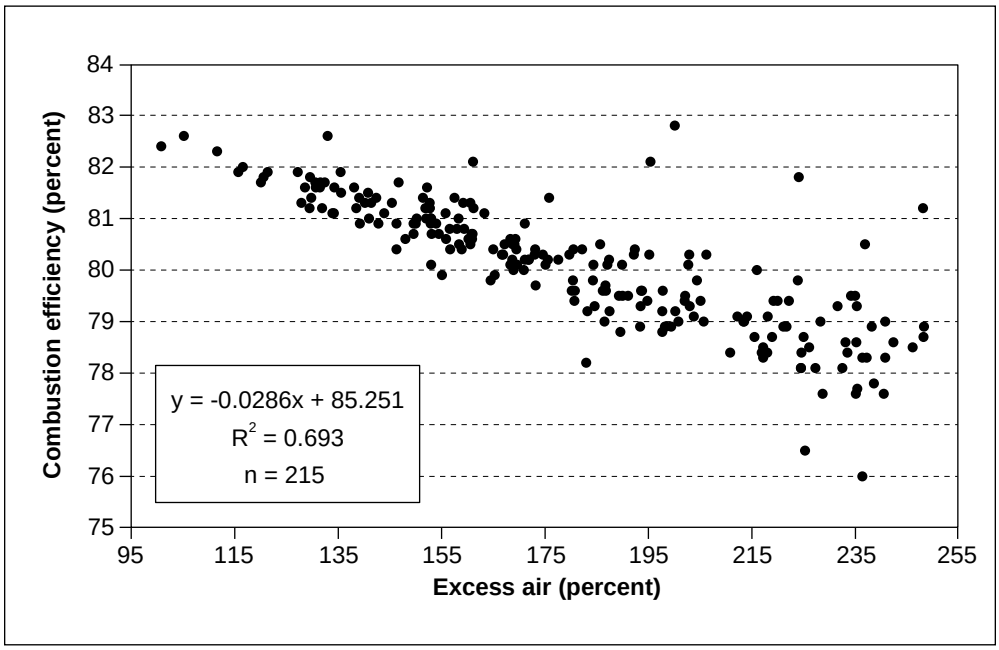

Figure 3—Excess air versus combustion efficiency for Delta/Greely School District wood energy system (all observations).

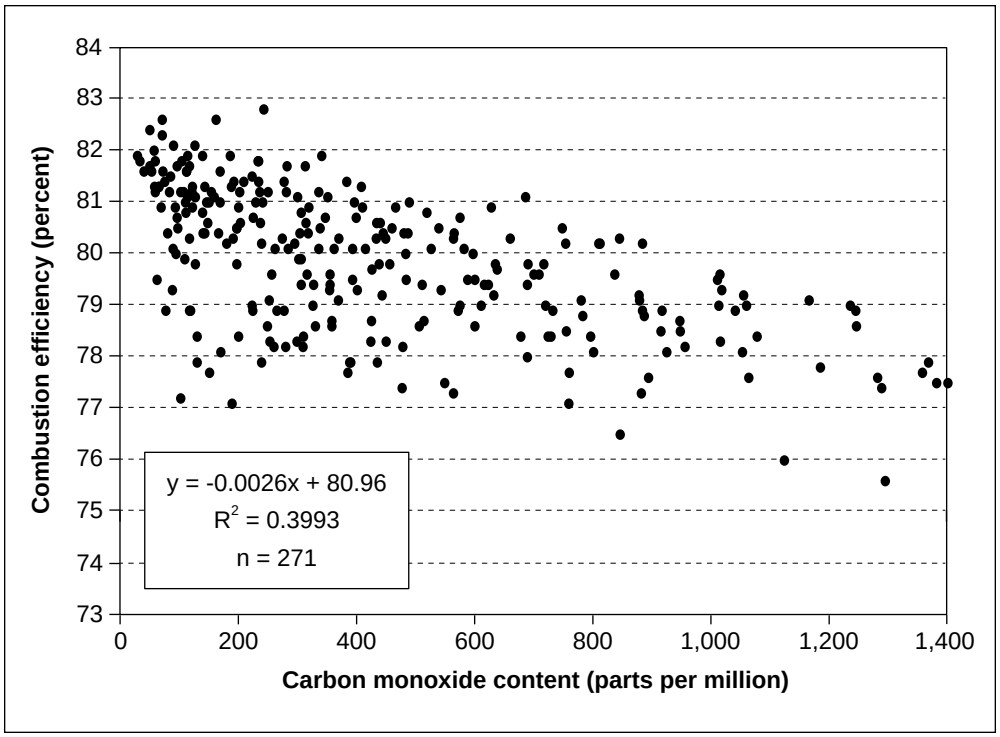

Figure 4—Carbon monoxide content versus combustion efficiency for Delta/Greely School District wood energy system (all observations).

