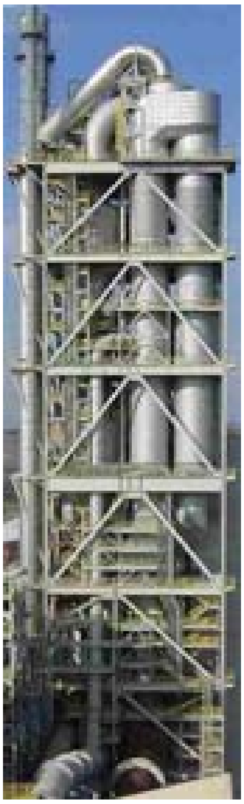
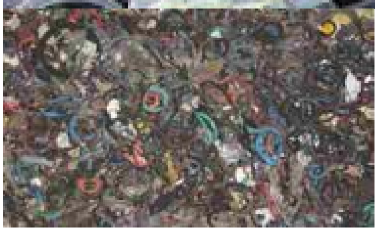
LAFARGE CEMENT

Technical agenda



Advance lever	**Production & Process**
Network	Process
Study	

Precalciner

February 2006 – Version 1

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Published by :
Direction des Performances Cimentières, France

Foreword

The Precalciner system, with its efficient decarbonation in a precalciner upstream of the kiln, was originally developed to increase the capacity of preheater kilns. Initially designed for liquid fuels, the systems have been adapted for more difficult to burn fuels such as petcoke and solid waste fuels. In addition, lower NOx limits have led to the development of staged combustion as an important method to lower NOx production. These developments have resulted in much larger and more complex designs and consequently different systems from the various suppliers.

The TA investigates the advantages of the different systems and gives proposals which design is the optimum for which fuel.

How should the Technical Agenda be used

- The TA has been written mainly for Technical Centres.
- When considering the optimisation of a existing calciner and/ or application of a new fuel the study should be used by the TC process departments, together with the plant.
- It is also a basis for TC process/engineering departments when selecting a new kiln system.

The study has been carried out by all TCs under the lead of ATC.

We want to thank all contributors and in particular:

- Chang Hyun Lee (ATC – Leader of the study)
- Julie Desseix (ERN)
- François Desmidt (CTI)
- Sam Fujimoto (CTS)
- Bernhard Koeck (CTEC)
- Christophe Landais (CTEO)
- Colin Paxton (DPC)

In addition to the those mentioned above there has been significant contribution from the process engineers in our precalciner plants who painstakingly collected the information, without which the survey would not have been possible.

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Executive Summary

1. Objectives

The objective of the precalciner study was to assess the ability of new and existing precalciners to burn petcoke and solid waste fuels.

2. Results

Precalciner Types

Precalciners types were described according to classical definition which relates to their geometry:

1. Riser Duct (Gooseneck) – extension of the kiln riser to increase the residence time to burn the precalciner fuel. Typical velocities at the inlet 16 m/s and main section 16-18 m/s.
2. Vessel – provision of a vessel with significantly larger cross section than the kiln riser. Typical inlet velocity range 20-30 m/s, main section velocity ranges from 4-10 depending upon supplier. Main suppliers FLS, Nihon and Onoda
3. Vessel Vortex – a vessel type precalciner with a special swirl chamber aimed at mixing the kiln gases with the tertiary air. Velocity range similar to the vessel design. Suppliers IHI and Fuller.
4. Separate Line – a vessel type precalciner but with only tertiary air passing through the precalciner vessel, kiln gases are kept separate. Inlet velocities range from 30-50 m/s and main section 4-6 m/s. Suppliers FLS, Kawasaki and Voest Alpine.
5. Combustion chamber – this formed the main part of the Onoda Reinforced Suspension Preheater (RSP) which is a combustion chamber to fire the fuel in tertiary air to provide a high temperature (hot spot) combustion. Swirling gases help to create a meal curtain at the walls of the chamber to prevent overheating. Today most suppliers offer a combustion chamber as an add on option to their standard precalciner design.

Modern precalciners offered by the major suppliers are a development of their older designs. They tend to offer their standard precalciner with a range of add on options designed for firing different fuels and meeting a range of NOx and CO limits.

Impact of Environmental Legislation

The more stringent limits for the emission of NOx and CO have had a significant impact on the development of the precalciner. In order to achieve NOx in the range of 500-800 mg/Nm3 (corrected to 10% oxygen) a reduction zone in the precalciner is used to limit the formation of NOx by the precalciner fuel and to reburn part of the NOx formed in the kiln to N2. This has meant the residence time of new precalciners has generally increased, by at least 0.5-1 seconds, to provide space for a reduction zone and still have time to burnt out

CO. (This assumes the same concentration of CO in the precalciner exit gas stream). In the event that lower NOx levels are to be achieved, below 500 mg/Nm3, SNCR will be required. The development of combined staged combustion and SNCR suggests even larger residence time is necessary, an additional 1.5 seconds, to allow burn out of CO. This is because the SNCR reactions further delay CO burnout. In addition to these impacts, modern precalciners are generally more complicated to operate, with several meal feeding points and splitting of the tertiary air addition to control the combustion atmosphere and temperature. Note that the above applies to a fuel such as bituminous coal with medium or high volatile matter. In the case where less reactive fuels such as petcoke are used NOx reduction is not as effective and SNCR will be required even with limits greater than 500 mg/Nm3.

A good example of the application of a reducing zone is the KHD Pyrotop, trials in Du Jiang Yang, China demonstrated less than 600 mg/Nm3 of NOx could be achieved, using a medium volatile coal.

In the case of an SLC or precalciner fitted with combustion chamber, less than 800 mg/Nm3 NOx cannot be guaranteed without firing some fuel into the kiln riser to reburn NOx formed in the kiln. Otherwise, SNCR will be necessary.

Note: The aim of this technical agenda study is to focus on the precalciner design, rather than the detail of NOx reduction. For more details on NOx reduction see the separate technical agenda study concerning this study.

<u>Burning Petcoke</u>

The survey of the Lafarge precalciner kilns shows a wide range of precalciner designs achieving more than 50% fuel replacement by high sulphur petcoke. These include all of the above designs, mostly without combustion chambers. They also include some precalciners with very short residence times <2 seconds. This indicates that generally low volatile fuels can be burned on most precalciners, provided the combustion is well mastered. One would expect plants with a 'hot spot' combustion chamber to be able to achieve high levels of petcoke substitution much easier than those without, due to the high temperature and higher oxygen atmosphere. The results of the survey tend to confirm this expectation by the fewer build up problems experienced by plants with 'hot spot' precalcincers.

Some modern designs of inline precalciners, e.g. FLS, are designed to create a high temperature zone, up to 1100 C to improve burnout of low volatile fuels. However, the oxygen content of the gas stream and operating temperature would still be less favourable for combustion than for a 'hot spot' design, although improved on conventional inline precalciners.

<u>Burning Lumpy Solid Waste Fuels</u>

Lafarge Kiln Survey

The result of the survey showed 12 kilns of the total of 52 precalciners replacing more than 10% precalciner fuel with solid wastes. The types of wastes include tyre chips, biomass (seeds, shells, husks and wood chips), plastics, solid shredded wastes, fluff and whole tyres (on fingers). Since the use of solid wastes is not extensive it is difficult to draw comparisons of the precalciner types for different fuels, although it does indicate some good examples:

1. Cauldon a vessel type precalciner replacing up to 90% precalciner fuel with tyre chips
2. Mannersdorf a separate line precalciner firing a range of biomass, with up to 50% precalciner fuel replacement.

Firing into the Gas Stream

Lumpy solid fuels are inherently more difficult to burn than pulverised fuels due to the longer burn out time. The precalciner was designed to burn pulverised fuels by entraining them in the gas stream and then providing sufficient residence time to allow them to burn completely. Thus the same approach could be used for lumpy solid fuels. Since we are dealing with much larger particle sizes the velocity in the precalciner becomes a critical constraint for efficient combustion. The velocity at the inlet needs to be high enough to entrain the fuel to avoid drop out to the kiln inlet. Good control of fuel size is also a key requirement. In the main section the velocity needs to be low enough to allow the fuel to be held in the precalciner to maximise combustion, prior to carry over to the lower cyclone stage. These velocity criteria are most closely met by vessel type precalciners, with much lower velocities in their main section than the riser type design.

The application of a 'hot spot' combustion chamber would be beneficial for small or light free flowing solid wastes, typically < 5mm, such as fluff and rice husks. However, for larger, heavier wastes the application would not be beneficial since there would be a tendency for the particles to drop out of the downward flowing gas stream.

New Precalciners - Design for Different Fuels and NOx Limits

The above conclusions regarding the precalciner design for different fuels and for several limits for NOx emission are summarised in the table below:

	FUEL			
	Conventional		**Solid Waste Fuels**	
	Coal	**Petcoke**	**size < 5mm / Light**	**Size >5mm / Dense**
PC Design	Any	Any	Any	Vessel ILC/SLC
'Hot Spot' Combustion Chamber	No	Yes	Yes	Only if petcoke also used
Residence Time (Secs)			Minimum values	
NOx > 800 mg/Nm3 (no NOx reduction)	2	3	3	
NOx < 800 mg/Nm3 (staged combustion)	3	3.5	3.5	
NOx < 400 mg/Nm3 (SNCR + staged combustion)	4	4.5	4.5	

The residence times shown for solid waste fuels were assumed to be at least equal to those required for firing petcoke. Since most plants will eventually have to achieve low NOx levels and will fire difficult wastes it would be prudent to design new precalciners with at least 4.5 seconds residence time or at least provide space in the preheater tower for future extension.

3. Recommandations

1. The most effective type of precalciner for firing petcoke and or light solid waste < 5mm is any the available designs, but fitted with a hot spot combustion chamber in the tertiary air duct.

2. The most effective design of precalciner for firing larger solid waste is a vessel type design. If petcoke is fired in addition a hot spot combustion chamber should be fitted for this purpose, but the heavier solid waste would still be fed into the vessel part of the precalciner.
3. The minimum recommended precalciner residence time for firing petcoke and or solid waste with a NOx limit < 400 mg/Nm3 is 4.5 seconds. This will employ staged combustion in addition to SNCR in order to minimise the use of reagent.

Further Developments

Waste Fuel Physical Properties

In order to help with the design of systems for firing solid wastes into precalciners there is a need to develop simple reliable tests for the aerodynamic and combustion behaviour of waste fuels. These characteristics are important in deciding on suitable fuel types, size and injection point for a particular precalciner and will minimise the need for trial and error in the industrial scale.

Firing Using Physical Supports

The idea of using physical supports, 'fingers' to hold a fuel in the gas stream, in order to minimise any impact on the combustion, until it has burned has been trialled in several plants, with the most success at Melon in Chile. In this vessel type precalciner whole tyres are suspended in the gas stream. Being able to burn whole tyres avoids the high cost of chipping which would otherwise be necessary if the tyres were to be entrained in the gas stream. However, several conditions and limitations exist with the application of this method:

The fingers must be located in an oxygen rich part of the precalciner

A maximum of 0.5 tph car tyres can be fired with a single set of fingers

There must be no ledges or shallow slopes in the precalciner geometry which can lead to build up of reinforcing wires and probable plant stoppages due to blockages.

This method could be extended for using smaller sized waste. Since the residence could be controlled and would be independent of the precalciner design and control of fuel particle size would be much less of an issue. It could prove to be a more attractive solution than entrainment in the gas stream, provided an engineering solution could be developed.

Waste Fuel Injection into Kiln Inlet

Guidelines need to be established for the potential to inject waste fuel into the inlet of precalciner kilns, including the impact on the process. Certainly this practice will tend to increase CO at the kiln inlet, potentially having an adverse impact upon the volatile cycle, build ups, clinker quality, kiln stability and ultimately kiln production. However, it is clear that several plants are able to successfully operate with more than 10% fuel injection into the kiln inlet, which needs to be well understood.

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1. Introduction

1.1. Scope

This report is a review of precalciners and their ability to use petcoke and solid waste fuels in accordance with the mandate for the Technical Agenda study it covers two main areas:

1) Investigation of our existing air separate precalciners with the target of characteristics of fuel, which can be used in what type of precalciner

2) Investigation of new precalciner types on the market and their abilities to burn petcoke and waste.

1.2. Development of the Precalciner Kiln

One of the principle chemical reactions in the manufacture of cement is the calcining of calcium and magnesium carbonate. In considering this part of the process separate from the main clinkering reactions it was possible to improve the process design and develop the precalciner process.

As the raw meal is heated in the process to form cement clinker the calcium carbonate decomposes at temperatures above 600 C forming Calcium Oxide with the evolution of carbon dioxide. The process of performing this breakdown of lime is called calcination:

$$CaCO_3(s) \xrightarrow{>600°C} CaO(s) + CO_2(g)$$

The reaction is endothermic requiring a heat input of 420 kcal/kg Calcium Carbonate

This reaction is also reversible. In the reverse direction, so called recarbonation, calcium oxide will react with carbon dioxide to reform calcium carbonate.

In long wet and long dry kilns all the heat exchange takes place in the kiln and hence all the calcination takes place in the kiln.

In the case of the suspension preheater (SP) kiln the temperature of the kiln exit gases entering the preheater tower are in the range of 1000 – 1200 C, which is sufficient to heat the raw meal to the calcination temperature and hence some calcination, around 40%, occurs in the preheater tower.

The capacity of the kiln tube in the SP process is governed by the quantity of gases passing through the kiln and reaches a limit when dust entrainment in the kiln hearth becomes excessive. The higher the quantity of calcinations performed in the kiln tube the higher gas volume and hence lower specific capacity of the tube. Therefore if some fuel could be injected into the preheater to perform a greater part of the precalcination then the fuel injection in the kiln could be reduced and the specific capacity of the kiln increased. This fact led to the development of the precalciner kiln (PC). Initially preheaters were equipped with precalciners for firing part of the fuel, with the combustion gases drawn through the kiln, referred to as Air Through Precalciners (PCAT). However, with these kilns the precalcination was limited due to limitations of flame cooling and hearth velocity as a consequence of the excess air drawn through the burning zone. This gave the idea of installing a separate duct from the clinker cooler to deliver combustion air (tertiary air) direct to the precalciner. Hence, the birth of the Air Separate kiln (PCAS). A given kiln size for an Air Separate Precalciner process can produce more than twice the capacity of the same size kiln in a Suspension Preheater process. This also meant that much larger kiln capacities could then be supplied whilst still maintaining practical sizes of rotary kilns, i.e.kiln diameters of 6m or less.

1.3. Precalcination

In order to ensure efficient operation of the process it is normal to monitor the precalcination level of the raw meal prior to entry of the kiln. Normally the precalcination level is targeted at 92 – 95 %. Higher values are avoided since this will increase the risk of clinkerisation and build ups in the precalciner, bottom cyclone and kiln inlet area.

Checking the precalcination level involves taking a sample of the raw meal from the meal chute of the lower stage cyclone. The sample needs to be rapidly quenched in order to avoid further calcination after extraction from the meal chute. The loss on ignition (LOI) of the sample is measured and compared to the LOI of the dried raw meal feed to the preheater. The formula for calculating the precalcination level is :

$$\%PC = 100\% \left\{ 1 - \frac{LOIpc(100 - LOIrm)}{LOIrm(100 - LOIpc)} \right\}$$

Where :

LOIrm is the LOI of the Preheater Feed raw meal

LOIpc is the LOI of the lower stage cyclone raw meal

The precalcination level depends on several operating conditions within the precalciner:

1. Temperature of the raw meal
2. Precalciner gas temperature
3. Heat Input to the precalciner
4. Concentration of carbon dioxide
5. Heat Transfer from the gas to the raw meal
6. Raw meal residence time in the precalciner
7. Material Recirculation in Preheater – especially affected by the lower stage efficiency

Considering the negative influence of carbon dioxide concentration in the gas stream upon precalcination, a higher efficiency should be achieved in a high oxygen environment such as a combustion chamber and an SLC type precalciner when compared to an inline precalciner.

