LIME KILN PRINCIPLES AND OPERATIONS

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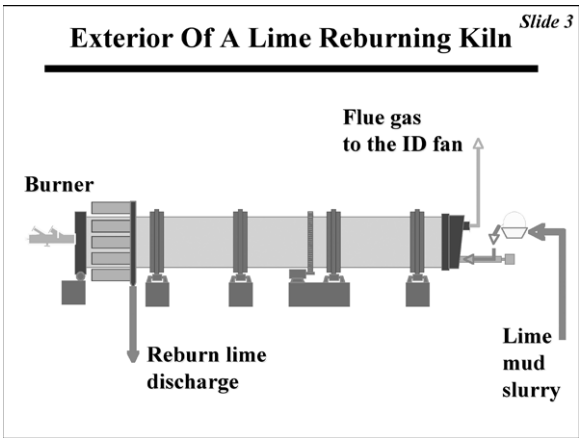
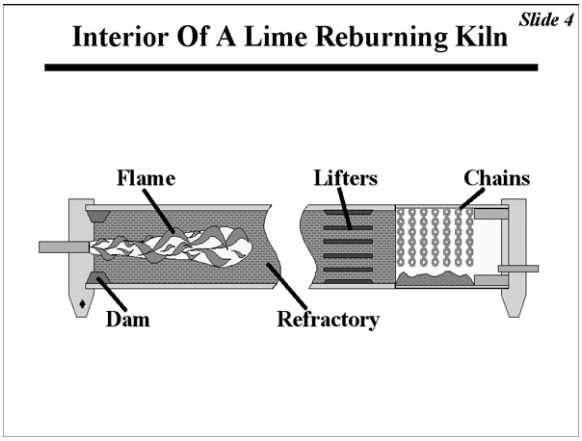
ROTARY LIME KILNS

Slides 1 and 2 are the title and outline for the presentation. **Slide 3,** below**,** shows a schematic of the exterior of a modern rotary lime-reburning kiln.



Slide 4 shows a schematic of the interior features of a lime-reburning kiln.



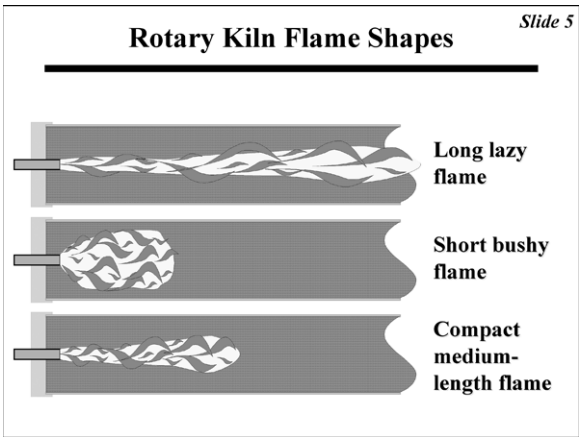
Rotary lime kilns are large steel tubes that are lined on the inside with refractory bricks. They are slightly inclined from the horizontal and are slowly rotated on a set of riding rings. Lime mud is introduced at the uphill, feed end and slowly makes its way to the discharge end due to the inclination and rotation. A burner is installed at the downhill or discharge end of the kiln where fuel is burned to form an approximately cylindrical flame. Heat transfer from this flame and the hot combustion gases that flow up the kiln dries, heats, and calcines the counter-flowing lime solids. Rotary lime kilns in the pulp and paper industry range in size from 7 ft (2.1 m) in diameter by 175 ft (53 m) long to 13.5 ft (4 m) in diameter by 400 ft (122 m) long. The refractory lining is from 6 in. (15.2 cm) to 10 in. (25.4 cm) thick. Production capacities for these units range from 50 tons/day of CaO (45 metric tons/day) to 450 tons/day of CaO (400 metric tons/day).

The weight of the kiln is supported on riding rings that encircle the kiln. These riding rings contact carrying rolls supported by concrete piers. A large electric motor operating through a reducing gearbox and pinion drives a main gear attached to the kiln. Typically the kiln is driven at speeds of 0.5 to 2 RPM, often with variable speed arrangements. Typical transit times for the lime through the kiln are from 1.5 hours to 4 hours under normal operating conditions. This is set by the speed and by the slope of the kiln, which is between 1.5° and 3° (5/16 to 5/8 inches/foot).

The rotation of the kiln necessitates the use of hoods and seals at each end for connection to stationary ancillary equipment. At the hot end, the firing hood provides support for the burner and the flame management equipment, as well as openings and passages for the discharge of the reburned lime product. At the cold end, the hood provides openings for a lime mud feed screw or belt, a connection to the induced draft fan and an important seal to limit the flow of tramp air. In older installations this hood is often an enlarged chamber in which dust and mud can be sluiced out of this area. Newer installations incorporate smaller hoods to improve the seal and shorten the length of the mud screw or belt.

