Impact of cofiring biofuels and fossil fuels on lime kiln operation

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ABSTRACT: Lime kilns are used to calcine lime mud to produce lime for reuse in the causticizing plant of pulp mills. With significant increase in fossil fuel costs and the sustained drive to minimize carbon footprint, there has been a great deal of research and development of the biorefinery concept and production of biofuels for use within pulp mills. Several new biofuels will become available, together with traditional mill derived fuels such as tall oil. In considering use of biofuels for replacement of fossil fuels in the lime kiln, each fuel has a different impact on kiln performance. An assessment on kiln performance can be achieved and compared to either heavy fuel oil or natural gas. In most cases, the lime kiln fuels with high oxygen content and moderately low calorific values burn in a similar manner as natural gas; hence, in assessing impact on kiln performance, production and induced draft fan limits together with kiln exit gas temperatures need to be considered.

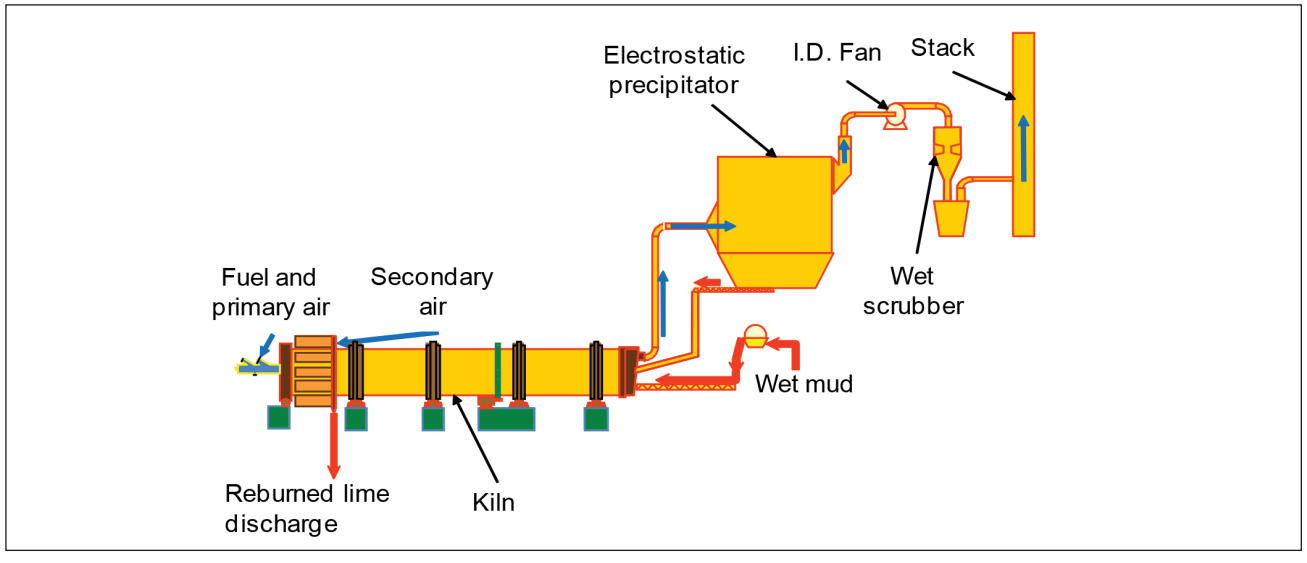
Application: This information will be useful to pulp mills wanting to assess the impact of replacing fossil fuels with biofuels on lime kiln performance.

In the chemical recovery process of pulp mills, calcium oxide (lime) is used to causticize the green liquor to white liquor by converting sodium carbonate into sodium hydroxide. The causticizing reaction precipitates calcium carbonate (lime mud), which is separated from white liquor, washed, and dewatered. The resulting wet lime mud, typically 70–80 wt% solids, is dried and calcined in a lime kiln to produce lime for reuse in the process.

Traditional low-cost fossil fuels derived from crude oil and natural gas have been used to provide the heat needed for drying and calcining the lime mud. With significant increases in fossil fuel costs (particularly fuel oil), the drive to minimize carbon footprint [1-3], and the resultant advent of the biorefinery concept, more focus is now on bioderived fuels and their potential use within pulp mills.