The levers to ensure efficient heat transfer from the gas to the raw meal are high gas temperature and good dispersion of the meal in the precalciner.

It is important to have a high collection efficiency of the lower stage cyclone in the preheater to minimise the quantity of raw meal that is carried further up the tower, since this has an adverse impact upon the fuel consumption in two ways:

1. The raw meal transports sensible heat further up the tower, which increases the preheater exit gas temperature.

2. It increases the contact time between the decarbonated raw meal and the CO2 rich preheater gases increasing the potential for recarbonation, which also releases heat to the upper stages and increases preheater exit gas temperature.

The consistency of the precalcination is also important to ensure stable kiln operation, which requires stable control of:

1. fuel quality and quantity
2. kiln feed quality and quantity
3. tertiary air temperature – good control of clinker cooler
4. Consistent gasflow through preheater/precalciner

Normally small variations in precalcination level are taken into account by automatically controlling the precalciner gas temperature to vary the precalciner coal feedrate. The best location for the thermocouple for controlling the gas temperature is often found after the lower stage cyclone, where gases are well mixed and combustion is complete. Although the actual location differs from plant to plant.

1.4. Combustion Control

The optimum quantity of combustion air needs to be provided to both the kiln and precalciner fuel to ensure proper combustion. To minimise fuel consumption it is necessary to provide as little excess air as practical for the fuel combustion. In an inline precalciner, a tertiary air damper is provided to balance the air between the kiln and precalciner. The oxygen level at the kiln inlet and precalciner exit are controlled to target levels by adjustment of the preheater fan and tertiary air damper. In a separate line precalciner with two preheater strings it is usual to have two preheater fans, one for each string, to make the balance. In a single string separate line calciner, or a plant with a downdraught combustion chamber, it is usual to have an adjustable orifice to help balance the airflows. Although, in practice this device usually cannot be moved easily due to riser build up and has to be left in a fixed position.

Reliability of gas analyzer systems is of great importance to be able to control the process properly. If the kiln O_2 is too low, the fuel will not be burnt properly and CO will increase. The CO measurement tells the operator how well the fuel in the kiln is being burnt. It is usual to have a few small CO spikes present, however if there is too much CO, rings can form and there is an increased chance of build up in the kiln inlet and lower part of the preheater due to sulphur volatilization in the burning zone. Therefore any increase in CO should be eliminated as soon as possible by:

By closing the tertiary air damper to force more air through the kiln.

And/or reducing kiln fuel

And/or increasing the total draught through the system (by increasing ID fan/s speed or damper)

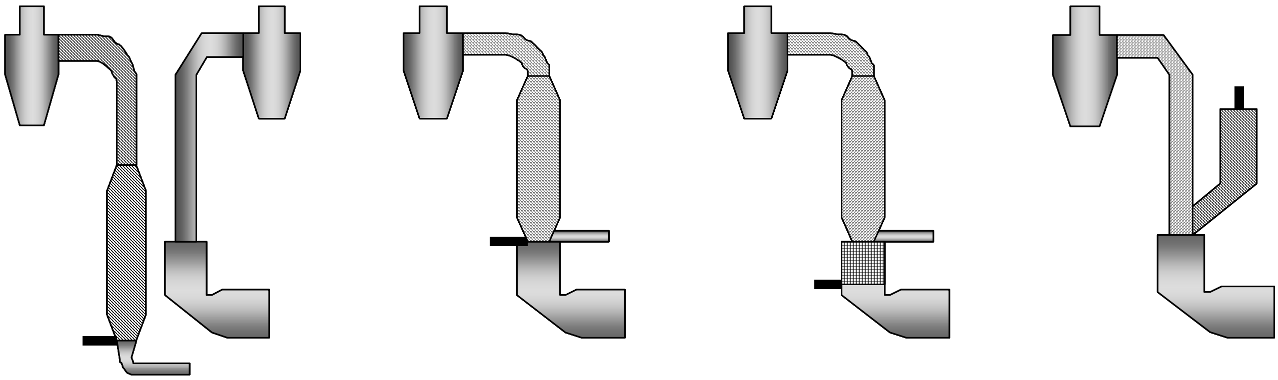
Excessive precalciner exit O_2 will result in excessive preheater exit temperature and adversely affect the fuel consumption. If there is insufficient O_2 there will be an increase in the CO level which will also increase fuel consumption due to wasted heat from incomplete combustion. Excessive CO level will also lead to problems with tripping of coal mill plant and electrostatic precipitator (if installed).

Target O_2 level is normally set by considering the CO level and the volatile cycle in order to minimize the riser build up to a manageable level. The actual level depends upon several factors, notably; the nature of the fuels, raw meal chemistry, burnability and combustion conditions. However, as a general guide with bituminous coal with +25% volatile matter expect O_2 at kiln inlet and precalciner exit in the range of 2-3%, with CO < 100ppm kiln inlet and CO< 500 ppm at precalciner exit. When using more difficult fuels or excessive volatile components in the raw mix, kiln inlet O_2 may have to be increased significantly to be able cope with riser build ups.

1.5. Precalciner Residence Time

The precalciner residence time is defined as the average time for the gas to pass from the point of fuel injection to the inlet of the lower stage cyclone. In the case of a single fuel firing point in an inline or separate line precalciner, this is calculated simply by dividing the precalciner volume by the average precalciner gas flow (.i.e average normalized flow at the average temperature and pressure). Precalciner gasflow is emphasized since in a true separate line precalciner the kiln gases do not flow through the precalciner. See the first two examples of figure 1.1, below. In the case of a reduction zone as in example 3 the residence time of the reduction zone is calculated, containing gases from combustion in kiln gas only. The total residence time of the precalciner is calculated by adding this value to the residence time of the rest of the precalciner containing gases from combustion in kiln gas and tertiary air.

FIGURE 1.1 PRECALCINERS WITH A SINGLE FIRING POINT

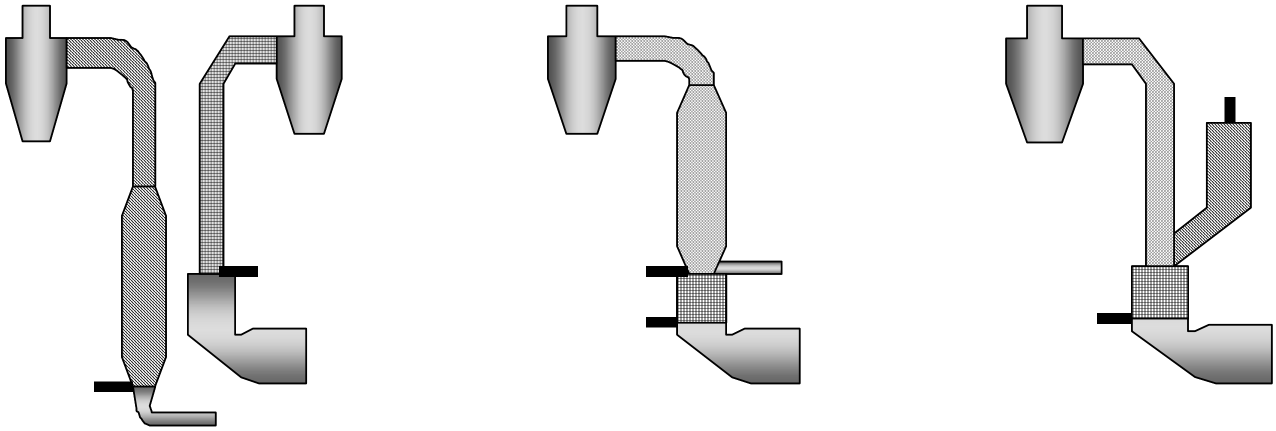


Separate line | Inline | Inline with reduction zone | Inline with comb chamber

- Fuel Firing Points
- Volume of precalciner containing gases from combustion in kiln gas only
- Volume of precalciner containing gases from combustion in tertiary air only
- Volume of precalciner containing gases from combustion in kiln gas and tertiary air

In the case multiple fuel feeding points the residence time is not so straight forward. See figures 1.2 below.

FIGURE 1.2 PRECALCINERS WITH DUAL FIRING POINTS AND REDUCTION ZONE



Separate line

Inline

Inline with comb chamber

In case of the separate line precalciner two residence times need to be quoted, one for the precalciner and one for the kiln riser. In the two examples of inline precalciner, the gas residence time from each firing point can be determined by adding the respective individual residence times for each section. If we would like to state a single figure more to reflect the precalciner volume we could state the maximum residence time of the two fuels. However, both residence times are of more interest when considering the combustion efficiency.

2. Precalciner designs

2.1. Precalciner Design For Fossil Fuels

As already described above, the basic functionality of the precalciner is to remove the majority of the CO_2 from the raw meal prior to entry into the kiln. This will reduce the heat required in the kiln and help to maximize the kiln production. In doing so it is important to combust the fuel as close to 100% as practically possible. Failure to do so will result in unburnt carbon being entrained within the raw meal stream from the lower cyclone stage and enter the kiln inlet. This will result in volatilsation of sulphur, potentially leading to build ups in the kiln inlet and riser. It is also important that the temperature of the gas in contact with the refractory on the walls of the precalciner is not allowed to reach too high a temperature <1100°C, otherwise it could cause build up and even refractory damage.

For a given set of conditions, the outlet gas temperature from a precalciner can be considered as a measure of the efficiency of the precalciner. A lower exit gas temperature whilst maintaining the same level of precalcination, normally around 92-95% would indicate a more efficient precalciner. Whilst the precalciner design will have an impact on this efficiency, there are many operating parameters that will also influence the precalciner performance, such as; tertiary air, excess air, raw meal chemistry, fuel characteristics, fuel split, kiln inlet temperature.

Precalciners were originally developed using oil firing and were simply just a vessel or an extended riser duct (or Gooseneck) with a gas residence time of around 1.2 - 1.5 seconds.

As fuel prices increased, coal firing largely replaced oil which needed a change in precalciner design to achieve good combustion. This was addressed by increasing residence time to 1.5 – 2.0 seconds, to account for the longer burn out time of the solid fuel.

As more difficult fuels, such as petcoke and anthracite with low volatile matter, became more frequently used designers not only had to consider increasing the precalciner residence time, but also to consider the burning conditions most favourable for these difficult fuels. So designers defined the levers that are available to maximize the fuel burn out. These are encompassed in the 5T rule:

1. Total Oxygen content – A higher oxygen content provides a greater driver for the combustion reaction
2. Turbulence – greater mixing of the oxygen and fuel, rapid transport of oxygen to the fuel particles
3. Tenuity of Fuel Particles (size) – greater surface area for reaction
4. Temperature of Combustion – higher temperature for combustion the faster the reaction
5. Time of Residence of Fuel Particles – increased residence time provides increased burnout

The main impact on precalciner design was the addition of a combustion chamber in the tertiary air duct to provide a high temperature burn out zone, see 2.6, and further increase in residence time to at least 3 seconds. Until recently this has been the basis for the design of many precalciners.

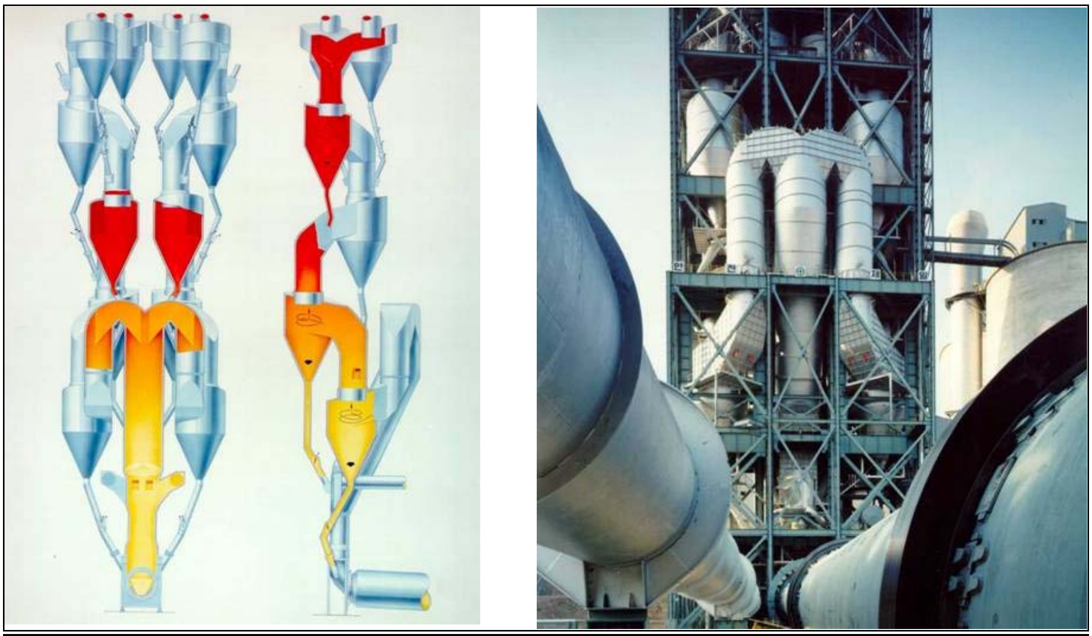
Nowadays, with sticter environmental targets consideration needs to be given to the NOx emission limit in addition to the fuel to be burned when designing a precalciner.

2.2. Riser Duct or Gooseneck (KHD, Polysius)

The standard design of riser duct type precalciner is merely an extended kiln riser duct with sufficient volume to allow combustion of the fuel in the mixture of kiln gas and tertiary air. Raw meal and fuel are injected in the lower part of the riser close to the connection for the tertiary air duct.

Typical velocities in these precalciners are around 16 m/s in the meal injection zone and 10 – 12 m/s in the main part of the riser where cross section is increased to try and promote some degree of mixing and to increase fuel and meal residence time. However, with the high gas velocities there is strong potential for stratification and poor mixing of the gases, fuel and raw meal.

FIGURE 2.1 POLYSIUS RISER DUCT



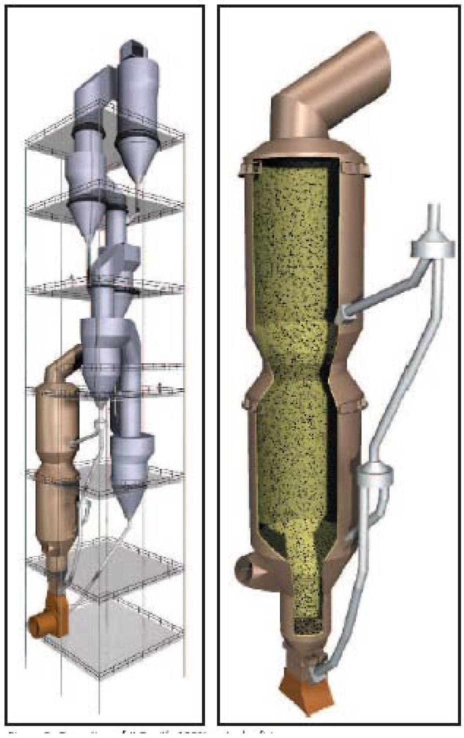
The connection point of the precalciner and the lower stage cyclones can be an area of concern, particularly with the earlier Polysius design. This has a long sweeping low angled bend that tends to deposit a significant quantity of raw meal, that has a tendency to occasionally surge into the bottom stage cyclone, causing instability in the kiln operation. In later designs this has been corrected by having a much steeper entry duct, which leads to only a small flat area, see Fig 2.1.