ROTARY KILN FLAMES

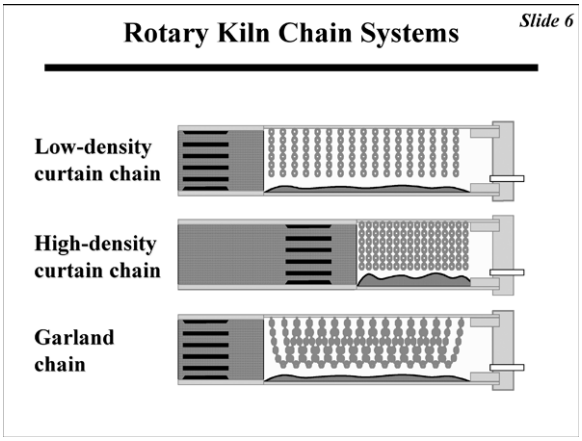
The burner and flame play an important role in product quality and refractory service life. As with all combustion fired heat exchange equipment, higher flame temperatures mean higher production capacity and efficiency. However, excessive temperatures cause refractory damage, and over-burned, slow-reacting lime product. This tradeoff in performance results in a compromise in flame length. **Slide 5** shows sketches of three types of rotary kiln flames.

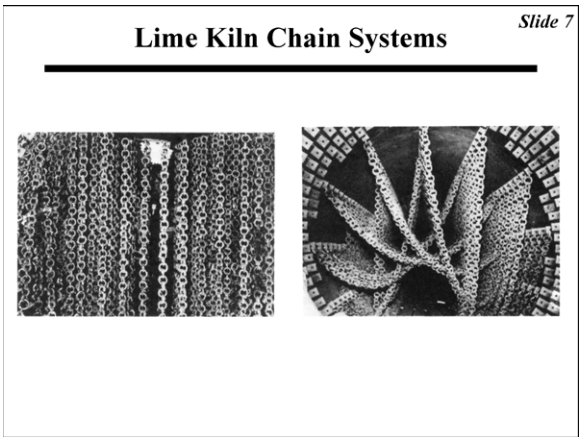


Shorter flames are too hot and cause refractory damage and overburned lime, while longer flames cause some loss in production capacity and efficiency, and loss of control of the product quality. A compact, medium-length flame approximately three times the kiln diameter in length is a good tradeoff between efficiency and refractory service life. However, irrespective of the shape, the flame must not touch the refractory, or serious refractory washing will occur.

ROTARY KILN CHAIN SYSTEMS

At the cold end of the kiln, the relatively low gas temperature hampers heat transfer. To improve this, a section of chain is hung from the shell in this part of the kiln. This chain is made up of links that are typically ¾ in. by 3 in. (1.9 cm x 7.6 cm). Hangers attach lengths of this chain directly to the kiln shell either from one end or both ends. When chain is hung from one end it is referred to as curtain chain. When hung from both ends it is most often called a garland system. **Slide 6** shows sketches of these two types of chain systems, and shows the difference between high-density and low-density chain hanging arrangements. **Slide 7** shows photographs of the two types of chain systems.



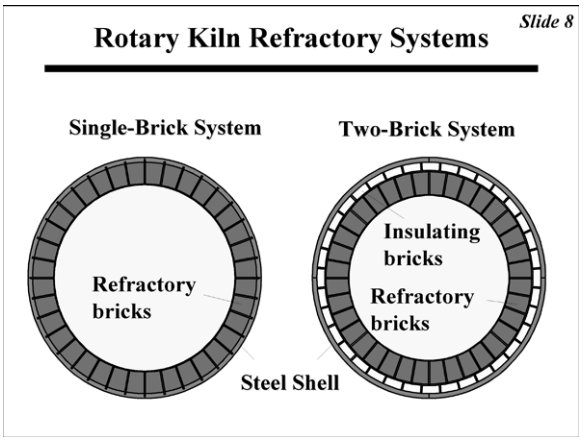


The method of hanging the chain makes little difference in its effectiveness as a regenerative heat exchange surface. As long as the chain alternatively contacts the combustion gases and the lime mud as the kiln rotates, it is effective. Like any low-temperature heat exchanger, it is the available surface area that is most important to effectiveness. The chain surface area in a lime reburning kiln can represent two-thirds of the entire heat transfer surface.

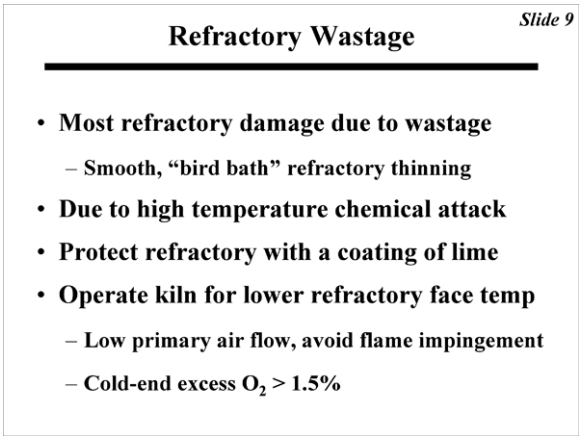
ROTARY KILN REFRACTORY SYSTEMS

There are several different types of refractory materials available for application in lime reburning, and usually two or three of these are used at different locations along the length of the kiln. A very common refractory system consists of bricks that are either shaped to fit the curvature of the shell or are in thin wedges that can be laid in an arch pattern in order to produce a complete shell lining.