Table 1—Combustion efficiency as related to other variables during early, mid, and late winter sampling

Variable	R^{2a}	Number of observations
Stack temperature	0.0005	272
Carbon monoxide	0.3993	271
Carbon dioxide	0.5611	271
Oxygen	0.5557	271
Excess air	0.693	215

[a] Versus combustion efficiency.

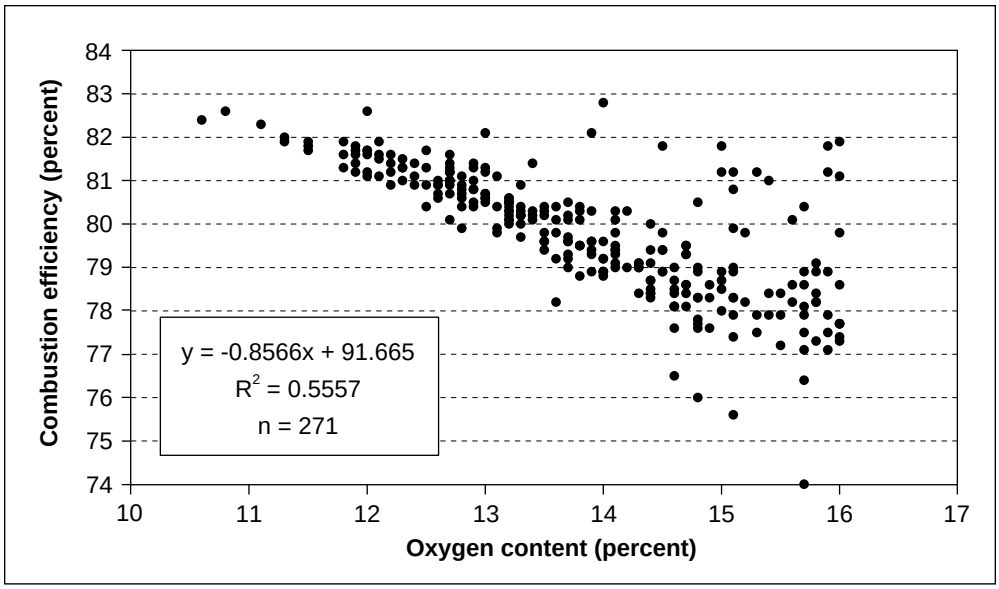

Figure 5—Oxygen content versus combustion efficiency for Delta/Greely School District wood energy system (all observations).

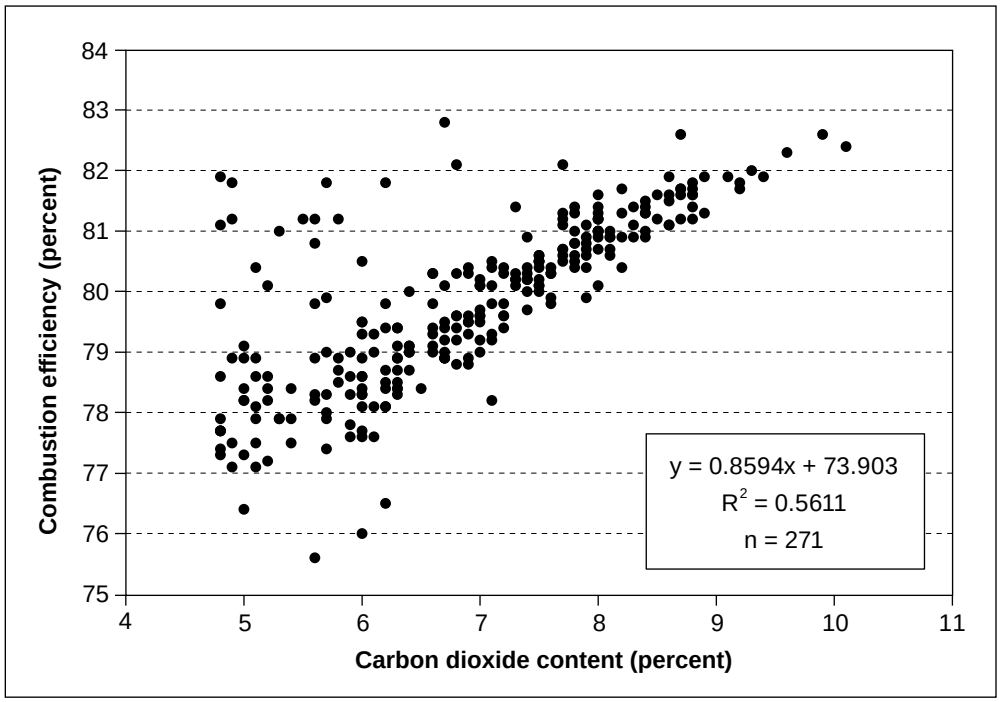

Figure 6—Carbon dioxide content versus combustion efficiency for Delta/Greely School District wood energy system (all observations).