2.3. Vessel Type Precalciner (FLS, Nihon, Onoda, CLE)

This precalciner type consists of a vessel to obtain the necessary volume for combustion of the fuel.

Entry of the kiln gases (together with the tertiary air in the case of FLS) is from the bottom into a cone with a velocity to 25 - 30 m/s at the entrance. The cone widens out into the main part of the vessel where the gas velocity is much reduced, to 4-6 m/s FLS and around 10 m/s for Nihon. The aim of this design is to promote some 'back mixing' with the aim of increasing the residence time of fuel and feed above that of the gases. Clearly the back mixing in this type of precalciner will be more pronounced than in the riser duct design. Although, some modeling studies have highlighted poor mixing of the tertiary air with the kiln gases.

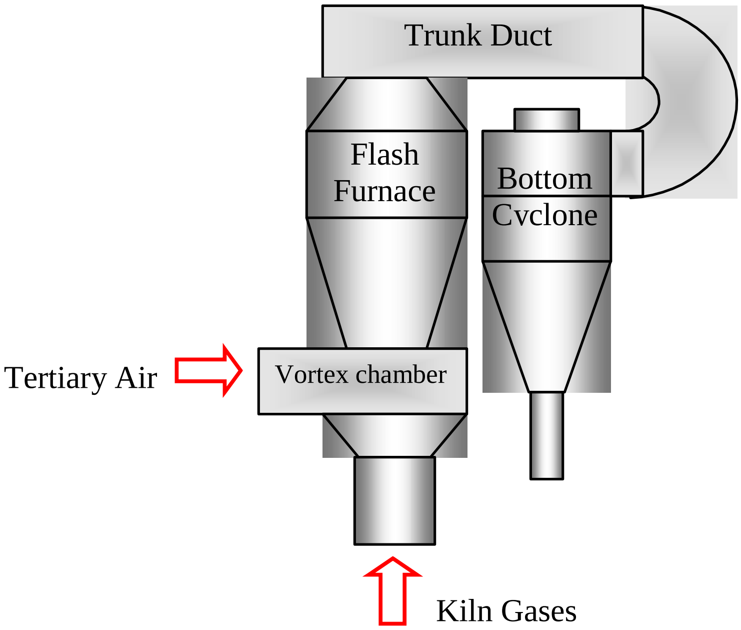
FIGURE 2.2 VESSEL TYPE PRECALCINER – FLS



2.4. Vessel Type with Vortex Chamber (Fuller, IHI)

The idea behind the vessel type precalciner with vortex chamber is to encourage a good mixing of the tertiary air with the kiln gas. This is achieved by providing a tertiary air inlet that wraps around the kiln riser. At the top of the vortex chamber sits the mixing chamber (flash furnace). Velocities are similar to those for the vessel precalciner, although the height of the vessel tends to be relatively short, which can give rise to bypass of gas and material due to the high velocity at the inlet penetrating the length of the vessel.

FIGURE 2.3 VESSEL CALICINER WITH VORTEX CHAMBER – IHI



The fuel is fed into the top of the vortex chamber using several burner pipes. Larger kilns have 4-6 burner pipes all fed from a single conveying pipeline from the coal dosing equipment. In several precalciners flames have been observed on the end of the burner pipes, which means the inner temperature of the vortex chamber is very high and acts as a hot core, it is not clear whether this is by design or not. This can lead to refractory damage when tertiary temperature is high and also gives potential for increased NOx emissions.

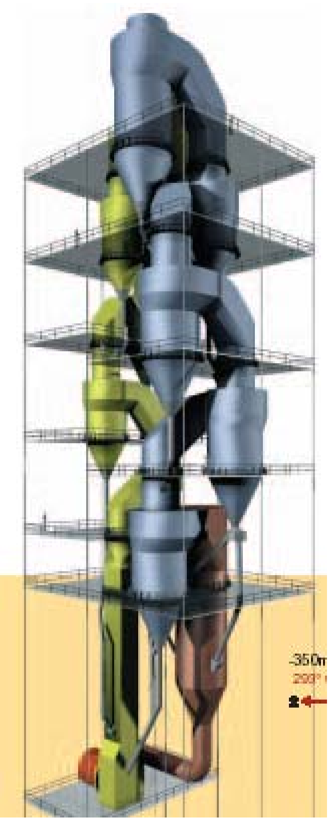
The wrap around inlet for the tertiary air is almost flat and is normally prone to settling of dust, which requires frequent cleaning. In some cases the dust can form a very hard build up making it very difficult to remove.

The IHI design also has a horizontal duct between the precalciner outlet and the bottom stage cyclone, known as the ‘Trunk Duct’. This can also be a source of material accumulation that can adversely affect the kiln production rate and stability.

2.5. Separate Line Precalciner (FLS, Kawasaki)

The separate line precalciner uses only tertiary air for the combustion of the precalciner fuel. In the single string design precalciner exit gases are mixed with kiln exit gases prior to the lower cyclone stage. In the twin string design the gases from the kiln and precalciner are kept totally separate. The use of only the tertiary air for combustion has a clear advantage for improving the fuel burnout, due to the high oxygen environment, and also means that the precalciner can be 40% smaller to give the same gas residence time.

FIGURE 2.4 SEPARATE LINE PRECALCINER - FLS



One of the main drawbacks of this design is during the start up phase and concerns the need to establish sufficient velocity in the tertiary air entering the precalciner to lift the raw meal. Failure to do so results in material drop out into the tertiary air duct, where a drop out flap is normally provided. The problem can be more serious with the single string type because gas balancing is more difficult. There is only one fan and control of the gasflow between the kiln and tertiary air duct is by manual adjustment of restrictor gates in the kiln riser.

Usually separate line precalciners are supplied with a small oil burner in the tertiary air duct for start up. This would be used until there is sufficient heat from the clinker in the cooler to lift the raw material in the precalciner entry. However, problems with overheating the tertiary air duct are common and several plants do not use the burner. In this case, the kiln is started up as a preheater kiln and run for 2-3 hours until there is sufficient heat in the clinker cooler and only then is the calciner string started up.

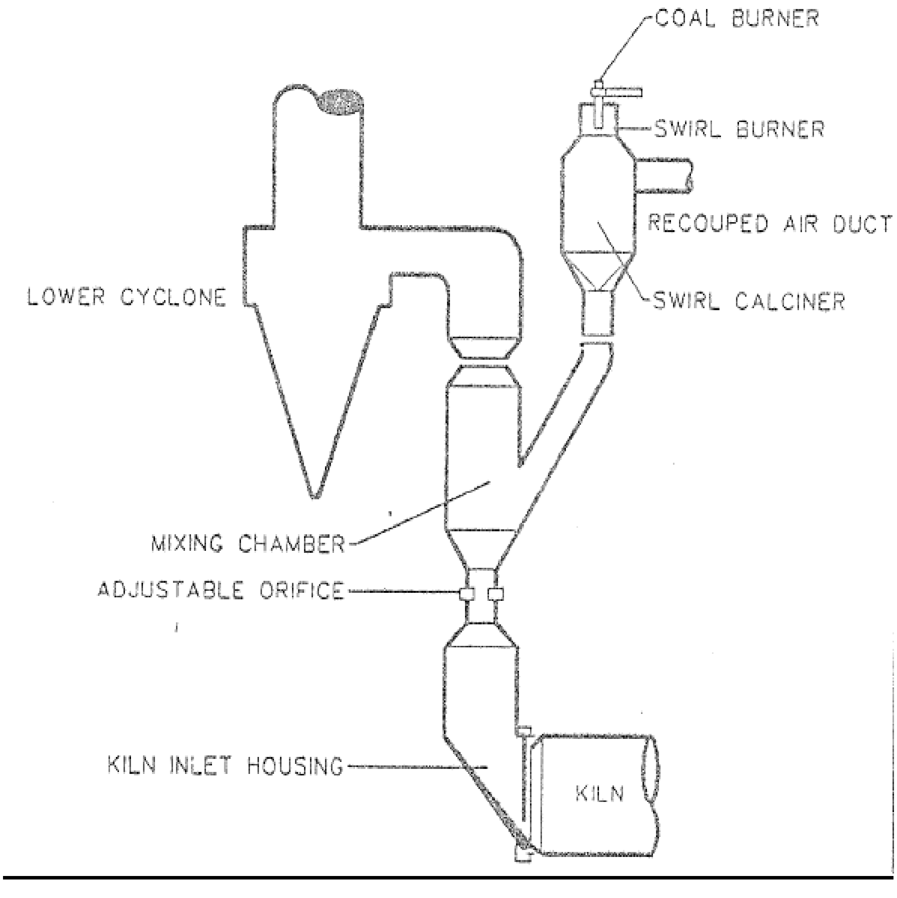
Separate line precalciners are often adopted for upgrading of preheater kilns, since the new preheater can be built with minimal interference of the existing one, which will remain as the kiln string.

2.6. RSP and Combustion Chambers

Onoda, developed the Reinforced Suspension Preheater kiln (RSP), which was the first 'hot spot' precalciner. The design of the precalciner consists of a combustion chamber in the tertiary duct with its outlet connected to the kiln riser where the RSP gases are mixed with the kiln gases in a mixing chamber. The tertiary air entry into the combustion chamber is tangential to provide a swirl which has two functions. Firstly it holds a curtain of raw meal at the walls of the vessel to protect the refractory from heat damage. Secondly it provides high turbulence which improves to the combustion efficiency. The design proved highly successful providing stable and reliable operation. It was originally made for oil firing and was then later adapted for firing coal and petcoke.

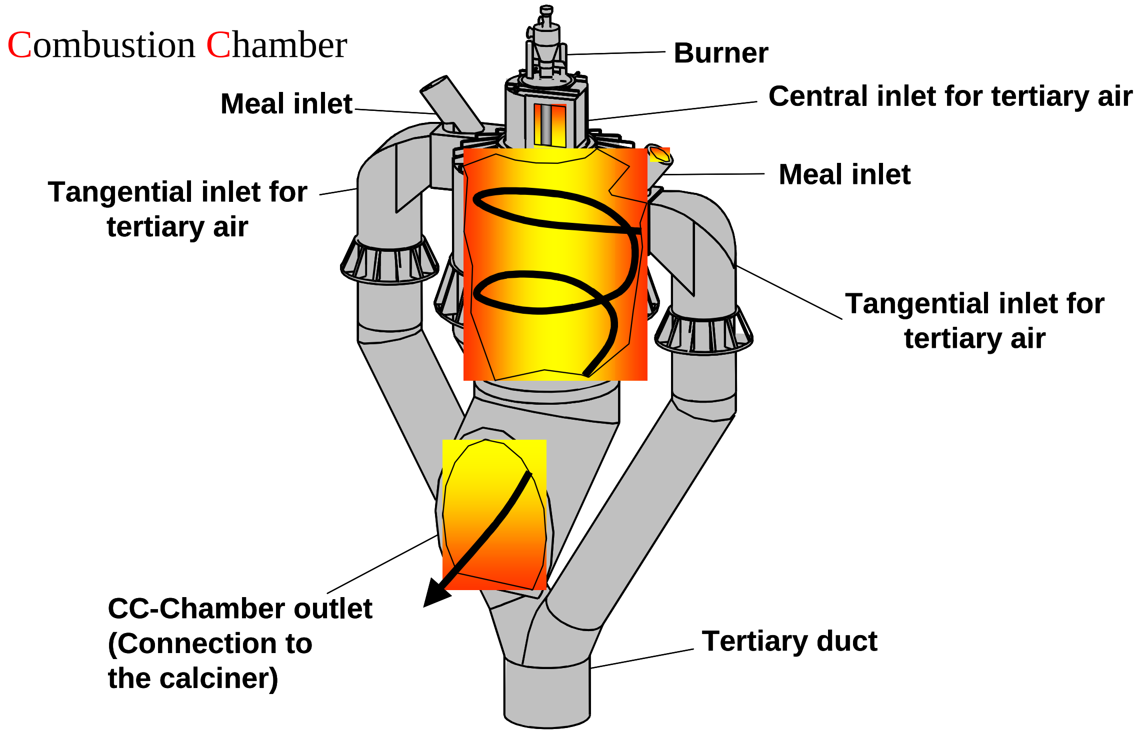
The use of petroleum coke and anthracite, with low volatile matter has become more common in the cement kiln and can now be considered as normal fuels. To improve the combustion of these more difficult fuels many plants were retrofitted or have been designed with pre-combustion chambers in the tertiary air duct. Since the raw meal injection in some designs is into the rising tertiary air some of the start up difficulties associated with separate line precalciners can also be experienced with these devices.

FIGURE 2.5 ONODA RSP PRECALCINER



An example of a combustion chamber is shown below :

<u>**FIGURE 2.6 EXAMPLE OF COMBUSTION CHAMBER – POLYSIUS**</u>



2.7. Modern Precalciners

The demand to burn more difficult fuels and at the same time aiming to comply with the more challenging environmental limits, particularly NOx and CO, has resulted in significant advances in precalciner design from all the suppliers.

In order to meet the standards required for NOx emissions the primary approach is to provide a reduction zone in the precalciner to reduce the oxides back to nitrogen, which requires additional residence time in precalciner. After this step is complete it is necessary to ensure that the CO is completely burned to CO_2 and further residence time is also added. Hence, it is not surprising that the trend is towards significant increases in precalciner residence time up to 6 seconds for modern precalciners, compared with 1.5 – 2.0 for earlier designs.

Although suppliers have adopted similar principles their approach to their product range is not identical. They have tended towards the same direction by developing a modular approach in their product supply. The base design would be for firing pulversied coal and then offer a number of add on options depending on the type of fuel to be used and the environmental limits to be applied. The possible modification to the base design could be according to the following:

1. Standard Low NOx design with reduction zone
2. Low NOx plus increased residence time for CO burnout
3. Addition of a Hot Spot combustion chamber in Tertiary air for difficult fuels

In addition the suppliers are also in the process of developing additional combustion devices (Pyro-Rotor, Hotdisc, etc) to be able to burn larger sized pieces of wastes without the need for shredding.

The early designs of precalciner made it straightforward to categorise the different precalciner types according to the arrangement of the precalciner. However, with the modern more complex designs employing a mix of vessel, riser duct and separate line features makes the differentiation more difficult.

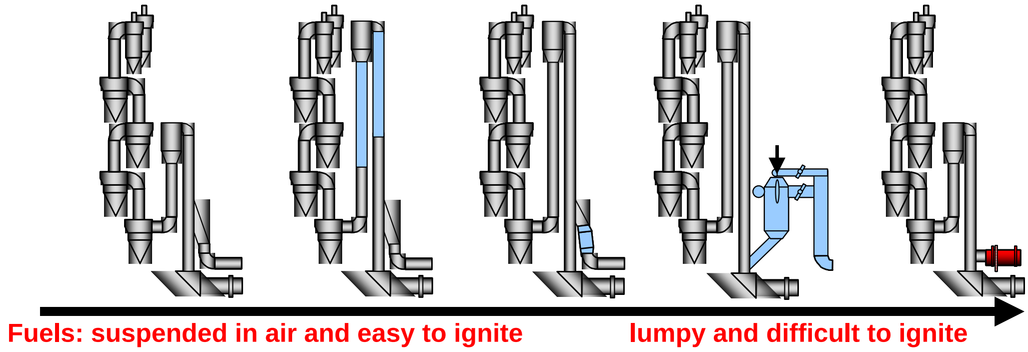
2.7.1. Precalciner Options KHD

KHD have developed from their traditional Pyroclon extended riser design to the Pryotop design as their standard precalciner. This consists of a riser type precalciner with an extended vertical section of tertiary air duct. There are two firing points for the precalciner fuel one in the riser and one in the tertiary air duct, which are accompanied by a raw meal splitter to both locations in order to control the gas temperature. The aim is to provide a reduction zone in the kiln riser to reduce NOx emissions. A greater fuel split to the kiln riser will increase the degree of NOX reduction. The Pyro-Top is a small vessel located after the junction of the tertiary air and kiln riser, which is designed to mix the gases and aid the NOx reduction.