Bioderived fuels for use or potential use in lime kilns include tall oil, rectified methanol, sawdust, biogas, bio-oil [4], and precipitated lignin [5-7]. Because of wide variations in their chemical, physical, and thermal properties, these fuels burn differently in the lime kiln, either when they are fired alone or cofired with fuel oil and natural gas. Cofiring may significantly alter burner flame pattern, temperature profile, gas flow rate, and composition that, in turn, can have a great impact on kiln operation and performance.

This paper provides the first-pass assessment of the impact of cofiring biofuels on lime kiln operation. The information



1. Process analysis of kiln system.

allows pulp mills to assess the viability of each fuel use within their operations based on practical experience in the field, together with detailed process analysis through audited mass and energy balances. The focus is placed on burner operation, flame stability, heat transfer, and kiln temperature profile and how these may affect kiln production capacity.

METHODOLOGY

The initial stages of evaluation involve determining the existing kiln process conditions through collation of process data and completing a mass and energy balance across the kiln (**Fig. 1**). Detailed analysis of the fuel properties is used to estimate the air requirements for combustion and to make preliminary assessment of combustion and heat transfer characteristics against other fuels. This information is fed back into the benchmark mass and energy balances to derive the new kiln operating profile and assess the impact on the following:

- Burner
- Fuel handling
- Flame monitoring
- Burner management system
- Kiln induced draft (ID) fan
- Primary air (forced draft) fan

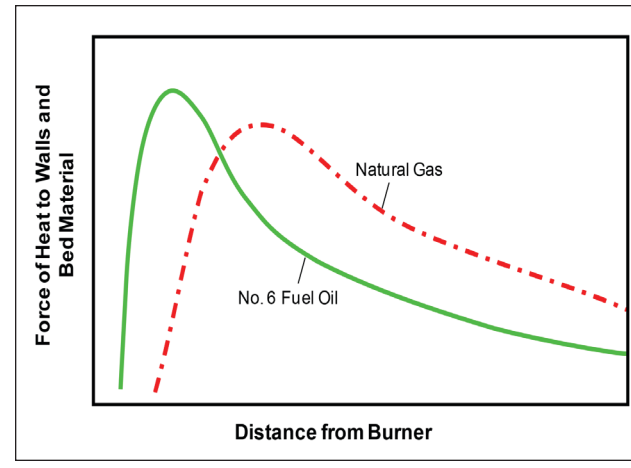
In each case, the dynamics of the specific kiln system can be compared to a database of more than 150 kilns of various sizes, shapes, and fuels.

BASELINE COMPARISON

The operation of lime kilns fired with heavy fuel oil (HFO) and natural gas is well known. **Table I** shows the key combustion data for kiln operation with HFO and natural gas. Although both net and gross heat release data are included here, the net heat release is more useful for assessing the kiln thermal performance. Kilns converting from HFO to natural gas are known be limited in production, due primarily to the increase in fuel usage (GJ/metric ton) and combustion air requirements. However, it is not widely recognized that the

	Heavy Fuel Oil	Natural Gas
C:H mass ratio	8:1	3:1
Combustion air per fuel	14 kg/kg	17 kg/kg
Combustion air per thermal load	354 kg/GJ	348 kg/GJ
Flue gas per fuel	15 kg/kg	18 kg/kg
Heat release (gross)	42.9 MJ/kg	40.7 MJ/Nm^3
Heat release (net)	40.5 MJ/kg	36.7 MJ/Nm^3

I. Changes in heat transfer: heavy fuel oil versus natural gas.



2. Heat transfer in lime kiln.

amount of air required for releasing the net heat in the kiln is in fact higher for HFO than for natural gas. So why does kiln operation change? The prime reason is the change in heat transfer as schematically shown in **Fig. 2**. The temperature profile, particularly the effective position of the heat transfer peak, moves away from the burner toward the kiln discharge when switching from HFO to natural gas [8,9]. The result of this movement has a compounding effect on kiln operation. First, by moving the heat zone away from the discharge, the effective available kiln length reduces. This causes the temperature at the kiln discharge to elevate if the heat cannot be transferred effectively with the same length of kiln. Second, with increased kiln exit gas temperatures, more heat leaves the kiln for the same heat input and hence less heat is available for drying, heating, and calcining the lime mud within the kiln. To maintain the same level of residual carbonates, more fuel is required to compensate for the heat loss. This increase in fuel usage results in more air being drawn into the kiln for combustion and hence higher gas velocities and higher ID fan requirements. In some cases, either kiln exit gas temperature or current ID fan capacity can be a limiting factor.