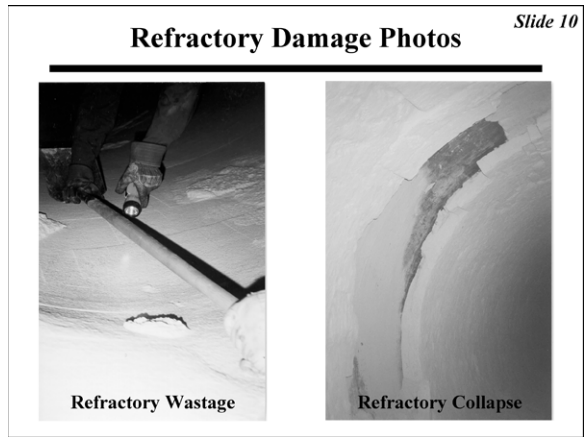
The refractory bricks are composed of special heat-resistant and chemical-attack resistant materials that are most often alumina and silica compounds. Traditionally, the bricks in the hot zone of the kiln near the flame are composed of 70% alumina in order to resist the high temperatures and chemical attack in this region. About one-third of the way up the length of the kiln, this is changed to 40% alumina bricks, which have better insulating characteristics. Finally, a castable low-temperature refractory is used in the chain section at the cold end of the kiln. Many modifications of this pattern are now available including cast or packed refractories in place of bricks, or two-brick systems that use insulating bricks against the steel shell and chemical-attack resistant bricks in contact with the lime solids and combustion gases. **Slide 8** shows the arrangement for a single-brick and a two-brick refractory system.



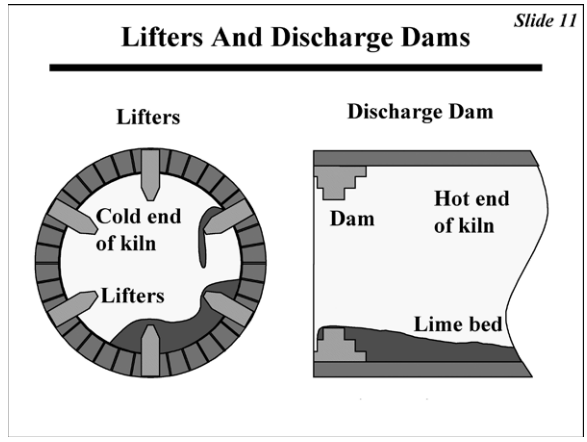
The ability of the refractory lining to withstand chemical attack by the lime and its constituents is crucial to the service life of this part of the kiln. Although sudden changes in temperature can damage the lining, it is primarily due to chemical attack that refractory is washed from the kiln and requires periodic replacement. Quite aside from the increased heat loss associated with thin, worn refractory lining, it is important for structural reasons to maintain the lining to avoid exposure of the steel shell to combustion temperatures. **Slide 9** describes refractory wastage and presents several methods for controlling wastage.



Slide 10 shows photographs of refractory wastage and refractory collapse, when the arch effect of the bricks is lost and several complete rows of bricks fall out.



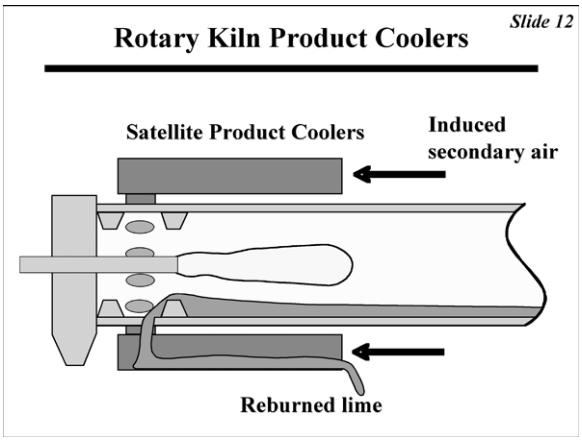
Slide 11 shows two other features of the interior lining of rotary kilns that are used to improve heat transfer. The first feature is a set of lifters that are installed in the cold end of the kiln, usually just downhill from the chains.



Lifters mix the lime mud and expose it to the hot gases. Discharge dams are usually located at the hot end of the kiln and cause the lime to pool behind the dam underneath the flame.