FIGURE 2.7 KHD PRECALCINER OPTIONS

KHD PYROCLON® Calciner Options

	Standard	Extended	Ignition Module	Combustion Chamber	Pryo-Rotor
Anthracite / Petcoke		✓	✓✓	✓✓✓	
Animal Meal	✓	✓	✓	✓	✓
RDF – Fluff Tyre Chips Sewage Sludge	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓
Lumpy Fuels				✓	✓
Whole Tyres Wood Pieces < 1m					✓ ✓

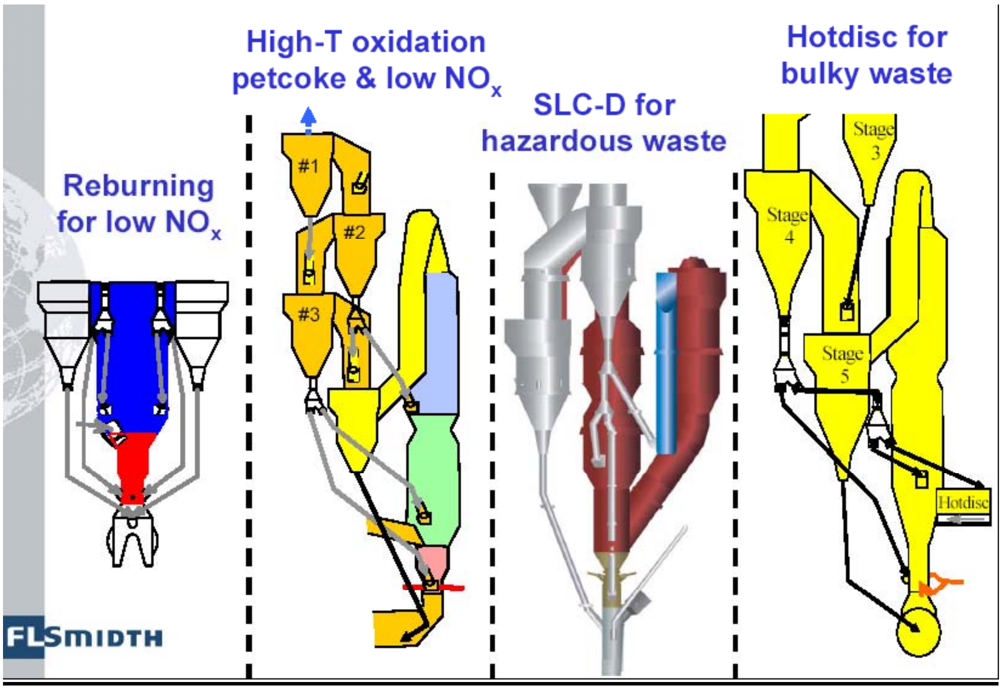


The first option for this design is to provide an increased residence time by extending the riser duct. The next option is to add an ignition module, which increases the volume of the combustion in the tertiary air. Then there is the option of adding a downdraught combustion chamber. Finally, for large solid wastes they propose the addition of the pyro-rotor, although this is still in development at this time.

2.7.2. FLS Precalciner Options

FLS have historically supplied two vessel type options the ILC – In Line Calciner and SLC Separate Line Calciner. Both the ILC and SLC designs have been modified to include a reduction zone for low NOx operation. In the ILC this is achieved by adding the fuel before the tertiary air is added to the precalciner. The ability to direct raw meal using a split between the upper and lower sections of the vessel gives the option to operate with a high temperature zone in the reduction part that helps to lower the NOx further, although this will be limited by the temperature resistance of the refractory and the tendency of the raw meal and fuel ash to form build ups at elevated temperatures. Typical residence time for the ILC calciner is 3.4 seconds. The same features described for the ILC are also possible with the SLC, although the NOx reduction is created by staging the tertiary air, since only tertiary air enters the vessel. The use of air only would tend to lower the potential level of NOx reduction when compared to an ILC. A further option is the SLC-D calciner which is an SLC with downdraught combustion chamber intended for firing hazardous wastes. The residence time in the combustion chamber is greater than 2 seconds, with an overall precalciner residence time of 3.9 seconds. The design is not strictly separate line any longer, since the kiln gases mix with the gases exiting the combustion chamber as they enter the second part of the precalciner. Hence, it is more like an inline precalciner with a combustion chamber.

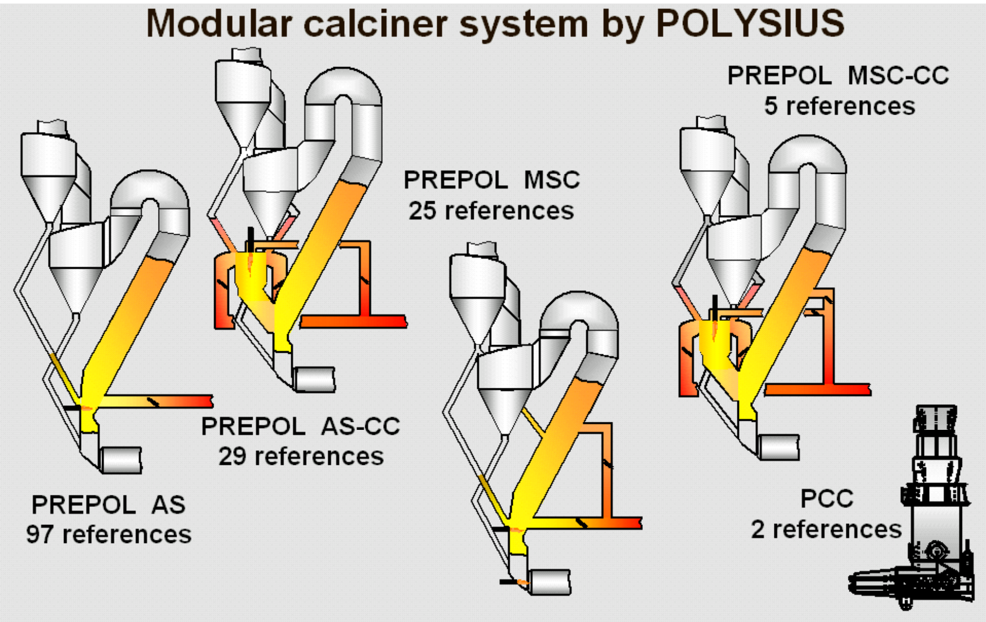
FIGURE 2.8 FLS PRECALCINER OPTIONS



2.7.3. Polysius Precalciner Options

Polysius have adopted a modular approach to their riser duct precalciner, Prepol AS. NOx reduction is an add on MSC, multi-staged combustion, which includes staging of the tertiary air and meal entry into the precalciner. In addition there is an SNCR option for further NOX reduction. In the case of burning low volatiles Polysius also offer a combustion chamber version, Prepol AS-CC.

FIGURE 2.9 POLYSIUS PRECALCINER OPTIONS



2.8. Impact of NOx limits

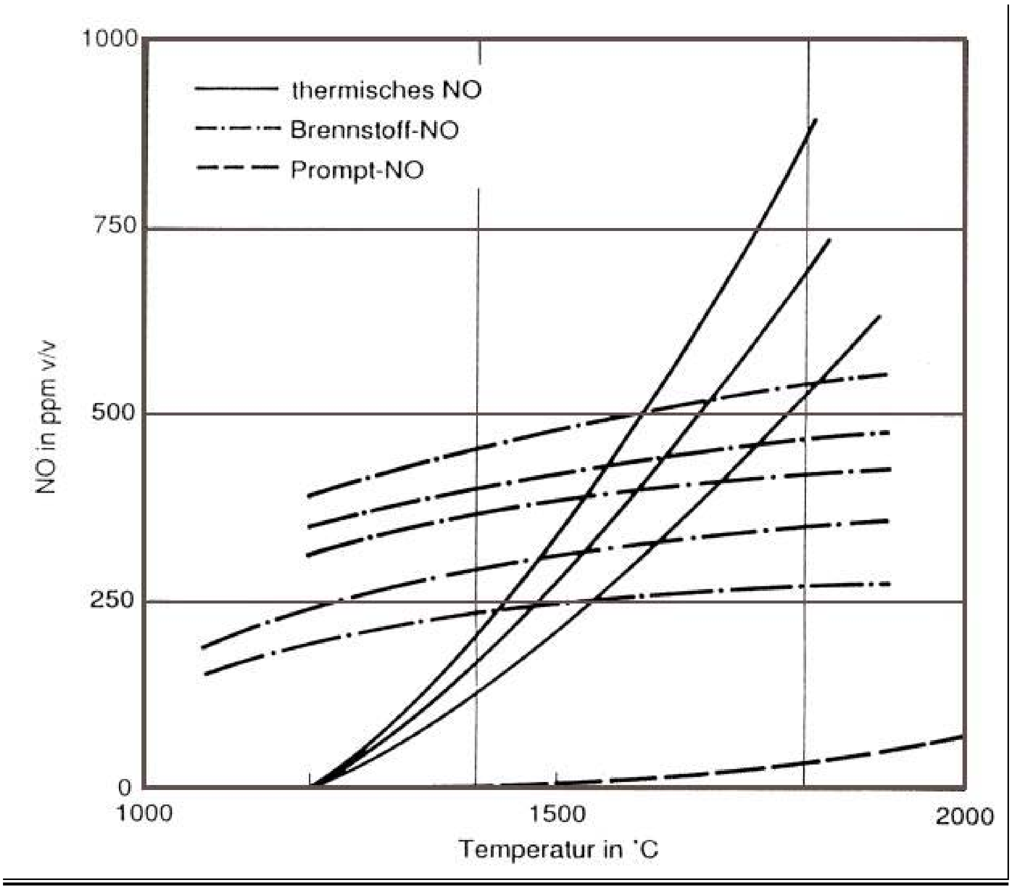
The design of the modern day precalciner has been greatly influenced not only by the burning of more difficult fuels, but also because of the need to operate at lower emission levels of the oxides of nitrogen (NOx) as dictated by stricter legislation. The precalciner plays a very important part in controlling NOx emissions from the process.

2.8.1. NOx Formation

NOx, which in the cement process contains more than 90% NO, is formed by two main mechanisms:

1. Reaction of fuel Nitrogen with Oxygen and occurs in the kiln and precalciner – known as **fuel NOx**
2. Reaction of Nitrogen and Oxygen in the combustion air starting at temperatures above 1200’C and exponentially increasing with increased temperature and excess air occurring mainly in the kiln burning zone - **Thermal NOx**

FIGURE 2.10 TEMPERATURE RANGE FOR NOX FORMATION



In considering the graph above showing the temperature range of formation of thermal NOx commencing at 1200C, it suggests for a 'hot spot' precalciner, that can be up to 1600C, there is the possibility to create some thermal NOx.

2.8.2. NOx Reduction

NOx can be reduced in the kiln system by several different methods:

1. Minimising the kiln exit oxygen
2. Flame Cooling
3. Low NOx burner
4. Good Control of the process using Lucie
5. Optimising raw material parameters to lower burning zone temperature
6. Use of a mineraliser to lower the burning temperature
7. Staged combustion
8. Selective Non Catalytic Reduction (SNCR)
9. Selective Catalytic Reduction (SCR)

Only the Staged Combustion and SNCR will be mentioned further, since here we are interested in the impact on the precalciner design rather than the actual NOx reduction methods. For more on NOx reduction see specific technical agenda study.

One of the most important techniques for reduction of NOx emission in the precalciner is called Staged Combustion, which involves a stagewise introduction of the combustion air and fuel. The principle is to create a highly reducing atmosphere in the inlet area of the precalciner by providing less than a stoichiometric air ratio for combustion of the precalciner fuel. The CO formed promotes a reduction of the NOx in the kiln gases to Nitrogen and also reduces the NOx generation from the burning precalciner fuel. The effect is greater at increased the temperature in the reduction zone. Some references suggest an increase in temperature of 100°C would reduce NOx by 10%. In some designs the fuel is added at a single point and others the fuel is added in stages and finally the balance of combustion air is then added to allow the CO to burn to CO2. The use of a low proportion of the stoichiometric air is important to achieve a significant NOx reduction, although too low a level would tend to increase riser build ups and increase CO emission from the precalciner.

Good mixing of gases also promotes lower NOx emissions and also helps to burn off CO after creating a reduction zone.

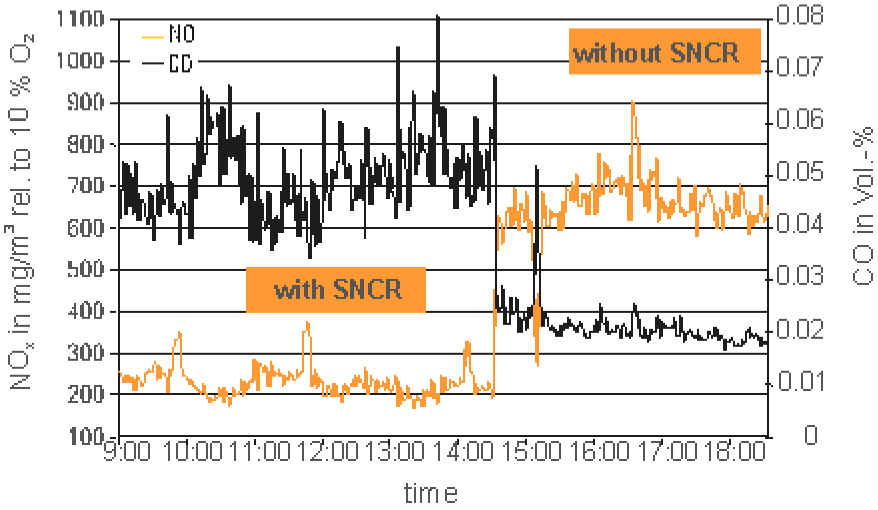
Kilns firing bituminous coals with medium volatiles using staged combustion can achieve a stack NOx emission as low as 500 mg/Nm3 @ 10% O2 with an optimised process. However, this depends on each particular kiln and its operating conditions and can very significantly from this figure. Fuel type is also important, Petcoke firing tends towards higher NOx emissions, as the potential reduction is less with low volatile fuels.

Firing of wastes in a precalciner can create a reduction zone due to poorer combustion or due to localised concentration of fuel which will also reduce NOx emission, effectively acting in the same way as staged combustion.

Selective Non Catalytic Reduction (SNCR) is a further technique that can be applied when staged combustion is not able to achieve the required NOx emission. Selective means that only NO and NO_2 are reduced by a chemical reagent (e.g. Ammonia solution, Ammonium salt solution, Urea, Liquid Photo wastes) to N_2 in a temperature range of 800 - 1150 [°C] and therefore no catalyst is necessary. The actual injection point needs to be optimised for each precalciner and each ammonium bearing reagent used.

The use of SNCR, although effective in reducing NOx emissions tends to increase the emission of CO since it delays the completion of combustion process due to competing reactions for oxidising CO and reduction of NOx, both requiring hydroxyl ions (OH^-).

FIGURE 2.11 EFFECT OF SNCR ON NOX AND CO EMISSIONS



The combination of staged combustion and SNCR is a developing technique designed to minimize the use of ammonia reagent and hence operating cost. The difficulty is that the competing NOx reduction reactions could create greater difficulties with CO emissions and therefore higher gas residence time is necessary to minimize interaction of the two techniques.