Because of the change in heat transfer, a kiln operating on HFO will generally require 8%-12% more ID fan capacity and 5%-7% more energy per ton of product when switching to natural gas. This knowledge is useful in determining the impact of bioderived fuels. When cofiring HFO with natural gas, the kiln dynamics move toward the characteristics of each fuel depending on the percentage of heat contributed by each fuel. In considering 100% firing of biofuels, or cofiring them with either oil or natural gas, the kiln dynamics will change depending on the type of each biofuel used.

BIOFUELS

Biofuel options range from gaseous fuel from gasification to liquid fuel such as bio-oils to solid fuel such as bark or more recently lignin. The evaluation starts with fuels that have been fired in lime kilns to understand their impact on kiln operation.

Tall oil

Depending on wood species, kraft mills typically produce 30-50 kg/metric ton pulp (60-100 lb/ton) of tall oil in their chemical recovery plants [10]. When used in the mill as a fuel, tall oil has combustion characteristics of a no. 4–6 refined oil (no. 6 is equivalent to HFO) with slightly lower heating values (35-40 MJ/kg) and lower sulfur content than a no. 6 oil. However, because it is highly acidic, tall oil requires the use of suitable stainless steel for its handling equipment, particularly near the burner tip where high temperature prevails. Many mills have successfully run lime kilns with tall oil as the prime, and in rare cases, only fuel.

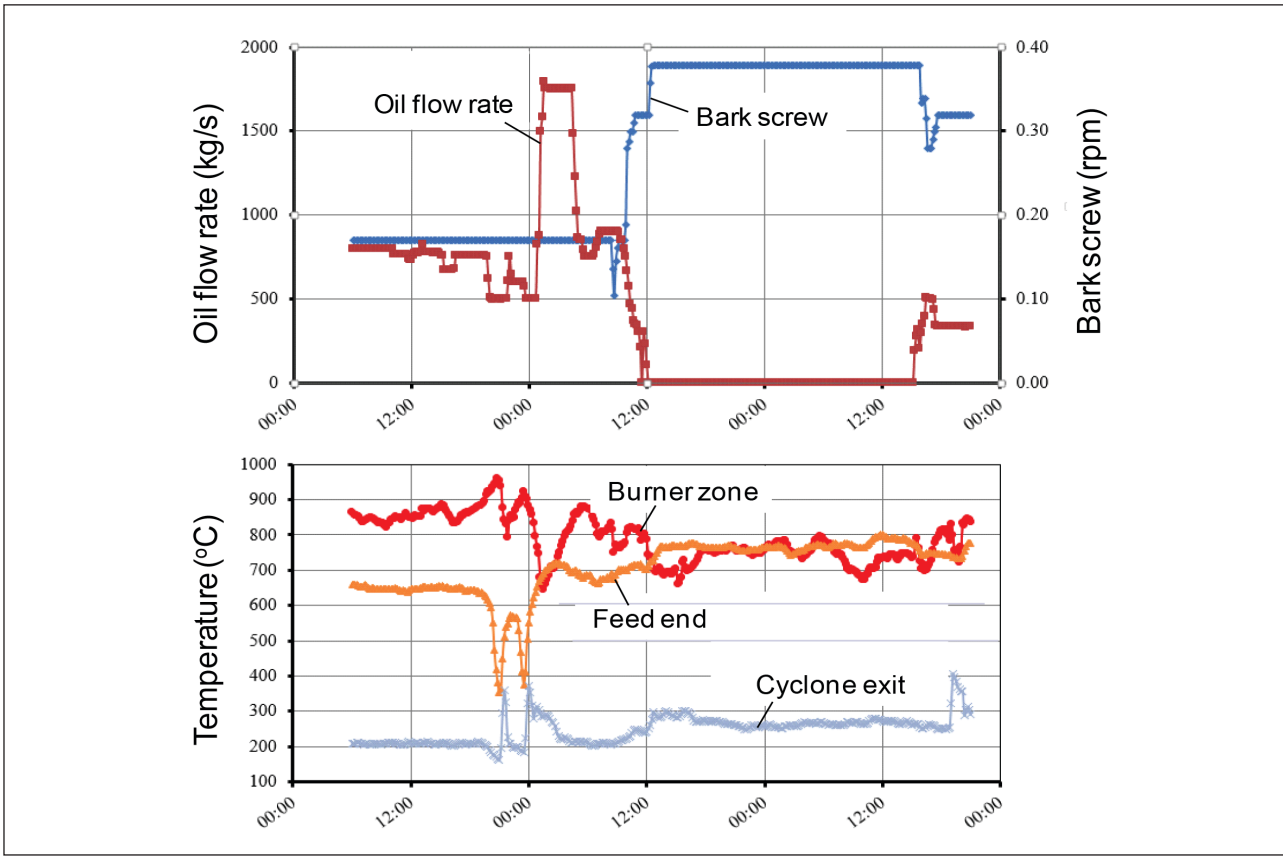
Care is required in producing a steady tall oil quality to the burner to maintain a reasonably constant heat flux profile. Variance in tall oil quality (viscosity and heating value) can lead to a number of operational problems, such as overheating, refractory damage, and ring formation due to poor atomization. However, the general kiln operation is similar to that of kilns firing HFO and therefore should not lead to any production limitations of existing equipment.