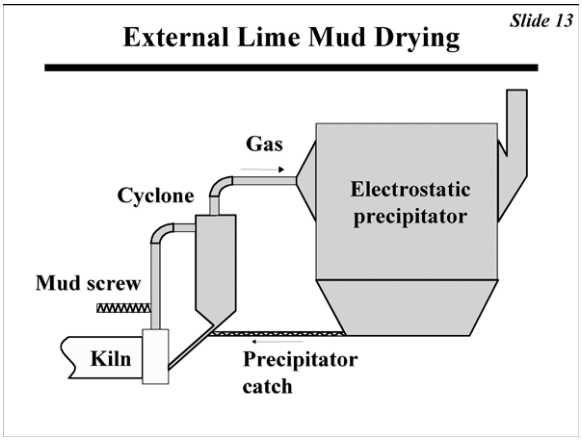
ROTARY KILN PRODUCT COOLERS

Slide 12 shows a schematic of satellite product coolers. All modern kilns are being offered with product coolers. Satellite coolers are tubes attached to the kiln shell and rotating with the kiln. The hot reburned lime product drops through holes in the shell just uphill from the lip of the kiln into the tube coolers. Internal structures move the lime back uphill in these tubes as they orbit with the kiln rotation. They also bring the hot lime into contact with air, which preheats this combustion air and results in a substantial improvement in energy efficiency for the kiln. There are now two other types of product coolers for lime reburning kilns that can be installed on new kilns or retrofit to older kilns.



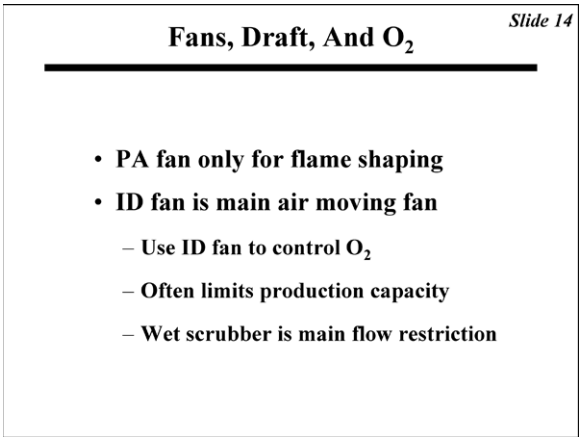
EXTERNAL LIME MUD DRIERS

Slide 13 shows a schematic of an external lime mud drier. The wet lime mud is introduced into the duct leading to a cyclone. The mud dries in flight, separates from the gases in the cyclone, and flows into the kiln as a dry powder. The lime dust that escapes the cyclone is usually captured in an electrostatic precipitator and also enters the kiln dry. With this system, chains are not needed to dry the lime mud; the entire kiln length is available for heating and calcining.



LIME KILN FANS

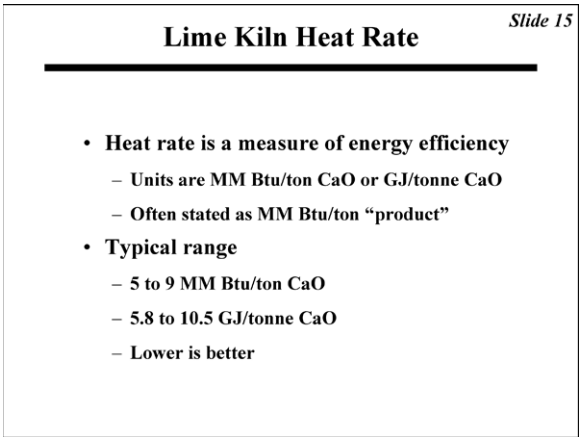
Slide 14 presents two important parts of the combustion system, the fans at the hot end and cold end of the kiln. The Primary Air (PA) fan is at the hot end and supplies a small amount of air to the burner for flame shaping and stability. Typically the PA fan supplies only 5% to 25% of the total air required for complete combustion. The Induced Draft (ID) fan at the cold end of the kiln is the main gas moving fan. It pulls the combustion products, carbon dioxide from calcining, and the water vapor from the wet mud out of the cold end of the kiln. The ID fan is used to control the total air flow into the kiln for combustion, so controls the excess air or excess oxygen in the flue gas from the kiln.



The capacity of the ID fan often limits the production capacity of the kiln. When the ID fan reaches its maximum capacity, no more combustion air can be brought into the kiln. This limits the fuel firing rate and the lime production rate. For many installations the wet scrubber that follows the ID fan in the flue gas system is the biggest resistance to flue gas flow, so can limit the ID fan capacity. Changes in wet scrubber pressure-drop for dust emission control or changes in fuel type can decrease the ID fan capacity and kiln production capacity.

LIME KILN HEAT RATE

The energy efficiency of lime kilns is expressed as the Heat Rate. Heat Rate is the reciprocal of energy efficiency, and is usually expressed as MM Btu/ton of CaO, or as GJ/tonne of CaO. Lower values of Heat Rate indicate more efficient operation as indicated in **Slide 15**.