FIGURE 2.12 COMPETING REACTIONS FOR NOX REDUCTION AND CO BURNOUT

NO reduction

$$NH_3 + \boxed{OH^*} \longrightarrow NH_2^* + H_2O \qquad (1)$$

$$NH_2^* + NO \longrightarrow N_2 + H_2O \qquad (2)$$

CO oxidation

$$CO + \boxed{OH^*} \longrightarrow CO_2 + H^*$$

2.8.3. Impact of NOx Emission on Precalciner Design

The main impact of the tighter NOx emission levels on precalciner design is to increase the gas residence time. This will depend upon the precalciner and the fuels burned. However, for staged combustion a minimum additional residence time of 0.5-1 seconds will be needed to allow for burn out of CO. In addition the changes in design with meal staging, tertiary air staging have increased the complexity of operation.

Research done by the Research Institute of the Cement Industry (Germany) suggests an addition of 1-1.5 seconds when using SNCR particularly if staged combustion is to be employed. A logical strategy for designing a precalciner for a new kiln line to cope with the increasing tighter demands for NOx emission would be to design for staged combustion to reduce the NOx as far as possible, typically 500mg/Nm3 for coal, and provide the option for SNCR addition to meet lower limits or to operate with more difficult fuels such as petcoke. Considering the precalciner residence time, we need 3 seconds for petcoke in addition with a reduction zone and SNCR we would need a total residence time of 4 - 4.5 seconds. This also should be a minimum residence time for firing waste fuels.

Trials at Du Jiang Yan, China, a KHD pyro-top with 5 seconds residence time showed the capability to reduce NOx emission to below 600mg/Nm3 (corrected) whilst firing normal coal.

Trials at Sugar Creek, USA, a Polysius Prepol with combustion chamber, air staging and 6 seconds residence time, whilst firing coal showed operating in reducing conditions in the combustion chamber can lower the NOx produced in the combustion chamber, but has no impact on reburning of the kiln NOx. Therefore, firing of some fuel into the kiln riser will be necessary to achieve a NOx level less than 800 mg/Nm3, if SNCR is to be avoided.

3. Survey of Lafarge precalciners

3.1. Summary of Survey

A questionnaire was made to collect design and operating data from the Lafarge precalciner plants. In addition, to analyzing data for petcoke and wastes some more general data and correlations have been included in this section.

Summary of data:

Number kilns completed survey : 52

Number Precalciners Firing Solid Waste into precalciners : 12

Number Precalciners Firing > 50% Petcoke into precalciners 14

Fuels fired : Tyre Chips, Raw Coal, Plastics, Biomass and SSW

3.2. Kilns with Petcoke

There were several kilns using or had previously achieved a high level of petcoke replacement, as shown below.

This shows that the precalciner designs of Riser Duct, Separate Line and Vessel, some with low residence time and without combustion chamber have been able to achieve high levels of petcoke replacement. The comments on the precalciner performance with petcoke were, in general, much more positive and recorded a lower cleaning frequency for those with combustion chambers than for those without. This applied equally to Darica, a Polysius Riser Duct with Combustion chamber and the Onoda RSP calciners in Meknes and Port La Nouvelle. This indicates that the application of petcoke is easier with addition of a combustion chamber, as one would expect since that was the aim of the design.

TABLE 3.1 KILNS BURNING PETCOKE IN THE PRECALCINER

KILN	Type Supplier	Name	Res Time S	Comb Chamb	Calciner Coke%	Coke S %	Coke 90um %	Meal Curtain	KFUI
TAV	Riser KHD	Pyrotop	5	No	100	4.5	6	No	10
REP	Riser KHD	Pyroclon	3.5	No	60	7.5	3	No	22
MON	Riser Polysius	Prepol AS	1.2	No	100	5.3	4	No	10
DAR	Riser Polysius	Prepol AS CC	4.7	Yes	100	4.5	2.8	No	8
LGK 2	Riser Polysius	Prepol AS	3.3	No	80	4.5	8	No	14
SCK	Riser Polysius	Prepol AS CC MSC	6	Yes	50	-	-	-	9.4
CTG	FLS Vessel	ILC	2.0	No	55	7.0	13.5	No	8.7
MKS 1	Vessel Onoda	RSP	4	Yes	100	4.7	4.8	No	20
PLN	Vessel Onoda	RSP	4.1	Yes	100	5.7	1	Yes	5
BSK 1	Vessel Onoda	RSP	4.1	Yes	100	6.5	4.8	Yes	13
SPL	Kawasaki SLC	KSV	3	No	75	7.1	7.2	Yes	10
VIL 2301	Vessel		3.5	No	100	5.5	3.8	No	12
VIL 2302	Vessel		3.5	No	100	5.5	3.8	No	12.5
MED	Vessel Cemprocim		1.5	No	100	4.4	1.6	No	11

3.3. Kilns Firing Solid Waste Fuels

The following kilns shown in table 3.2 reported firing solid wastes into their precalciners.

Since the usage is not extensive it is not possible to compare the different types of precalciner. However, this data could be used as a benchmark for the precalciner type, (also see Fuel Flexibility Technical Agenda Study).

TABLE 3.2 KILNS FIRING SOLID WASTE FUELS

KILN	Type Supplier	Name	Residence Time Sec	Combustion Chamber	Waste	(Max) Waste % calciner	Max Size mm
CIZ	Riser PSP		2.3	No	Raw Coal	17	8
DUN	Riser Polysius	Prepol AS	2.3	No	Tyre Chips	35	50
KNT 3	Riser KHD	Pyroclon	2.0	No	PKS	7	10
MDF	Separate Line Voest Alpine	Pasec	2.2	No	Plastics Sunflower Husks Mycelium	43	2d-50 3d–10 Sun&M-10
SPL	SLC Kawasaki	KSV	3	No	Saw Dust Spheres	13	10
TAG	SLC FLS	SLC	3	No	Plastics	13	50
CTG	Vessel FLS	ILC	2	No	Mixed	45	50
CLD	Vessel FLS	ILC	2	No	Tyre Chips	90	50
LCA	Vessel FLS	ILC	3.5	No	Whole Tyres on Fingers	10	-
RWN	Vessel Vortex IHI	NSP	1.8	No	PKS	12	10
RMD	Vessel FLS	SLC-D/ILC	3,5	Yes	Tyre Fluff, paper residue,shredded wood and plastics	15	30
KNT 4	Vessel Vortex IHI	NSP	2.6	No	PKS	25	10

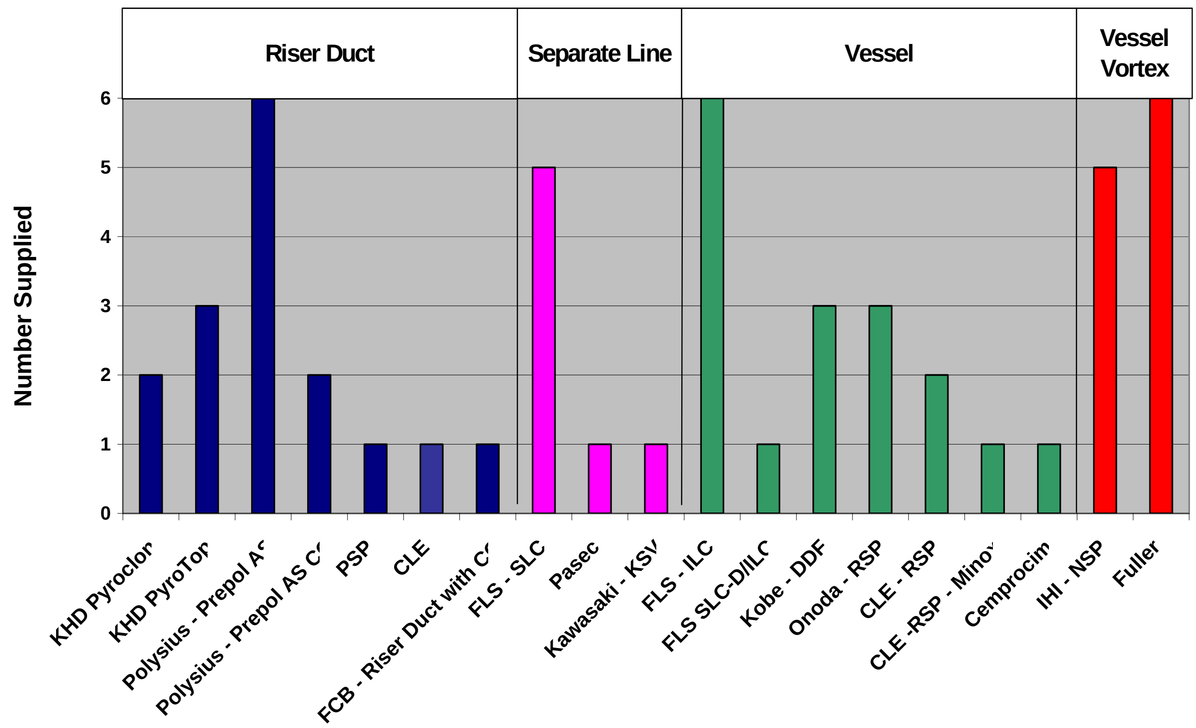
3.4. Lafarge Suppliers and Types

Precalciners operated in Lafarge are shown in the graph 3.1 below:

The distribution of types of precalciner in Lafarge:

- Riser Duct 16
- Separate Line 7
- Vessel 18
- Vessel Vortex 11

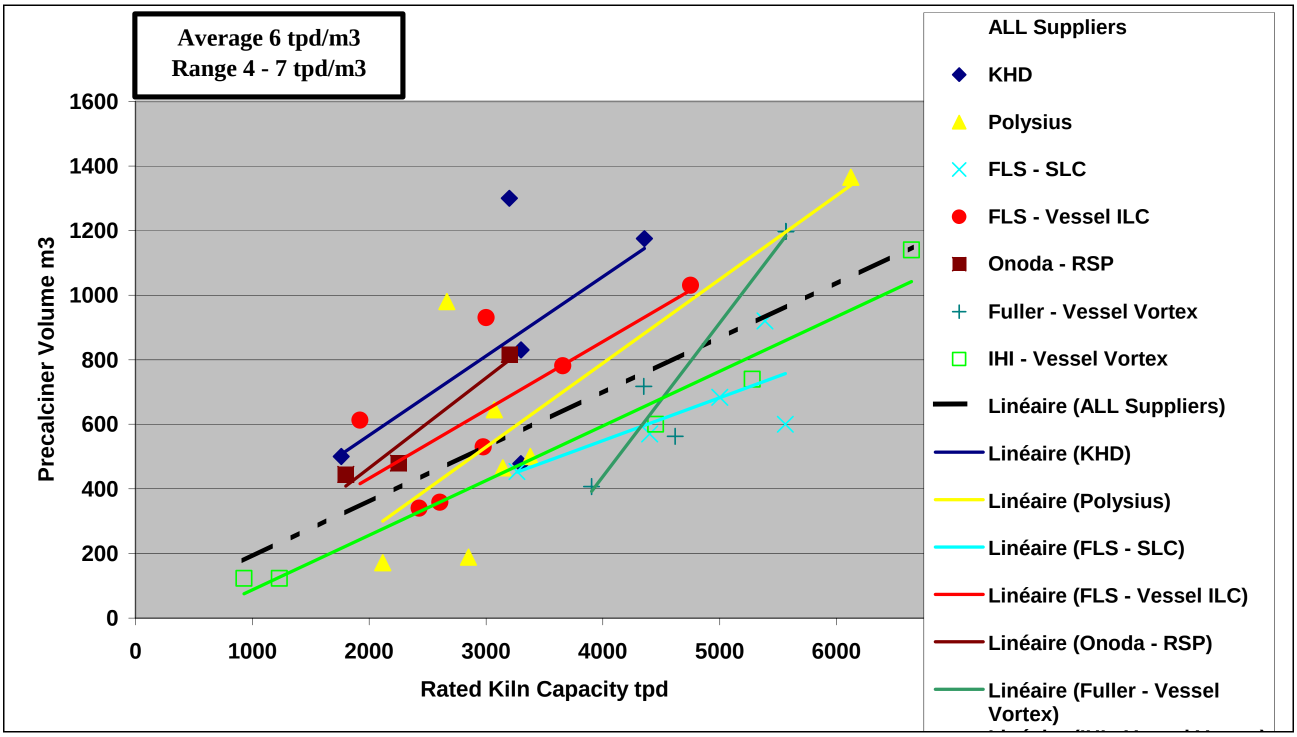
<u>**FIGURE 3.1 – PRECALCINER TYPES AND SUPPLIERS**</u>



3.5. Precalciner Volume vs Kiln Capacity

Normally each supplier would have his own rules to determine the size of the precalciner for a given kiln capacity. Hence, the data was used to try and draw some insights into the rules applied by the different suppliers and what might be achievable in kiln production with a given size of precalciner vessel, clearly the individual figures achieved will depend on the other limits to the kiln system in addition to the precalciner. Figure 3.2 shows the graph of precalciner volume against kiln capacity. In the earlier design of precalciners the main consideration for the residence time was for firing coal or oil and the capacity of the kiln. Then the introduction of more difficult fuels such as petcoke became a consideration. More recently NOx has had an impact on the precalciner size with the introduction of a reduction zone and CO burnout. Hence, since the precalciners in Lafarge have been designed for different fuels, different NOx limits it makes the comparison of the different kilns more difficult and hence the spread of residence against kiln capacity is naturally large.

<u>**FIGURE 3.2 PRECALCINER VOLUME VS RATED KILN CAPACITY FOR LAFARGE PLANTS**</u>



The plotting of such a graph clearly ignores some of the specifics associated with particular installations quality requirement, fuel fired, environmental considerations and limitations/demands imposed by the customer. Even so it is interesting to compare the results for different suppliers where there is sufficient data. Note that actual rated capacity has been used rather than design capacity.

Considering the Lafarge precalciners the range of precalciner loading is given for each supplier below.

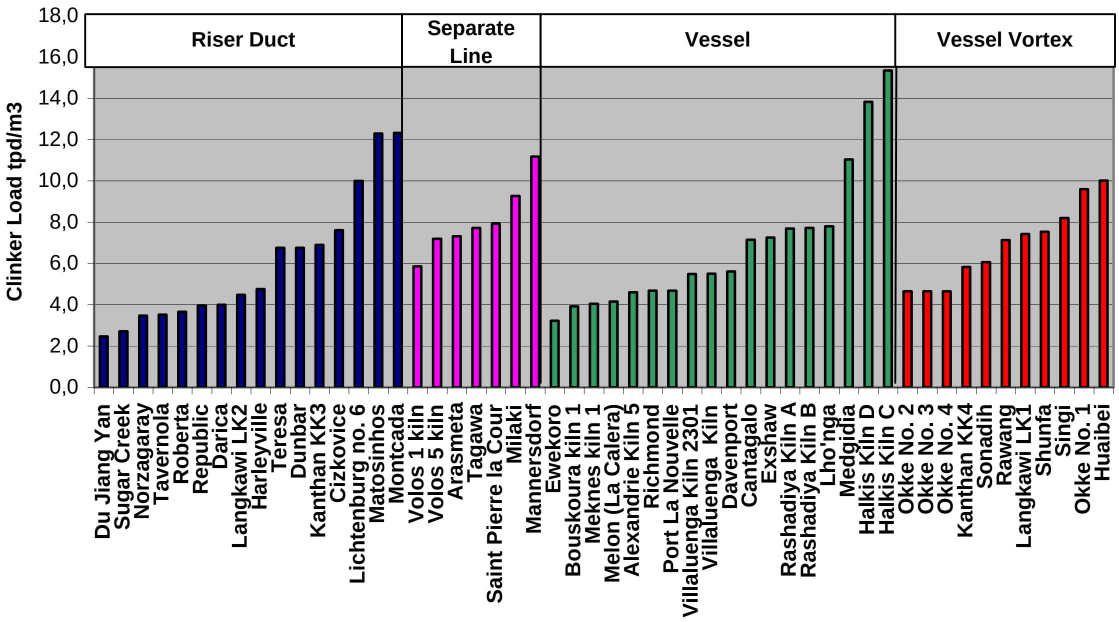
This shows a large range of sizes of precalciner installed by the different suppliers for a given size of kiln. Even allowing for the differences in precalciner efficiency of different designs some impact on operation would be expected.