Bark

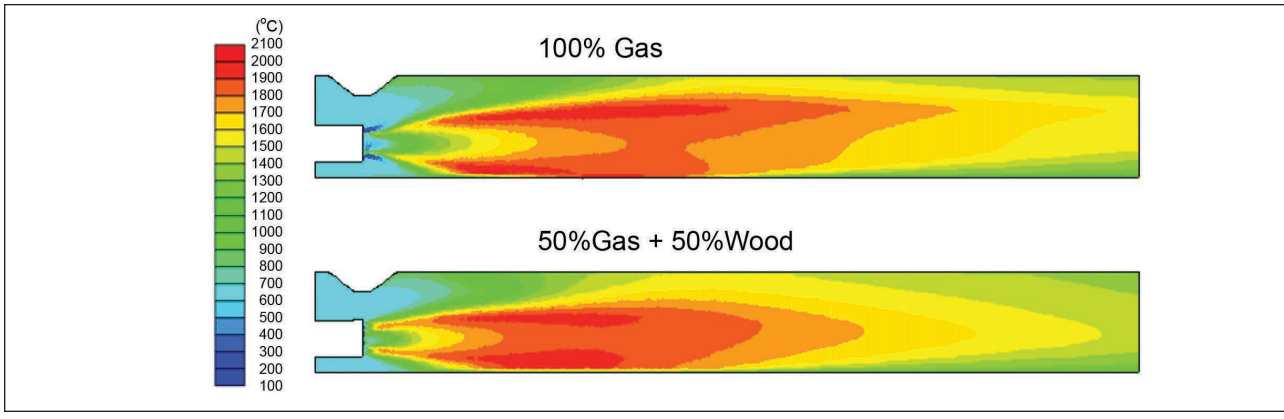
Bark has been used as a prime fuel for power boilers in kraft pulp mills for years. More recently, successful 100% firing of bark has been achieved in lime kilns in Scandinavia. **Table II** summarizes a typical characteristic of bark used at a pulp mill. The material is usually pulverized for air conveying into the lime kiln. **Figure 3** shows the kiln temperatures when cofiring HFO with bark. Increasing % heat load from bark firing lowers the burning zone temperature while increasing the feed end and cyclone exit temperatures. These changes in temperature profile are expected when switching HFO to natural gas; hence, when assessing the impact of bark firing, a comparison of current operation projected to 100% natural gas is required. An example of this is shown in **Fig. 4**; it is further supported by comparison of computational fluid dynamics (CFD) modeling that exhibits similar temperature profiles with 100% gas and 50:50 gas:wood firing.