The main chemical reaction in a lime kiln is calcining, the conversion of the calcium carbonate ($CaCO_3$) in the lime mud into calcium oxide (CaO) in the kiln product. Energy is required to cause this endothermic reaction to occur, but there are other energy components to the overall energy demand of the kiln as shown in **Slide 16**.

Slide 16

Lime Kiln Energy Balance Components

- **Drying**
- **Calcining : $CaCO_3$ + heat ➔ CaO + CO_2**
- **Losses**
  - **Heat loss through shell**
  - **Heat loss in hot lime product**
  - **Heat loss with gas and dust exiting at cold end**
- **A portion of fuel higher heating value is unavailable**
  - **HHV is measured and reported**
  - **Only Lower Heating Value (LHV) is actually available**

There is the energy required to dry the mud, as well as losses of energy as heat from the kiln shell, with the hot lime product, and with the flue gases exiting the cold end of the kiln. There is also a "loss" due to the fuel. This is not a real heat loss, but an artifact of the way the fuel energy is reported.

In North America the heating value of fuels is reported as the "Higher Heating Value" (HHV). This is the energy per unit weight of fuel that is measured by an Oxygen Bomb Calorimeter. The HHV includes the energy available when the water vapor in the combustion products is condensed. This energy is not really available in any practical combustion system, so using the HHV gives a false indication of the energy that is actually available from the fuel. Outside of North America the Lower (or Net) Heating Value (LHV of NHV) is used, and this value does not include the energy from condensing water vapor. For the current purpose of calculating Heat Rate, a "heat loss" term must be included, and this can be a significant correction to the Heat Rate.

Slide 17 shows the lime kiln parameters that are used in the examples below to show the impact of various equipment and operating conditions on the Heat Rate of a lime kiln. The example kiln is an 11 foot (3.4 m) diameter by 275 foot (84 m) long kiln with satellite coolers and single brick refractory. This is typical of an older kiln.

Slide 17

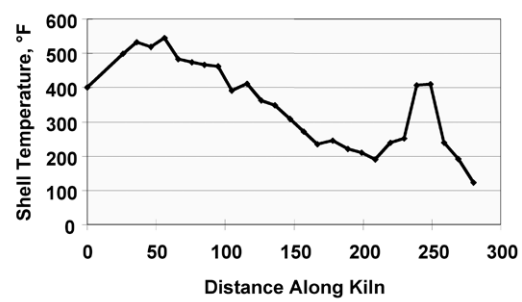
Example for Kiln Heat Rate

KILN PARAMETERS	
Fuel	Nat Gas
Production rate	250 TPD
Mud dry solids	78%
Kiln exit O2	3%
Lime availability	85%
Dust loss	18%
Product temp	600°F
Cold end gas temp	600°F
Shell Heat Loss	11.4 MM Btu/hr

Slide 18 shows a temperature profile along the kiln shell. This data is needed to calculate the shell heat loss. The method for calculating this loss and for the other calculations involved in determining the kiln Heat Rate are contained in the Appendix to this paper.

Slide 18

Shell Temperature Profile



Slide 19 shows the example kiln has an overall Heat Rate of 8.4 MM Btu/ton of CaO using the parameters listed in Slide 17. Slide 19 also shows the individual contributions to the overall Heat Rate and the potential remedy for improving the Heat Rate. This is useful for identifying changes that can make significant differences in fuel use at the kiln.

Slide 19

Lime Kiln Heat Rate

- **Overall Heat Rate = 8.4 MM Btu/ton CaO**

Contribution	Heat rate	Fraction	Remedy
Calcining reaction	2.82	34%	No change possible
Heat to evap water	1.75	21%	Increase mud dry solids
Heat in exit gas	1.50	18%	Decrease exit gas temp
Shell heat loss	1.10	13%	Insulating refractory
LHV/HHV loss	0.82	10%	Change fuel
Heat in product	0.29	3%	Product coolers
Heat in dust	0.11	1%	Improve chain system

Slide 20 emphasizes that caution must be exercised in calculating and using Heat Rate results. The calculation is for steady operation of the kiln without upsets or downtime, so it underestimates the Heat Rate for the kiln over the long term. As well, changes in some of the parameters affect more than one of the loss terms, so experience and judgment are needed to interpret the results. Despite these limitations the Heat Rate calculation quickly identifies changes that have major and minor impacts on overall energy consumption at the kiln.