Table 2—Average combustion gas concentrations by season for wood energy thermal system at a school in interior Alaska[a]

		Season		
		Early winter	Mid winter	Late winter
Oxygen (percent)	Average	18.45 a	15.36 b	17.49 c
	Variance	3.82	7.76	5.30
		151	318	132
Carbon dioxide (percent)	Average	5.45 a	7.35 b	5.79 a
	Variance n	0.32	1.07	0.51
		28	196	48
Carbon monoxide (parts per million)	Average	514.41 a	613.32 b	440.35 c
	Variance n	143,403	139,352	36,948
		340	325	300
Combustion efficiency (percent)	Average	79.05 a	80.02 b	79.35 a
	Variance n	1.98	1.99	1.69
		28	196	48
Stack temperature (°F)	Average	255.45 a	289.45 b	227.39 c
	Variance n	1,355.17	772.71	1,387.46
		340	325	300

[a] Averages having common letters are not statistically different at the 5-percent level by the Bonferroni multiple comparison test.

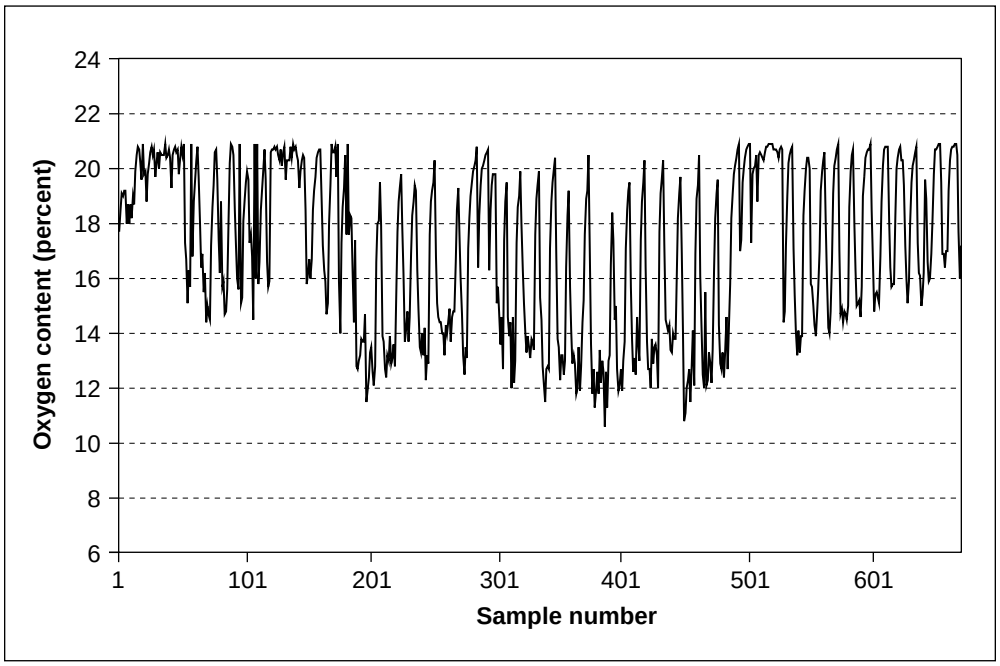

Figure 7—Oxygen content of combustion gases for early, mid, and late winter samples.