Composition, % vol	Value
Carbon (C), wt%	48–52
Hydrogen (H), wt%	4–8
Nitrogen (N), wt%	0.1–0.5
Oxygen (O), wt%	36–42
Sulfur (S), wt%	<0.05
Ash, wt%	2–4
Net Heat, MJ/kg	17–19

II. Bark characteristics (on dry basis).



3. Impact of bark firing on lime kiln operation.



4. Computational fluid dynamics (CFD) modeling of gas temperatures in a lime kiln burning natural gas and wood blends.

Potential concerns from bark firing include the following:

- Variable quality feedstock leading to kiln instability
- Fuel preparation and storage (important to minimize risk for explosion)
- Feeder system (important in delivery of consistent and steady fuel flow to the kiln)
- Blockages in feeder, conveying line, and burner causing excessive downtime
- Wear in transport line and burner from bark at high velocity

All the above concerns, with the exception of variable quality feedstock, can be addressed by thorough and careful system design.

Pyrolysis oil

Pyrolysis oil, known also as biocrude or bio-oil, is a synthetic fuel produced by thermochemical conversion of biomass at temperatures below 500°C. Pyrolysis oil is often considered to be a hydrocarbon liquid, but it is not quite so technically because it contains condensed volatile organic compounds (tars) as well as organically bound oxygen and water [11-13]. Therefore, it has a lower net heating value and is distinctly different from similar petroleum products such as HFO (**Table III**).

Parameter	Pyrolysis Oil	No. 2 Diesel Oil	Heavy Fuel Oil
Carbon (C), wt%	48.5	86.3	86.1
Hydrogen (H), wt%	6.4	12.8	11.8
Oxygen (O), wt%	42.5	0.9	0
Sulfur (S), wt%	0	0.15–0.30	2.1
Ash, wt%	0.13	<0.01	0.03
Water content, wt%	20.5	0.1	0.1
Density at 15°C, kg/L	1.22	0.85	0.96
Kinematic viscosity at 50°C, cSt	13	2.5	351
Net heat, MJ/kg	17.5	42.9	40.7

III. Characteristics of oils.

Due to its high volatility, high oxygen content, and low net heating value, pyrolysis oil is expected to perform in a similar manner as natural gas.

Potential concerns from pyrolysis oil firing include the following:

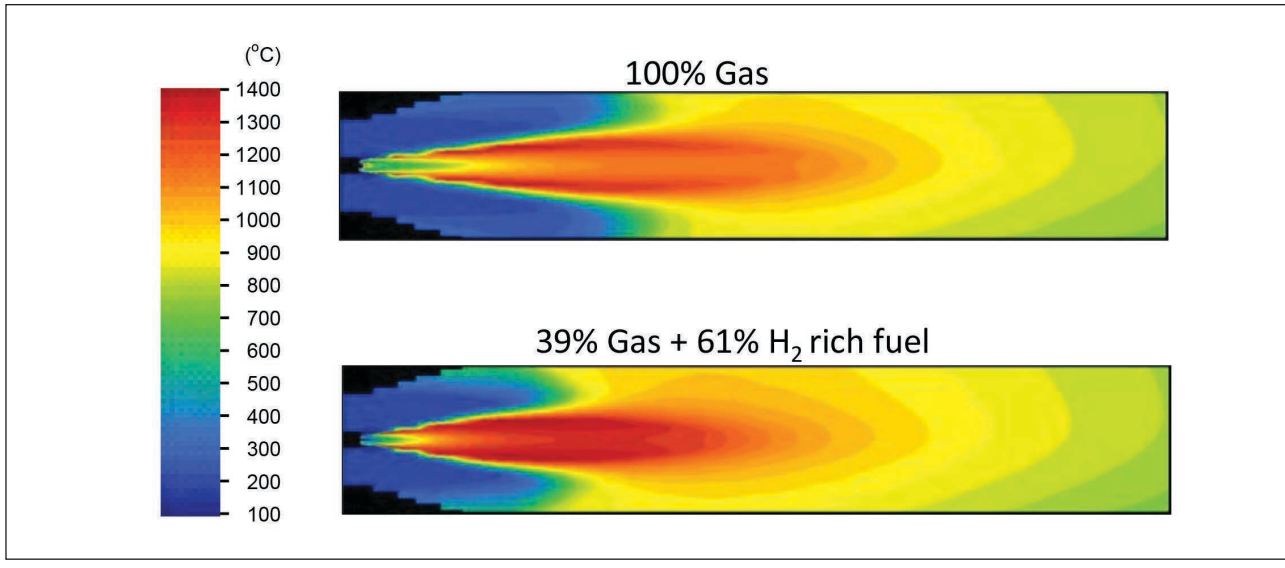
- Variable composition leading to changing viscosity properties (variation in atomization)
- Variable composition leading to changing heat content and kiln instability
- May contain small char particles (potential erosion problems; filtering required to minimize oil gun tip blockage)
- Acidity of oil (piping and storage equipment must be made of corrosion resistant materials)
- Typically contains 20-25 wt% water, making it more difficult to ignite