Slide 20

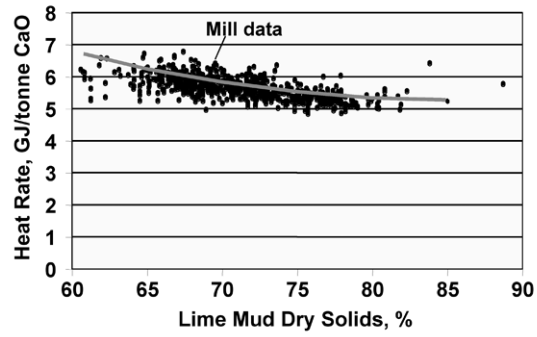
Caution With Heat Rate Calculation

- **Gives instantaneous value**
  - **Doesn't include down time, upsets**
- **Good to assess where improvements needed**
- **Some changes affect more than one parameter**
  - **Refractory changes shell loss & exit temp**
  - **Mud solids affects evaporation loss and exit temp**
  - **Fuel changes LHV/HHV, exit gas temp, and dust loss**

One of the parameters that initially would seem to have a major impact on energy use of the kiln is the moisture of the mud entering the kiln. Increasing the dry solids content of the mud entering the kiln definitely reduces the energy required for drying, but it also has the impact of increasing the flue gas temperature, and the heat loss with the flue gas. The overall impact is shown in **Slide 21** based on operating data for one kiln. The benefit in increasing the dry solids of the mud entering the kiln decreases as the mud dry solids reaches the mid-70s. This is partly due to the decreasing amount of moisture that must be evaporated, but is also due to the increase in the temperature of the flue gas exiting the feed-end of the kiln. **Figure 22** for a different kiln shows that as mud dry solids increases from 72% to 84% the exit gas temperature increases from about 400°F to almost 650°F for this particular kiln. The increased heat loss due the hotter flue gas offsets the reduction due to lower energy for drying. The net effect is that Heat Rate changes only a little over the range of dry solids tested. The response for most kilns is similar, but the magnitude of this effect depends very much on the configuration of the kiln.

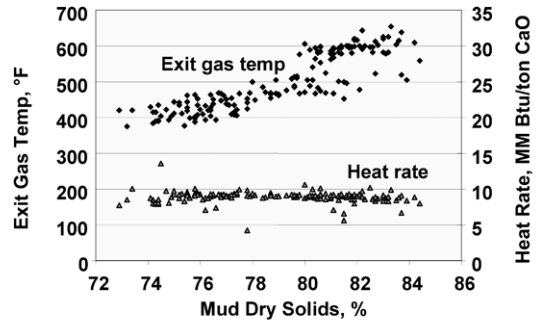
Slide 21

Impact of Mud Dry Solids on Heat Rate



Slide 22

Impact of Mud Dry Solids on Heat Rate



Slide 23 shows the base case for the example kiln along with major improvements in Heat Rate due to changes in refractory, fuel type, and the chain system.

Slide 23

Major Heat Rate Improvements

KILN PARAMETERS	Base	Refractory	Fuel Type	Chains
Fuel	Nat Gas	Nat Gas	Fuel Oil	Nat Gas
Production rate, TPD	250	250	250	250
Mud dry solids	78%	78%	78%	78%
Kiln exit O2	3%	3%	3%	3%
Lime availability	85%	85%	85%	85%
Dust loss	18%	12%	18%	18%
Product temp, °F	600	600	600	600
Cold end gas temp, °F	600	475	500	525
Shell Heat Loss, MM Btu/hr	11.4	6.3	11.4	11.4
Heat Rate, MM Btu/ton	8.4	7.0	7.4	8.0
Change		-17%	-11%	-4%

Improving the kiln refractory to reduce the shell heat loss obviously has a very major impact on kiln Heat Rate, but the fuel used in firing the kiln is almost as important.

Slide 24 shows some minor changes in Heat Rate with changes in excess air, changes in dust loss, and changes in inerts, or non-process elements (NPEs) in the lime mud.

Slide 24

Minor Heat Rate Improvements

KILN PARAMETERS	Base	Excess air	Dust	Inerts
Fuel	Nat Gas	Nat Gas	Nat Gas	Nat Gas
Production rate, TPD	250	250	250	250
Mud dry solids	78%	78%	78%	78%
Kiln exit O2	3%	2%	3%	3%
Lime availability	85%	85%	85%	92%
Dust loss	18%	18%	12%	18%
Product temp, °F	600	600	600	600
Cold end gas temp, °F	600	575	600	600
Shell Heat Loss, MM Btu/hr	11.4	11.4	11.4	11.4
Heat Rate, MM Btu/ton	8.4	8.1	8.2	8.2
Change		-3%	-3%	-2%

LIME KILN FUELS

Slide 25 shows the common lime kiln fuels used in the pulp and paper industry. Natural gas and fuel oil are widely used, but a growing number of kilns are at least partially fired with petroleum coke. Pet coke is an efficient, though messy, kiln fuel as long as the sulfur and metals contamination are not too high. The sulfur content of petroleum coke slightly derates the kiln due to the formation of $CaSO_4$, and the metals require somewhat higher use of purchased lime, but these two are offset by the lower cost and better efficiency.

Slide 25

Common Lime Reburning Kiln Fuels

- **Nat gas and fuel oil are most common**
  - **Fuel oil is more efficient, gives higher capacity**
- **Petroleum coke**
  - **Many applications, low cost**
  - **Sulfur and metals can be high**
  - **Thermal NOx can be high**
  - **Improves heat rate**

Slide 26 deals with other solids and liquid fuels for lime kilns. Wood and bark powder have been fired directly in kilns as the main kiln fuel. The NPEs in these fuels are usually low enough so that modest increase in lime makeup can control buildup of NPEs in the recovery loop.