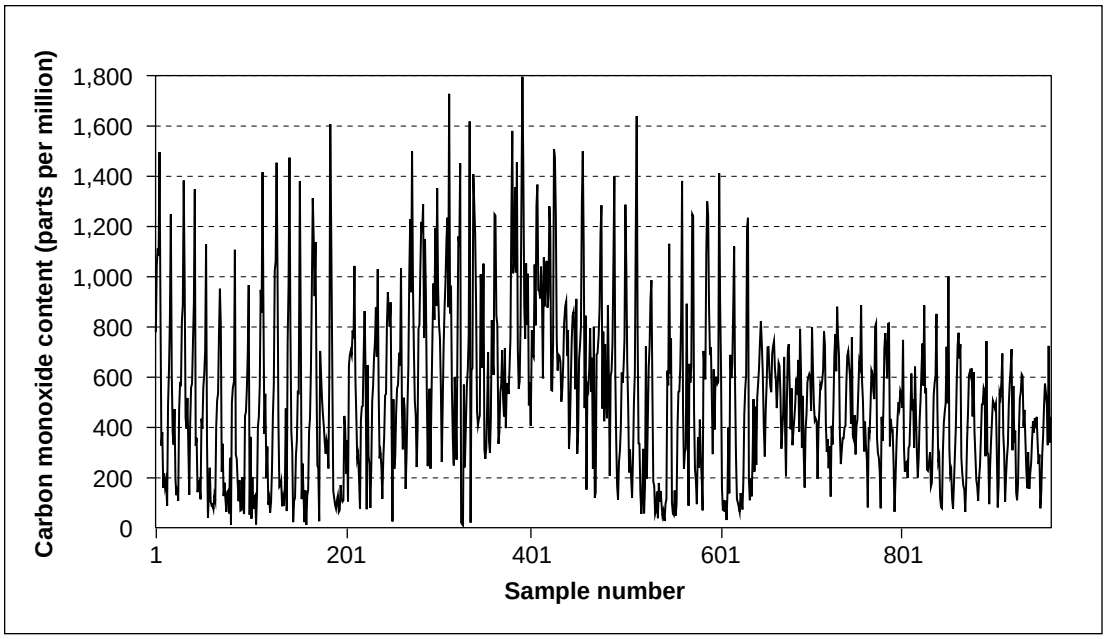

Figure 8—Carbon monoxide content of combustion gases for early, mid, and late winter.