Biomass gasifier gas

Biomass gasifier (or producer) gas is produced by processing biomass material at high temperatures in the absence of sufficient oxygen for complete combustion. As summarized in **Table IV**, biomass gasifier gas is a mixture of carbon monoxide (CO), hydrogen (H_2), methane, and small amounts of ethane and propane. It also contains a larger amount of nitrogen

Composition, % vol	Value
Carbon monoxide (CO)	16–19
Hydrogen (H_2)	11–12
Methane (CH_4)	4–6
Ethane (C_2H_6)	1–2
Propane (C_3H_8)	0–0.1
Carbon dioxide (CO_2)	11–16
Water vapor (H_2O)	6–15
Nitrogen (N_2)	37–42
Temperature, °C	690 - 700
Net heat, MJ/Nm^3	5.8 - 6.7

IV. Biomass gasifier gas composition.



5. CFD modeling of gas temperatures in a lime kiln burning hydrogen-rich fuel versus gas temperatures in the same kiln with optimized natural gas burner.

(N_2) and combustion products carbon dioxide (CO_2) and water vapor. Depending on the process, the gas is hot (about 600°C-700°C) and thus requires the mechanical design of the burner to allow for changes in positioning and direction during commissioning.

The main combustion components of biomass gasifier gas are H_2 and CO. Because these gases have a relatively low luminosity, they can cause reduced heat transfer in the kiln front end. More importantly, because of the low heating value of gasifier gas, the combustion air requirements would normally be higher than for natural gas for the same heat release. The gasifier gas is often delivered to the burner at high temperatures (600°C-700°C); thus, it provides additional heat to the kiln, resulting in a lower fuel usage per ton of lime product impacting the kiln profile. Depending on the gasifier gas temperature, the kiln operation can vary between HFO (high temperature) and natural gas firing (lower temperature) in terms of kiln performance.

Potential concerns from biomass gasifier gas firing include the following:

- Variable composition leading to changing heat content and kiln instability
- Handling high temperature gas delivery to the burner
- High kiln exit gas temperatures and ID fan limitations

Hydrogen gas

Hydrogen is the main byproduct gas in the manufacturing of sodium chlorate ($NaClO_3$) used in pulp mills to generate chlorine dioxide (ClO_2) for bleaching wood pulp. The gas typically contains 95% H_2 by volume, which can be a good fuel for use in lime kilns. Smaller bleached pulp mills cannot justify having their own $NaClO_3$ plant; they need to purchase $NaClO_3$ for their ClO_2 generators and hence do not have H_2 available on site. For mills located near an $NaClO_3$ plant, or for larger bleached pulp mills equipped with their own $NaClO_3$ plants, H_2 is available and is often one of the fuels that is burned in the lime kilns.

The combustion and heat transfer properties of H_2 are similar to biomass gasifier gas due to the absence of hydrocarbons and heat released from a nonluminous combustion process. In a recent CFD modeling study conducted by KFS for a North American pulp mill, the combustion and gas temperature profiles in a lime kiln burning hydrogen-rich fuel were found to be similar to the same kiln burning natural gas, with higher feed end temperatures as shown in **Fig. 5**.

Burning hydrogen can be challenging due to extremely high flame temperatures and flame propagation velocities. It is essential to maintain high exit velocities at the burner tip to stabilize combustion at the tip and not overheat the burner.