There are several schemes to separate lignin from the black liquor and use it as a product or as a fuel for the lime kiln. Tests of lignin as a fuel both in test facility and in the field have shown this is feasible, though the sulfur content is relatively high.

Pyrolysis oils have also been proposed for lime kilns, but fuel handling problems need to be overcome to make this attractive.

Slide 26

Other Solid/Liquid Kiln Fuels

- **Wood and bark powder**
  - **NPEs can be high**
  - **Lime purge & makeup needed to control NPEs**
- **Lignin**
  - **Sulfur can be high**
- **Pyrolysis oils**
  - **Not currently used, pH & ■ possible issues**

Slide 27 presents information on gasification of wood, coal and other materials, which have been used for many years to provide clean fuel-gas for firing lime kilns. The lower cost of the gasification fuel offsets the high capital cost of the equipment needed to gasify these fuels. Good, stable operation is possible with gasification with production capacity and Heat Rate similar to that for natural gas.

Slide 27

Gasification Fuels

- **Coal, wood and other fuels can be gasified**
- **Fuel-gas can be used to fire kiln**
  - **Similar to natural gas**
  - **Lower inert level, well established technology**
  - **On-line availability ~ 85%**
  - **Wet gasifier feedstocks derate kiln**
  - **Burner and chains must be designed for fuel-gas**

Slide 28 addresses the "fuels" that are generated in the pulp mill. Turpentine, methanol, stripper off-gas (SOG), and non-condensable gases (NCG) have all been burned in lime reburning kilns. The energy content of these "fuels" varies considerably, but each makes a contribution to overall heat input. These materials contain some sulfur that can derate the kiln capacity, and all of them lower the Heat Rate of the kiln.

Tall oil has been used to fire lime kilns where its value as a mill product is low. It is a good kiln fuel with relatively low sulfur and good heating value. It would have a Heat Rate similar to fuel oil.

Slide 28

Fuels From the Pulp Mill

- **Turpentine or methanol liquid**
- **Stripper Off-Gas (SOG)**
- **Non-condensable gas (NCG)**
  - **Can be wet and sulfur level can be high**
- **Tall oil and tall oil pitch**
  - **Can fire 100% tall oil, similar to fuel oil**
  - **16,000 Btu/lb and low sulfur**

Slide 29 summarizes the steps to improve lime reburning kiln performance.

Slide 29

How To Improve Lime Kiln Performance

- **Improve refractory system**
  - **thicker bricks, two-brick system**
- **Switch fuels**
- **Improve chain system**
  - **amount for heat transfer, layout for dust**
- **Improve ID fan/scrubber**
- **Dry mud externally**

FURTHER READING ON LIME REBURNING KILNS

1. "Lime Reburning: The Rotary Lime Kiln", by Venki Venkatesh, in Chemical Recovery in the Alkaline Pulping Processes, R. P. Green and G. Hough editors, TAPPI Press, Atlanta, GA, 1992.

2. "Lime Reburning", by Terry N. Adams, in Pulp and Paper Manufacture, vol. 5, Alkaline Pulping, T. M. Grace and E. W. Malcolm, technical editors, M. J. Kocurek, editor, Montreal, 1989.

APPENDIX 1- LIME KILNHEAT RATE CALCULATION

HEAT RATE CALCULATION NOMENCLATURE

G_f = Fuel flow rate
G_{CaO} = CaO production rate
G_{CO2} = CO2 flow rate
G_{CaCO3} = CaCO3 flow rate
G_i = Inerts flow rate
G_w = Flow rate of water in mud
G_d = Dust flow rate
G_a = Air flow rate
G_{cp} = Combustion product flow rate
HR = Kiln heat rate
ΔHr = Heat of reaction of $CaCO_3 \Rightarrow CaO + CO_2$, at T_{ref}
HHV = Higher heating value
LHV = Lower heating value
T_p = Kiln product temperature
T_{ge} = Kiln exit gas temperature
T_{ref} = Reference temperature
Cp_i = Specific heat of component i
h_i = Heat in component i above T_{ref}
f_{LHV} = Fraction of HHV in LHV
f_{cp} = Fraction of HHV in combustion products at T_{ge}
AFS = Stoichiometric air-to-fuel ratio
e = Excess air
s = Mud solids
a = Lime availability
d = Dust loss
h_{fg} = Enthalpy of vaporization of water
Q_{sh} = Shell heat loss