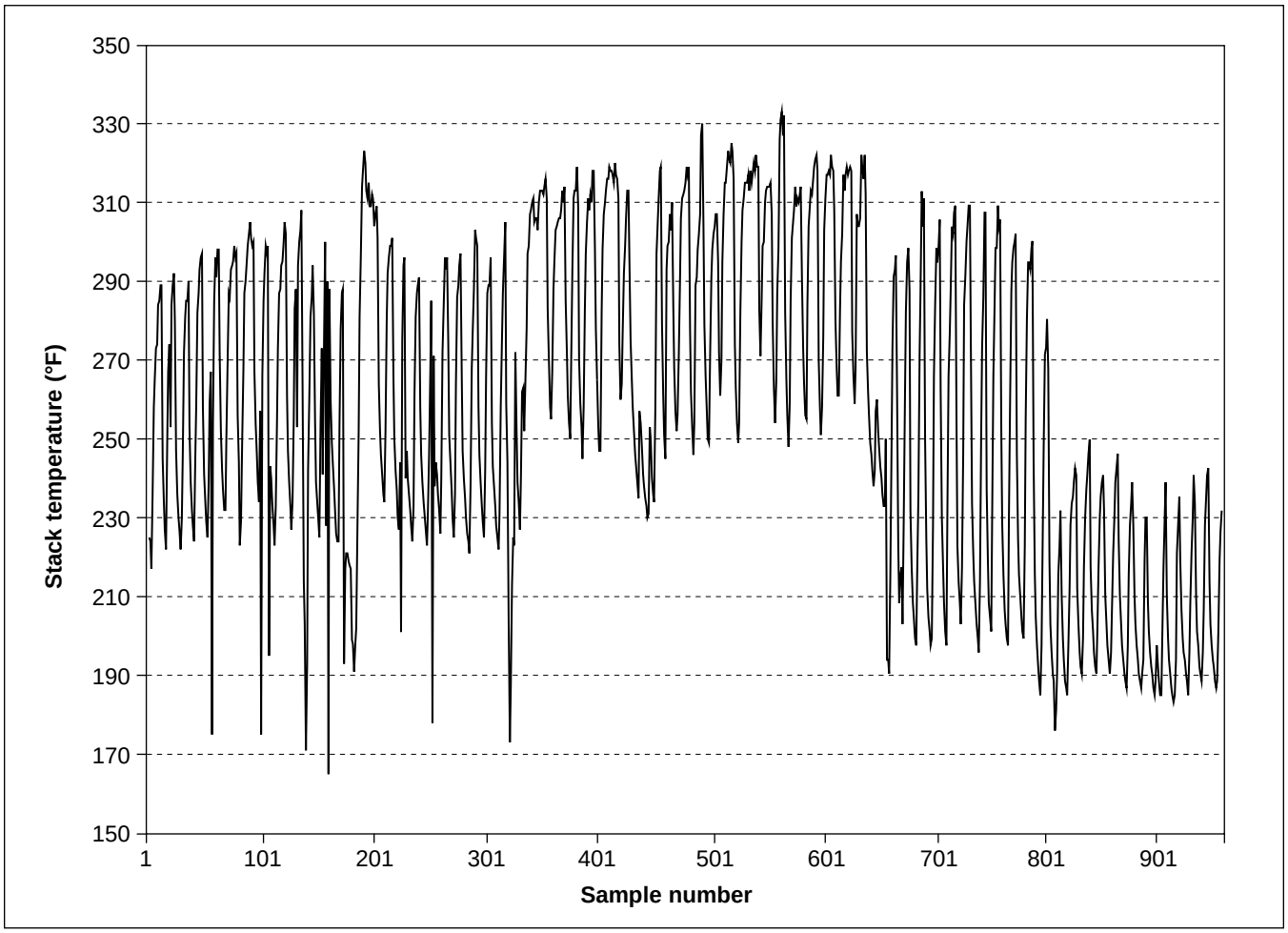

Figure 9—Stack temperature of combustion gases for early, mid, and late winter.

Discussion and Conclusions

This research was among the first to investigate combustion gas emissions of a chip-fired wood energy school heating system. We found that there was relatively little daily variation in combustion gas emissions of CO, CO_2, and O_2 during normal operations of the chip-fired wood energy system. However, because of differences in firing modes (low-fire and high-fire), there were pronounced short-term variations in combustion gas concentrations. Combustion efficiency (often a measure of fuel usage and economy) also varied cyclically, however, to a lesser degree than O_2, CO, or stack temperature. Several variables were well correlated with combustion efficiency, including excess air, O_2, and CO_2. However, stack temperatures were poorly correlated with combustion efficiency. Combustion gas composition was found to vary, depending on heating season (early, mid, or late). For O_2 and combustion efficiency, mean mid-winter values were different from early season or late season values. For CO, O_2, and stack temperature, responses also varied significantly by season. Mean values for each season were significantly different from each other.

Combustion efficiency is important because of its relation to fuel use and therefore cost, as well as its impact on air pollution. Actions to fine-tune combustion efficiency (such as adjusting overfire and underfire air rates, regulating fuel-feed rate, and optimizing fuel moisture) can often be easily accomplished by onsite personnel. This research found that more efficient combustion of wood fuels should lead to cost savings, especially during shoulder heating seasons such as late winter, when conditions can be more easily controlled. During shoulder seasons, facility operators also are assessing when to stop heating for the summer season. This research will also help enable this decisionmaking process. The findings should also be relevant to other school wood energy sites in Alaska and other high-latitude interior locations experiencing severe mid-winter conditions coupled with milder shoulder seasons.

These study results may benefit Delta/Greely schools in Alaska because they provide operating data under a range of conditions, outdoor temperatures, and heating loads.

These study results may benefit Delta/Greely schools in Alaska because they provide operating data under a range of conditions, outdoor temperatures, and heating loads. This information can be used to fine-tune operating parameters, potentially reducing wood fuel consumption and saving money for the school district. A standard “currency” for savings attributable to wood energy has been in terms of the number of teaching positions saved. Delta/Greely School District reported that savings from the first 3 years of operation allowed at least one new teaching position to be established (Tressel 2016). Furthermore, the educational benefits for students learning to operate a wood energy system at a high school are not to be overlooked, including moisture content measurements, wood properties, and the environmental benefits of using renewable biomass energy.

Results of this study will also benefit the broader wood energy community in Alaska because similar systems are either under construction or have recently started being used. For example, a system in Tok, Alaska, has much of the same equipment and infrastructure (though it also includes an electrical cogenerating unit). Potential wood energy adopters will be able to learn firsthand lessons in optimizing wood energy system performance, evaluating combustion gas analysis, and determining economic benefits. Several Alaska schools (including those in Tok, Thorne Bay, and Coffman Cove) have added wood-energy-heated greenhouses as an efficient use of excess thermal load. These greenhouses increase the quantity of locally produced and consumed food, while also eliminating lengthy transport distances. Efficient wood energy operations will ultimately save money for schools and other adopters, which could be used for additional employment or other constructive purposes.

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Metric Equivalents

When you know:	Multiply by:	To find:
Feet (ft)	.305	Meters
Gallons (gal)	3.78	Liters
Tons (ton)	907	Kilograms
British thermal units (Btu)	1,050	Joules
Degrees Fahrenheit (°F)	.56(°F – 32)	Degrees Celsius

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