Potential concerns from hydrogen gas firing include the following:

- Handling and storage (very low density and ability to leak through extremely small openings)
- High peak flame temperatures
- High peak flame velocity (impact on burner design to accommodate flame velocities)
- Variable composition leading to changing heat content and kiln instability

Lignin

Lignin is another biofuel that has been considered to partially replace fossil fuels burned in lime kilns. In kraft pulp mills, lignin may be precipitated and separated from black liquor by acidifying it with CO_2, sulfuric acid, or both. Because of the high cost of the production process, burning lignin in lime kilns economically makes sense only if it allows pulp mills to burn more lignin-lean black liquor in the recovery boiler, thereby increasing their pulp production capacity.

A commercial process for producing lignin from black liquor is LignoBoost [5,6], developed by Innventia and Chalm-

Composition, % vol	Value
Carbon (C), %wt (dry)	64.0
Hydrogen (H), %wt (dry)	5.7
Nitrogen (N), %wt (dry)	0.1
Oxygen (O), %wt (dry)	26.4
Sulfur (S), %wt (dry)	1.8
Chlorine (Cl), %wt (dry)	<0.01
Ash, wt% (dry)	1.4
Moisture, wt%	4.0
Net heat, MJ/kg (dry)	25.6

V. Composition and heating value of lignin.

ers University of Technology and acquired by Valmet (formerly Metso) in 2008 in its entirety. The technology has been subsequently developed, with its first commercial plant started up at the Domtar mill in Plymouth, NC, USA. Several other processes are also available for lignin precipitation, including the one developed by FPInnovations [7].

The first commercial integrated LignoBoost/lime kiln operations will be installed at the Stora Enso mill at Sunila, Finland. Valmet will be responsible for the production of dried lignin for storage with plant startup due in early 2015. The lignin storage, feeder system, and burner by Tanki, Clyde and KFS (High Wycombe, UK) was scheduled to be installed in 2014.

The properties of dried lignin are shown in **Table V** [5]. The relatively high oxygen content of the fuel makes it similar in composition to pyrolysis oil and bark, suggesting that operation with 100% lignin will produce a gas temperature profile similar to that of natural gas. As shown in **Fig. 6**, in spite of lower oxygen content than bark, lignin's burning characteristics are similar with the kiln operating with lower discharge temperatures and higher kiln exit gas temperatures [6].

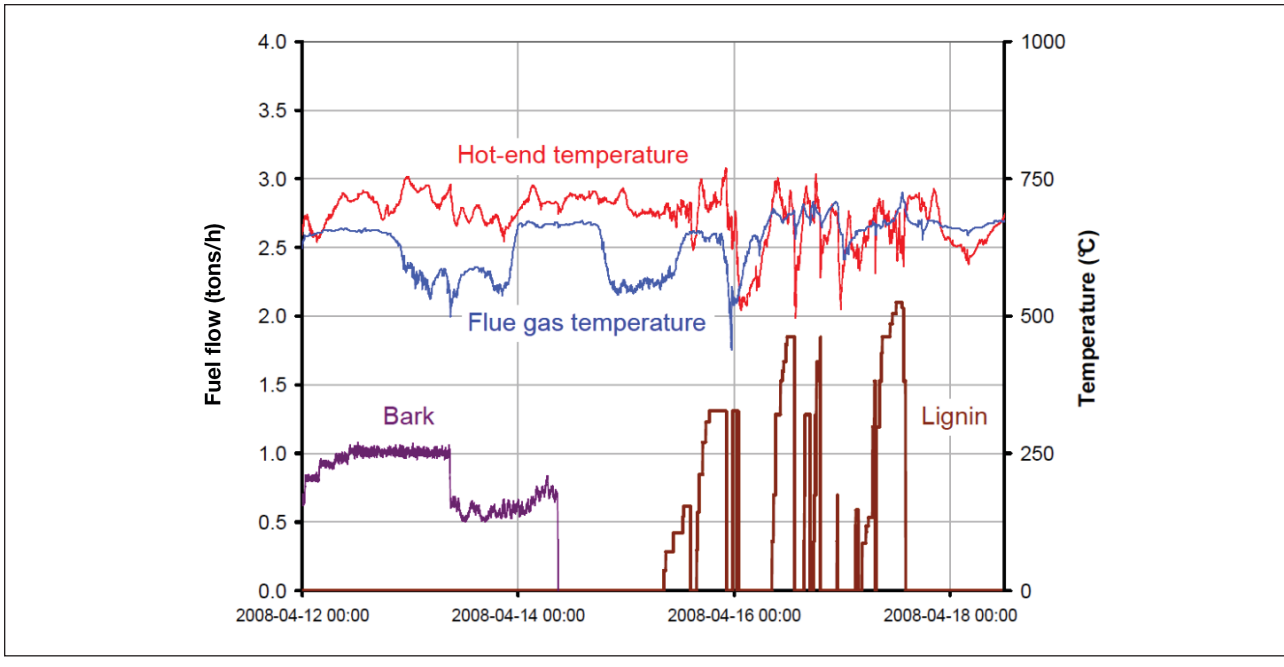
Preparation and handling of lignin does have some safety issues that need to be considered. System design is important with lignin material because of low melting point, high volatiles content, and high potential for explosion. While air conveying is normal for solid fuels, the conveying material for lignin needs to be vitiated to lower the oxygen to below the threshold for sustained combustion. The potential for explosion also extends to material storage and feeder systems.