MASS FLOW RELATIONSHIPS

$$G_m = G_{CaO}\frac{1+0.786a}{a}\frac{1}{1-d}$$

$$G_d = G_{CaO}\frac{1+0.786a}{a}\frac{d}{1-d}$$

$$G_w = G_{CaO}\frac{1+0.786a}{a}\frac{1}{1-d}\frac{1-s}{s}$$

$$G_i = G_{CaO}\frac{1-a}{a}$$

$$G_{CO2} = G_{CaO}\frac{44}{56}$$

$$G_{cp} = G_f\left[1+(1+e)AFS\right]$$

FUEL HEATING VALUE LOSSES

• Loss due to use of higher heating value

$$f_{LHV} = \frac{LHV}{HHV}$$

• Loss due to flow of combustion products

$$f_{cp} = \frac{\{1+(1+e)AFS\}Cp_{cp}\left(T_{ge}-T_{ref}\right)}{HHV}$$

KILN ENERGY BALANCE

$$G_f HHV\left(f_{LHV} - f_{cp}\right) = G_{CaO}\left[\Delta H_r + Cp_{CaO}\left(T_p - T_{ref}\right)\right]$$

$$+G_{CO2}Cp_{CO2}\left(T_{ge} - T_{ref}\right)$$

$$+G_i Cp_i\left(T_p - T_{ref}\right)$$

$$+G_w\left[h_{fg} + Cp_w\left(T_{ge} - T_{ref}\right)\right]$$

$$+G_d Cp_d\left(T_{ge} - T_{ref}\right) + Q_{sh}$$

• Heat rate definition

$$HR = \frac{G_f HHV}{G_{CaO}}$$

HEAT RATE CALCULATION
(Heat loss method)

$$HR\left(f_{LHV} - f_{cp}\right) = \left[\Delta H_r + Cp_{CaO}\left(T_p - T_{ref}\right)\right]$$

$$+\frac{44}{56} Cp_{CO2}\left(T_{ge} - T_{ref}\right)$$

$$+\frac{1-a}{a} Cp_i\left(T_p - T_{ref}\right)$$

$$+\frac{1+0.786a}{a}\frac{1}{1-d}\frac{1-s}{s}\left[h_{fg} + Cp_w\left(T_{ge} - T_{ref}\right)\right]$$

$$+\frac{1+0.786a}{a}\frac{d}{1-d} Cp_d\left(T_{ge} - T_{ref}\right) + \frac{Q_{sh}}{G_{CaO}}$$

HEAT RATE CALCULATION PARAMETERS

FUEL CONSTANTS			
	Nat. gas	**Fuel oil**	
HHV	5.37E+07	4.27E+07	J/kg
LHV	4.84E+07	4.07E+07	J/kg
AFS	16.80	13.44	

EXCESS AIR "CONSTANTS"			
Dry basis factor	5.40	5.62	
Wet basis factor	8.96	8.60	
Assumed HR	7		GJ/tonne

PROPERTIES			
Comb. prod. specific heat	Cp_{cp}	1,267	J/kg/°C
Reburn specific heat	Cp_{CaO}	989	J/kg/°C
CO_2 specific heat	Cp_{CO2}	919	J/kg/°C
Inerts specific heat	Cp_i	1,046	J/kg/°C
Steam specific heat	Cp_s	1,991	J/kg/°C
Heat of calcination	ΔHr	3,270,045	J/kg
Enthalpy of vaporization	h_{fg}	2,439,465	J/kg

EXCESS AIR CALCULATION

$$e = \frac{X_{O2}}{1 - 4.76\left(X_{O2}\right)}\left(factor\right)$$

• Fuel oil with dry-basis O_2 probe

$$factor = \left\{4.53 + \frac{5.65}{HR}\right\}$$

• Fuel oil with wet-basis O_2 probe

$$factor = \left\{4.99 + \frac{5.65}{HR}\left[1 + 5.56\left(\frac{1 + 0.56\frac{1-a}{a}}{1-d}\right)\frac{1-s}{s}\right]\right\}$$

• Natural gas with dry-basis O_2 probe

$$factor = \left\{4.28 + \frac{5.82}{HR}\right\}$$

• Natural gas with wet-basis O_2 probe

$$factor = \left\{5.24 + \frac{5.82}{HR}\left[1 + 5.56\left(\frac{1 + 0.56\frac{1-a}{a}}{1-d}\right)\frac{1-s}{s}\right]\right\}$$

SHELL HEAT LOSS CALCULATION

• Convection, W/m^2

$$q_c = 1.175\left[22.75 * V^2 + 1.8 * \left(T_{sh} - 25\right)\right]^{0.35}\left(T_{sh} - 25\right)$$

• Radiation, W/m^2

$$q_r = 5.668x10^{-8}\,\varepsilon_{sh}\left\{\left(T_{sh} + 273\right)^4 - 298^4\right\}$$

• Shell heat loss, W

$$Q_{sh} = \Pi D \sum_i \Delta x \left(q_c + q_r\right)_i$$

where:

V = Wind velocity, m/s

T_{sh} = Shell temperature, °C

ε_{sh} = Shell emissivity

D = Kiln outside diameter, m