TABLE 3.3 PRECALCINER LOADING

Supplier	Precalciner Name	Precal Loading tpd/m3	Comments
Polysius	Prepol	4 – 6	
FLS	Inline Separate Line	4 – 4.5 7 – 7.3	PC combustion in TA only
Fuller		4.5 – 6	
IHI	NSF	6.0 – 7.5	
KHD	Pyroclon PyroTop	3.5 – 4 2.5	Able to operate < 600 mg/Nm3 NOx
ALL Kilns		5.5	

The fact that precalciner volume has in general increased by greater than a linear proportion to kiln capacity is reflected in the lower loadings for the larger precalciners, see figure 3.3.

FIGURE 3.3 – PRECALCINER LOADING

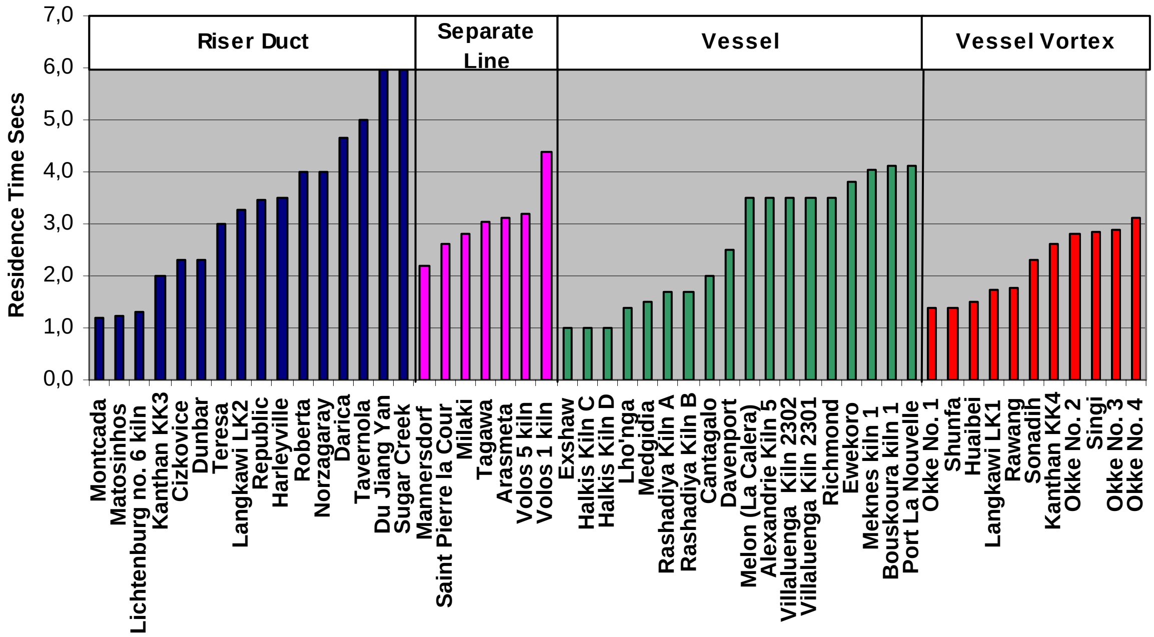


3.6. Residence Time

The residence time for all the Lafarge precalciners is shown in figure 3.4. In this graph the precalciners are categorized into their generic type for comparison against each other. This information closely reflects the comments made for precalciner loading, since the clinker production rate affects the gas volume through the precalciner and hence residence time.

Each of the types show a very wide range of residence times, the more modern kilns tending to have the longer residence time as explained above.

FIGURE 3.4 PRECALCINER RESIDENCE TIME

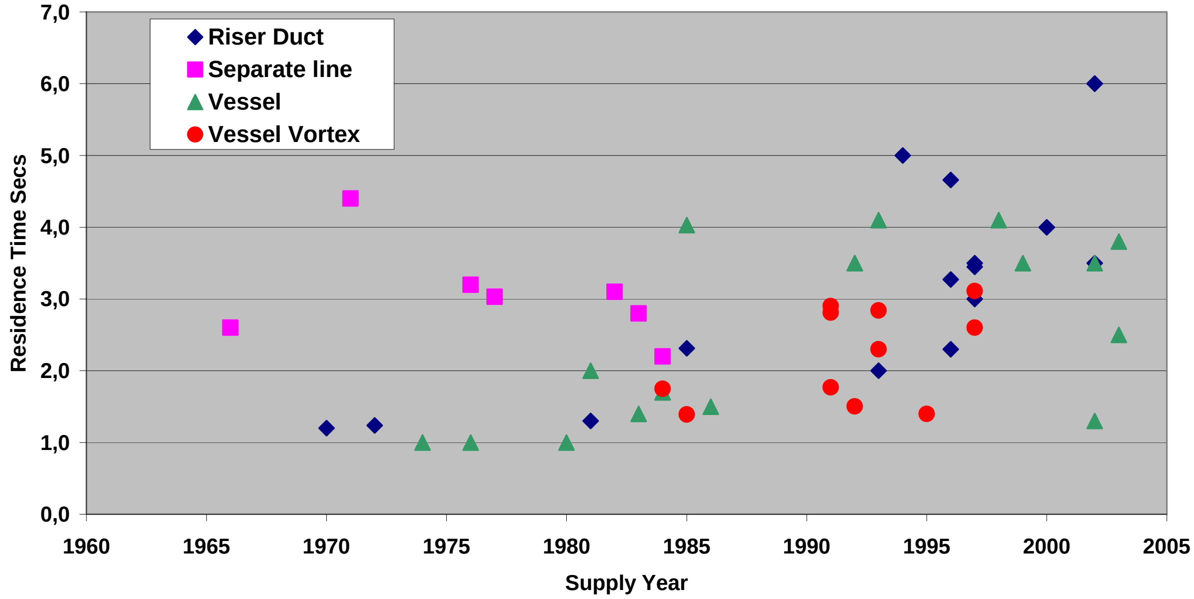


It is clear from this graph that several plants have precalciners with less than 1.5 seconds residence time which would severely limit the flexibility of fuels to be used in the precalciner. In addition even with easily burning fuels there would be a strong tendency to have high CO emissions.

3.7. Precalciner Residence Time Trends

In order to confirm the trend towards increased precalciner residence time with the newer plants. Residence time was plotted against year of installation. However, the trend of increase in residence time for the more recently supplied precalciners is clear

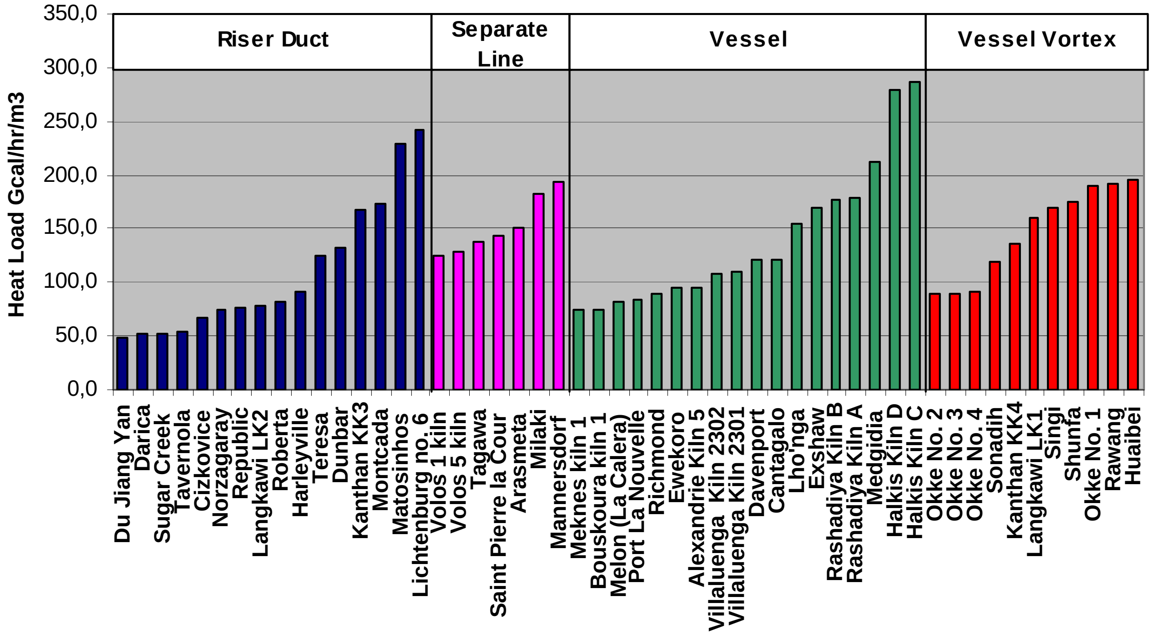
FIGURE 3.5 PRECALCINER RT TRENDS



3.8. Heat Load

A common way of benchmarking precalciners is to express the fuel fired in the precalciner per unit volume of the precalciner. This is similar to the two preceeding measures since the higher the clinker production the higher the quantity of fuel. This also takes into account the fuel split to the precalciner. The trend is towards precalciners with heat load of 50-70 Gcal/hr/m3.

FIGURE 3.6 – HEAT LOAD

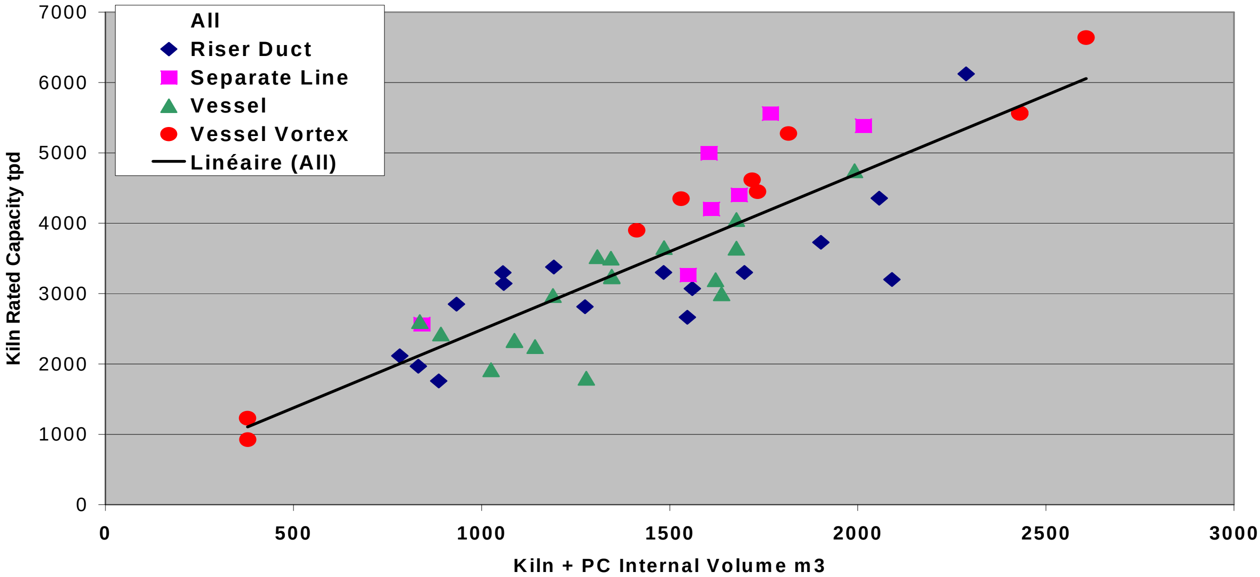


3.9. Plant Capacity vs Total Internal Volume of Kiln and Precalciner

A clear trend was shown when plotting the kiln rated capacity against the combined internal volume of the kiln and precalciner. This is expected since this represents the capacity to burn fuels. A large kiln with a small precalciner could have the same capacity as a smaller kiln with a large precalciner, provided other parts of the kiln system also have a sufficient capacity.

The specific capacity of the precalciner kilns are in the range of 2 –3 tpd clinker per m3 kiln and precalciner volume with an average of 2.5 tpd/m3.

FIGURE 3.7 KILN RATED CAPACITY vs PC + KILN VOLUME

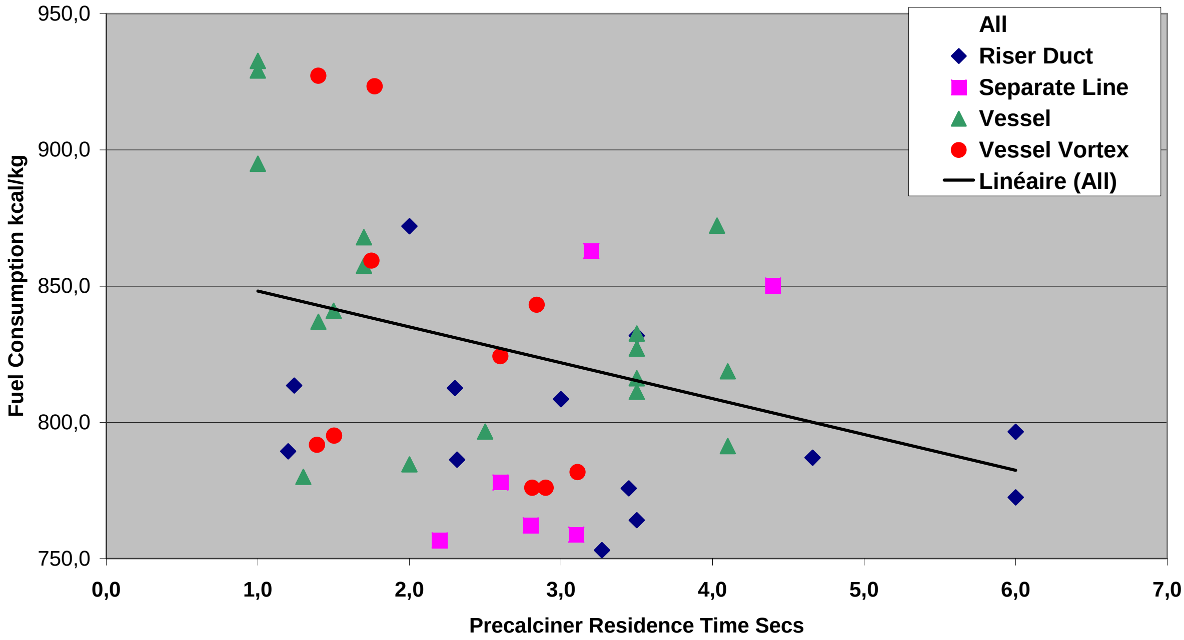


3.10. Effect of Residence Time Upon Fuel Consumption

The precalciner residence time was plotted against fuel consumption for all the survey kilns, see figure 3.8

There is a clear tendency for higher precalciner residence time to improve the fuel consumption, as might be expected, by providing time to properly burnout the fuel and avoiding carrying excessive heat to the upper stages of the preheater. There are several other factors, fuel residue, fuel type, kiln stability, raw meal burnability, number preheater stages, etc, that affect fuel consumption that increase the spread of the trend. The graph indicates that an additional one second residence time will reduce fuel consumption by 15 kcal/kg clinker.