Potential concerns from lignin firing include the following:

- Variable quality leading to kiln instability
- Fuel preparation and storage (important to minimize risk for explosion)
- Feeder system (important in delivery of consistent and steady fuel flow to the kiln)
- Blockages in feeder, conveying line, and burner causing excessive downtime
- Wear in transport line and burner from lignin at high velocity
- Risk for explosion during storage and transport

CONCLUSIONS AND SUMMARY

In the majority of cases, fuels with high oxygen content and moderately low calorific values mirror kiln operation when using natural gas (**Table VI**). Hence, in assessing impact on kiln performance, production and ID fan limits together with kiln exit gas temperatures need to be considered. This will



6. Experiences from feeding and cofiring of lignin powder in a lime kiln.

Fuel	Kiln Behavior Similarity
Tall oil	Heavy fuel oil
Bark	Natural gas
Pyrolysis oil	Natural gas
Biomass gasifier gas	Heavy fuel oil or natural gas (depending on fuel temperature)
Hydrogen gas	Natural gas
Lignin	Natural gas

VI. Summary of fuel behavior in lime kiln.

depend on the original fuel used (oil or natural gas) and amount of original fuel substituted with the biofuel. With significant increases in fossil fuel costs and the sustained drive to minimize carbon footprint, there has been a great deal of R&D of the biorefinery concept and production of biofuels for use within pulp mills. Several new biofuels will become available together with traditional mill-derived fuels such as tall oil.

In considering use of biofuels for replacement of fossil fuels in the lime kiln, each fuel has a different impact on kiln performance. An assessment on kiln performance can be achieved and compared to either HFO or natural gas. In the majority of cases, fuels with high oxygen content and moderately low calorific values (such as bark, lignin, and pyrolysis oil) behave similarly to natural gas when burned in lime kilns. Hydrogen also behaves similarly to natural gas, although it produces a much hotter and higher velocity flame. Tall oil burns in the same manner as HFO, while biomass gasifier gas can behave like natural gas or HFO, depending on its initial temperature.

Therefore, in assessing impact on kiln performance, production and ID fan limits together with kiln exit gas temperatures need to be considered. These will depend on the original fuel used (HFO or natural gas) and amount of original fuel substituted with the biofuel. **TJ**

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We chose this topic to research because it is useful to have information on the potential impact of replacing fossil fuels in lime kilns with various types of biofuels summarized in one place. That had not been done before.

This research complements previous work by other groups. However, we focused on burner operation, flame stability, heat transfer, and kiln temperature profile and their potential effects on kiln production capacity.

In our work, we discovered that the majority of new biofuels generated at pulp mills can be used in replacing conventional fossil fuels in lime kilns with careful consideration to impact on kiln performance. It was surprising to realize there is a wide range of biofuels that are being used in kiln operations around the world.

Pulp mills may use the information to assess the impact of replacing fossil fuels with biofuels on lime kiln performance.

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