FIGURE 3.8 – PRECALCINER RESIDENCE TIME VS FUEL CONSUMPTION



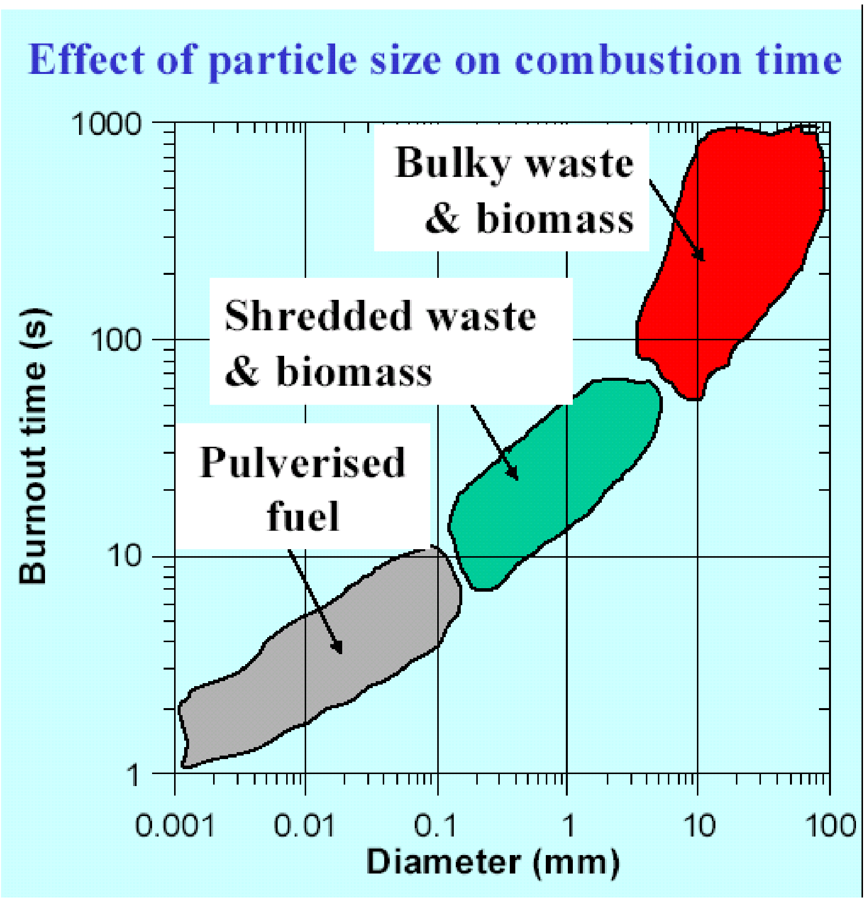
4. Utilisation of solid waste fuels in precalciners

4.1. Properties of Solid Waste Fuels

The burn out time of lumpy solid fuel is much greater than the time required for ground coal, typically taking minutes rather than seconds. The actual time depends on the type of combustible material and particle size.

Therefore the fuel residence time in the precalciner needs to be increased significantly above that used for ground coal. It is important to ensure a fuel residence time as long as possible to give the fuel the best chance to burn out and minimise carry over of unburnt to the lower cyclone stage.

FIGURE 4.1 EFFECT OF PARTICLE SIZE UPON COMBUSTION TIME



The way that the material burns can also become significant when using waste fuels. The material my just simply shrink as it burns, without much change to its shape or density, alternatively it may swell in size, or break up into smaller pieces; In each case the combustion of the fuel in the precalciner will be different.

4.2. Success Factors for Firing Solid Waste Fuels

In applying any new fuel to the process it is important to assess the potential effects on the process and define the constraints that affect its successful utilisation. Clearly from a financial perspective the application of the waste should generate a positive EVA at a rate sufficient to meet the desired return on investment. This will depend on prevailing the cement market condition affecting the plant operating regime and also on the technical aspects that will influence the success in a positive or negative manner. The technical aspects that affect the success are:

- Precalciner exit gas temperature or hot meal temperature on target, stable +/- 5°C.
- CO calciner exit gas < 500 ppm.
- TOC (unburned Carbon) in hot meal < 0,2%. Combustion efficiency > 95%.
- Calcination degree on target 92-95%.
- Stable pressure profile – no critical build ups.
- Stable operation (for RSP and KHD pyrotop - meal lifted in tertiary air,…)
- Stable fuel splitting kiln / calciner, with > 50% for the calciner.
- Stable O2 after calciner, preferable around 2%, without CO.
- Hot meal SO3 / Chlorine in acceptable range. Typically SO3% 2.5 – 3.5, Cl% 1-1.5, but should refer to SO3 vs Cl graph (see TA Study – Build Up control)
- Stable temperature in hot spot area (combustion chamber).
- Low NOx emission respectively reduction of NO formed in the kiln.

A calciner fulfilling all indicators listed above can be seen as very good, but it might be only reachable with traditional fuels like fine coal, which is generally not the target today.

The challenge is to reach the success indicators as far as possible but in parallel firing as much as possible difficult fuels which are economically interesting. Finally every plant has to set its own specific limits for CO, hot meal results,etc, that give satisfactory performance and acceptable product quality.

There cannot be a general rule for a calciner to achieve hot meal TOC < 0,2% when in parallel plants (mainly preheater plants) are adding entire tires to the kiln inlet.

Out of the Lafarge survey the average of hot meal TOC is 0,46%. Only 20 plants have reported a TOC result and 4 of the 20 reported 0,0%! Although the result is influenced by reporting errors and differences in sampling or analytical methods, it shows that most of the plants are running outside the traditional targets mentioned in literature.

For calciner exit CO the average out of the survey is 780 ppm (35 results), again some plants reporting 0,00% (possibly no gas analyzer) and some report preheater exit analyse which is already impacted by TOC coming from raw mix. Again a high number of plants are running above usually recommended levels.

The final acceptable limits for criteria like calciner exit CO, hot meal TOC, hot meal SO3/Cl, calciner temperature stability,… are plant specific and dynamic.

Results and acceptable limits can be influenced by optimizing operation (O2 level, calcinations degree,…), by optimizing cleaning (further air canons, Cardox, ….) or by installations like meal curtain and Chlorine bypass.

Important is:

(1) To constantly optimize in direction of reaching the success criteria.
(2) To have a regular record of the basic success criteria results and to investigate the reason of deterioration.
(3) To have plant specific limits for some success criteria requiring actions when over-passed.

One example how to transfer these 3 points into practice:

- Exit gas temperature (or hot meal temperature) on target, stable at +/- 5°C.

  (1) To constantly optimize in direction of reaching the success criteria by:

  - ✓ Kiln operator awareness, clear defined temperature targets for a given production.
  - ✓ Installing and optimizing an automatic loop for the exit gas temperature.
  - ✓ Use of Lucie and Lucie fuel manager for the calciner temperature control.
  - ✓ Optimizing burner positions, fuel type and fineness, O2 target,.. in direction of temperature stability.

  (2) To have a regular record of the basic success criteria results and to investigate the reason of deterioration:

  - ✓ Daily reporting of average / stdev. / max / min of the calciner temperature. This should be done whenever possible by automatic created report using comparable data (for example periods > 80% of nominal production).
  - ✓ Investigate every deterioration compared to the plant history or plant limits. Deterioration might come from change in fuel properties / unstable fuel dosing / tertiary air temperature fluctuations / CO peaks from kiln / instable meal flow to the calciner/ fluctuations in raw mix burnability, …

  (3) To have plant specific limits for some success criteria requiring actions when over-passed:

  - ✓ Definition of plant specific targets (achievable optimum) and limits (not acceptable deviation) for stdev. / number of T peaks / delta daily average versus temperature target / …
  - ✓ If out of plant experience a high temperature fluctuation is known as critical for the kiln stability, action should be taken if over-passing a limit. Action might be the reduction of a critical fuel type.

4.3. Waste Fuels Fired into the Gas Stream

The method of firing a pulverized fuel in a precalciner is to entrain the fuel in the gas stream and to provide sufficient fuel residence time to allow it to completely burn out. Precalciners have been designed for using pulverized fuels, so normally there is no need to be concerned about the gas speed when firing these fuels. However, if we want to fire lumpy solid fuels by entraining in the gas stream then we need to be concerned about the required gas velocity for a given fuel.

One of the difficulties in firing such waste is to determine the velocity required for a given type of fuel and size. The characteristic parameter that determines the aerodynamics of a particle is the terminal falling velocity in the actual gas conditions of the precalciner. The terminal falling velocity represents the minimum velocity that the gas must have to lift the fuel into the precalciner, rather than allowing it to fall into the kiln inlet. In cases where the particles are spherical this can be determined by a semi-empirical method, developed by Haider and Levenspiel (1989).

$$u_* = \left(\frac{4}{3}\frac{\mathrm{Re}}{C_D}\right)^{\frac{1}{3}} = v_t\left[\frac{\rho_f^2}{g\mu(\rho_s-\rho_f)}\right]^{\frac{1}{3}}$$

$$d_* = \left(\frac{3}{4}C_D\,\mathrm{Re}^2\right)^{\frac{1}{3}} = d\left[\frac{g\rho_f(\rho_s-\rho_f)}{\mu^2}\right]^{\frac{1}{3}}$$

$$u_* = \left[\frac{18}{d_*^2}+\frac{(0.5909)}{d_*^{0.5}}\right]^{-1}$$

$$C_D = \frac{24}{\mathrm{Re}}(1+0.1806\,\mathrm{Re}^{0.6459}) + \frac{0.4251}{1+\frac{6880.95}{\mathrm{Re}}}$$

where u_* and d_* are dimensionless velocity and diameter, respectively, ρ_f the fluid density and ρ_s the particle density.

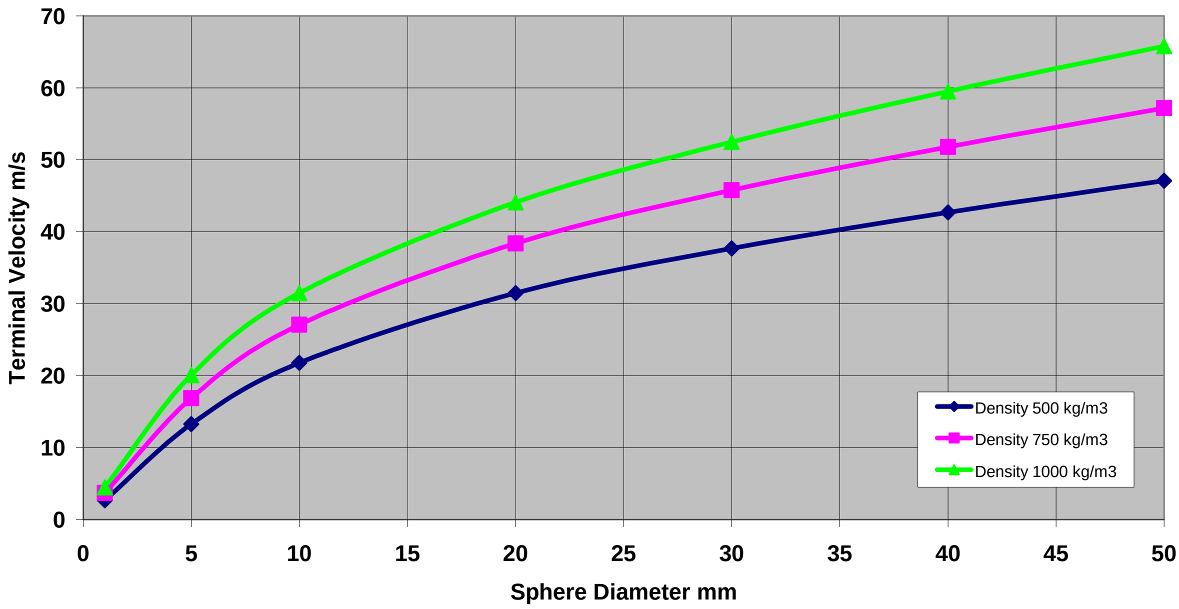
Using this method Terminal velocities have been determined for ranges of sphere sizes, with different densities at the typical gas conditions in the precalciner, see below.

Gas velocities in precalciners are rarely above 30 – 35 m/s, so in the case of spheres with density in the range of 500 – 1000 kg/m3 to avoid any drop out from the gas stream the maximum particle would need to be in the range of 15 – 30 mm diameter, which is relatively small and would require size reduction for many wastes.

Unfortunately, most (if not all) the solid wastes are not spherical and no reliable method exists to predict the terminal velocity of large irregular shaped particles, although, particles with large flat areas tend to have lower terminal velocities than the equivalent size of sphere.

So far, in the application of lumpy wastes in our kilns the required velocity at the injection point has been determined more by a trial and error approach on the plant. This obviously can be costly in time and resources to achieve good results. Occasionally mathematical modeling work has been done to support the implementation of a waste, but even this requires some practical tests to input into the model to overcome limitations of the theoretical mathematical approach. In the mathematical modeling work done for studying injection of tyre chips into Cauldon precalciner some simple cold air tests were done in a laboratory to determine the terminal velocity. These results were then corrected to the actual operating conditions of the precalciner for use in the model. Surprisingly for the tests made for Cauldon, chips terminal velocity was determined in the range of 20 – 25 m/s for the full range of chip sizes measured. Since the range of chip sizes was large and the range of terminal velocity was small, it raises some question about the sensitivity of the tests performed. (Chip sizes ranged from 5 cm2 projected surface area, weight 5g to 66 cm2 area, weight 53 g).

FIGURE 4.2 TERMINAL VELOCITIES OF SPHERES IN PRECALCINER GASES



In general, it would be useful to do similar practical tests to those in Cauldon, provided the results can be reliable, for any solid fuel to be used in precalciners to help with the design of a system or trouble shoot with an existing one. This data will also help in being able to apply a fuel used on one type of precalciner to a different design. A simple standard test method and apparatus needs to be developed for application in laboratories.

Theoretically, provided the fuel particles are lifted by the gases, when they enter the precalciner, they will remain in the precalciner until their weight has reduced and they are light enough to be carried out of the precalciner by the exit gases. Their residence time is a function of several parameters:

1. Initial particle size, shape and density
2. Rate of burning – depends temperature, oxygen and the reactivity of the fuel
3. Velocity in the precalciner
4. Effect of burning on particle shape and density – does the particle swell, break up or just shrinks as it burns
5. PC volume, although this may be only have a small influence on a lumpy solid waste fuel

If we consider the case where particles retain their shape and just shrink as they burn (the so called 'shrinking core' model), then for a given precalciner and operating conditions the residence time would be a function of the reactivity of the fuel. In practice, with low reactivity fuels there would be a limit to this assumption since there would be a tendency to overload the gas stream in the precalciner to the point where it could no longer support the quantity of fuel in suspension. As an example assume we wanted to replace 90% of the precalciner coal with a waste fuel with a calorific value 3000 kcal/kg that also required 200 seconds to burn out, in a precalciner vessel with 2 seconds gas residence time. Assuming suitable gas velocities and a completely well mixed precalciner, the fuel would need to recycle in the precalciner 100 times to complete combustion, which would raise the material load in the vessel to around 7 kg/Nm3, for the total fuel and raw meal. This is a very high load for the gas stream to support. Note that in this example the precalciner gas residence time is very small compared to the required fuel residence time.

4.3.1. Precalciner Conditions to Optimize Combustion

To evaluate the suitability of the various designs for burning wastes, it is useful to first consider what features would be useful in overcoming the more difficult combustion conditions.

For optimizing the use of a lumpy solid fuel the 5 T rule could still be used to maximize the combustion as before, except that fuel tenuity or size is even more critical since it affects the combustion and the aerodynamic behaviour. In view of the size of the waste fuel, consideration needs to be given to the gas velocity at the fuel feeding point to the precalciner to avoid any drop out directly to the kiln. In general, drop out into the kiln should be avoided as it would lead to formation of CO and may have a negative impact on the volatile cycle in the riser, leading to increased tendency for build up formation which would have an impact on kiln stability and production rate. In a non-sold out market some loss of production may be tolerated, depending on the EVA generated by the fuel compared to the actual loss in performance. Clinker quality and kiln inlet refractory lifetime could also be adversely affected by large fuel pieces dropping into the kiln inlet. The need to carefully control the fuel size has been shown in practice at Cauldon, with tyre chips and at Rawang with PKS. In both cases, when the fuel size increased above the normal level, significant problems were experienced because of unburnt fuel dropping into the kiln inlet.

At the point of waste injection, the direction of gasflow in the precalciner should ideally be upwards, since downwards motion will tend to allow drop out of fuel from the gas stream.

Precalciners are designed to burn finely ground fuel and where the residence time of the fuel is the same order of magnitude as the gases and raw meal. In several designs to improve the combustion efficiency an expanded section was installed to reduce the gas velocity with the intention of holding the fuel and the raw meal in the precalciner longer than the gases, so called ‘back mixing’.

For a new kiln line, to burn lumpy solid wastes, we could consider increasing the size of the precalciner. However, whilst increasing the volume and hence gas residence time of the precalciner will obviously help the combustion, it is limited practically and economically to only a few seconds, and hence could not be the only solution. Another way to increase the fuel residence time in the precalciner is to have a low enough gas velocity in the main section that would prevent particles from escaping from the precalciner until they had reduced significantly in size, giving chance for better burn out. However, the actual fuel residence time will also be affected by any changes in the particle shape, structure and density during the combustion process itself. This will vary depending on the type of fuel used.

So if we combine the principles of the 5T rule with the additional requirements for gas velocity we have the list of attributes a precalciner needs to have to be able to burn the maximum of lumpy solid waste fuel:

1. High inlet velocity to the precalciner, around 30 m/s – avoid drop out of fuel particles to the kiln inlet
2. Low velocity in main section, 4 m/s – increase fuel residence time in the precalciner

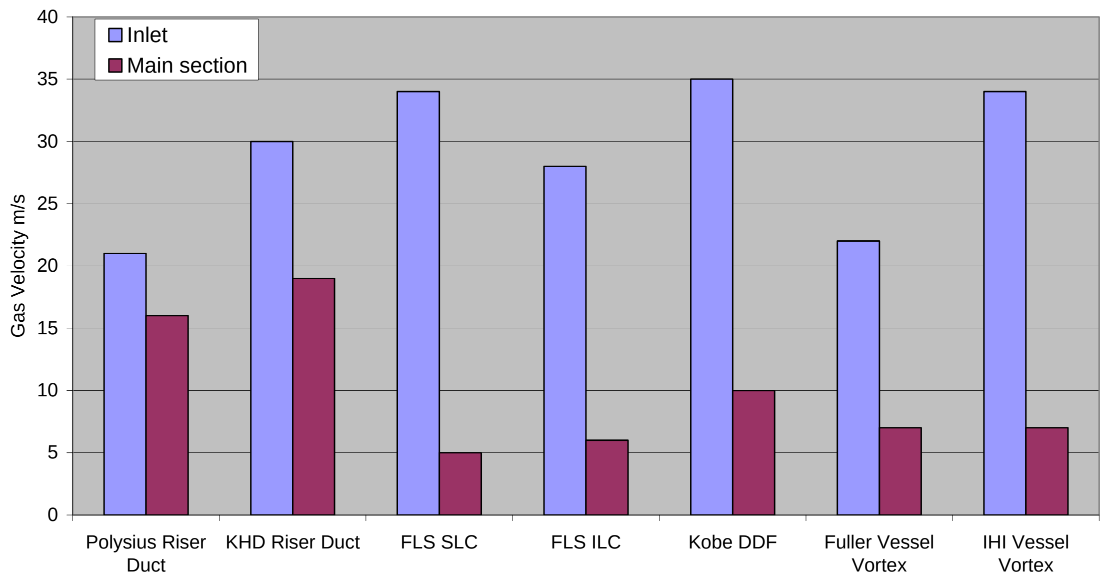
3. High oxygen environment – increased burn out rate, although negative impact on NOx
4. Gas residence time > 3.5 secs (needs to be 4 - 4.5 secs to allow for NOx reduction) – allow burnout of CO
5. High temperature combustion zone – rapid burnout of fuel
6. Vertically upwards gas stream – avoid material drop out

4.3.2. Characteristics of Precalciner Types

In order to determine the relative potential of the precalciners to utilize solid waste fuel, characteristic gas velocities were determined at the inlet and main section of the equipment. These are shown in figure 4.3 below. Not surprisingly there is a significant range in the velocities of the various designs since the gas velocity was not a critical design parameter for pulverized fuels. Inlet velocities range from 20 m/s to 35 m/s and outlet velocities range from 5 m/s to 18 m/s. Clearly after considering the necessary velocity for lumpy solid fuels, these ranges in velocity would be expected to produce different levels of performance.

As stated above a high inlet velocity combined with a low main section velocity is the preferred design to allow sufficient fuel residence time. An inlet velocity of 30 m/s or more will be required for many fuels, although this will depend on their size, shape and density. Plant trials with shredded tyres, with maximum size of 50 x 50 mm, have determined velocities of 30-35 m/s at the point of injection. As shown in the graph, the normal design gas velocity is often below this value. However, in most cases the gas can be accelerated, using a simple refractory restrictor, to achieve the desired gas speed at the point of injection. The restrictor would increase the preheater pressure loss and could have an adverse effect on kiln production, if the preheater exhaust fan is a limitation.

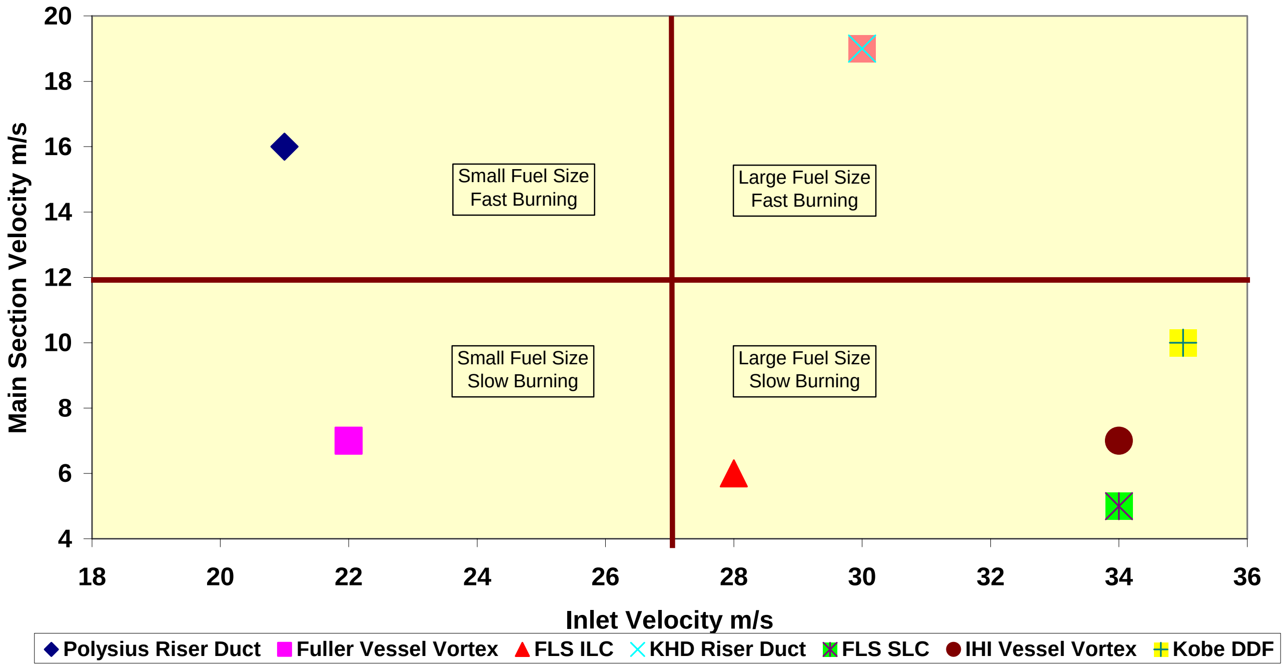
FIGURE 4.3 TYPICAL PRECALCINER GAS VELOCITIES



The velocity in the main section of the precalciner is fixed and cannot be altered so easily, as it would involve almost complete replacement of the precalciner. Therefore this velocity is the main characteristic to determine the success of burning a particular fuel with a given lump size.

An alternative way to show the velocity data is to plot the two gas velocities against each other, see figure 4.4. Since the fuel size the precalciner can handle is determined by the inlet velocity, as shown on the X-axis, this axis also represents the trend for fuel size, for a given density and shape. The velocity in the main part of the precalciner affects the fuel residence time. A precalciner with a short fuel residence time, that is with a high velocity is more suitable for a quick burning fuel. Therefore, the main section velocity on the Y-axis represents the trend for fuel burnout time. Thus if the graph is split into four quadrants the suitability of each precalciner design can be shown in terms of fuel size and burn out rate.

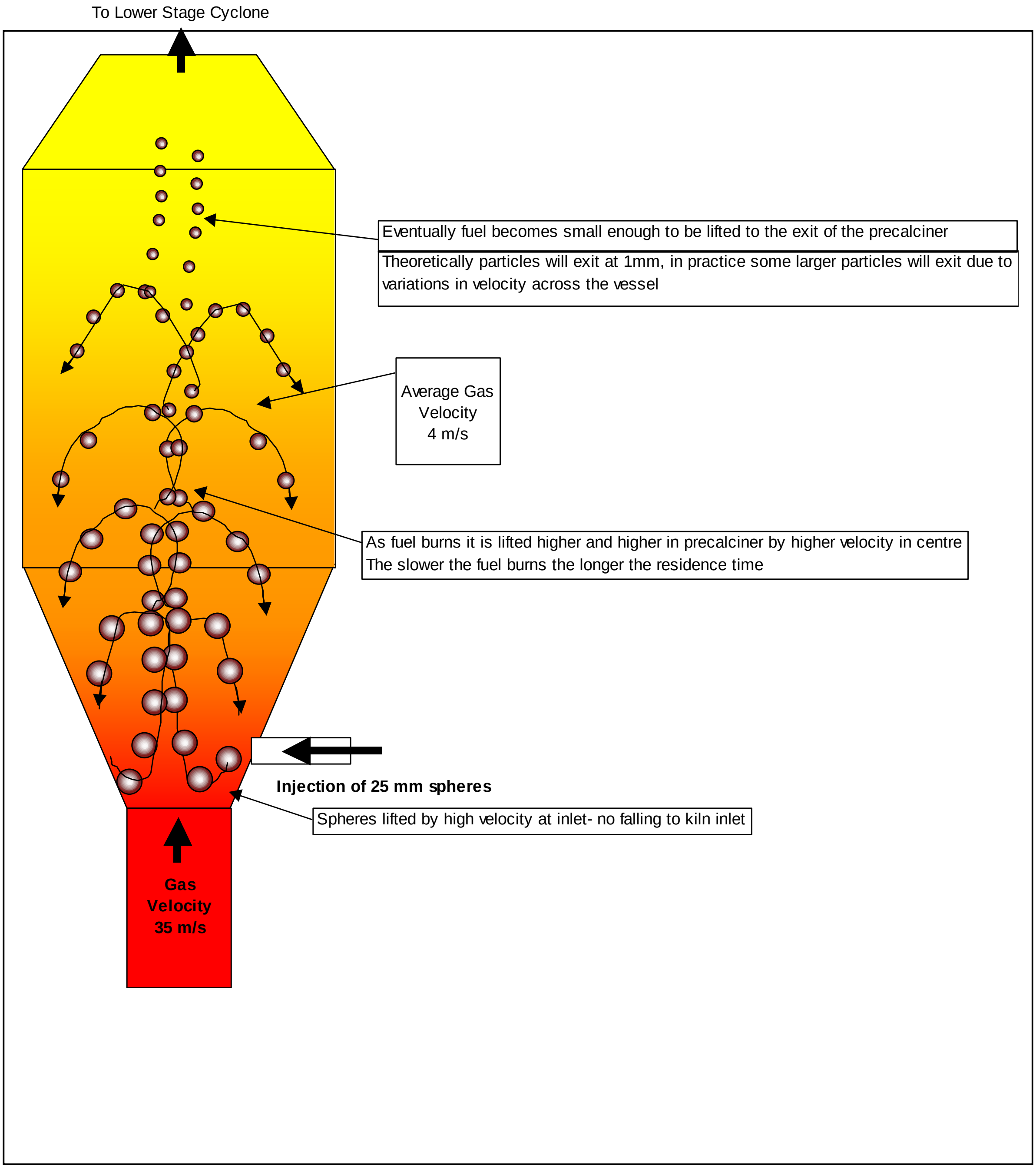
FIGURE 4.4 – PRECALCINER FUEL FLEXIBILITY



This graph indicates that all the vessel type precalciner designs, with their low main body velocities, should have more flexibility with solid fuels than the riser duct type with their high main section velocities. This assumes that the gas velocity is consistent across the cross section of the vessel and no high velocity stream exists, e.g. from the high inlet velocity, which shortens the effective residence time. This tendency would be more pronounced in the Vessel with Vortex designs that have a relatively short body section.

The terminal velocity graph, Figure 4.2, can be used to indicate the difference in performance between a riser duct type and vessel type precalciner. As an example consider the application of a fuel made of 25mm spheres and particle density 500 kg/m3. If we assume the same operating conditions in both precalciners and that as the particles burn they reduce in diameter and keep the same density. If we also assume 35 m/s inlet velocity for both, by fitting a suitable accelerator, if necessary. The typical velocity in the main part of a riser duct type is 16 m/s, so potentially, fuel particles can exit the precalciner to the lower cyclone stage once they reduce to 7 mm diameter. In the case of the vessel type with main section velocity at 4 m/s, fuel particles can exit once they are less than 1 mm diameter, improving the potential fuel burn out, see figure 4.5. However, if we consider the case where fuel particles were only 5mm diameter (either as fed to the precalciner or larger particles broke up as they were heated) again with density 500kg/m3 as above. In the riser type the residence time of the fuel particles would be close to the gas residence time, a few seconds, whereas in the vessel type the residence time would be the time to burn down to less than 1mm which would mean a significant increase in fuel residence time. Thus a highly reactive fuel would be needed to achieve an efficient burn out for the riser type precalciner.

FIGURE 4.5 LUMPY WASTE FUEL RESIDENCE TIME IN A PRECALCINER



In addition to the velocity, considering the other criteria to improve combustion the high oxygen environment of the SLC design would reduce the burnout time, compared to that for an inline precalciner. In the case of low NOx emission levels the SLC would incur a higher usage of reagent for SNCR than the ILC. The choice would be made depending on the EVA comparison, SLC more waste, but higher reagent, ILC lower waste and lower reagent. In the case of a negative cost reagent (photo-liquid or chicken manure) then the SLC would be an obvious choice.

Generally, addition of a combustion chamber in the tertiary duct would also provide high oxygen atmosphere together with the added advantage of a high temperature core, although in the downdraught design larger solid waste particles will drop out of the gas stream and fall into the kiln inlet, which has to be avoided to optimize the combustion. This would be even worse with fuels that became sticky during combustion. A vertically rising high temperature zone would be preferred to avoid this risk. However, no commercial design of this nature exists at this time.

Injection of tyre chips into the RSP and mixing chamber in Morocco, Bouskoura and Meknes, were inconclusive. The same 10% limit was found for both positions, although the mixing chamber was preferred due to 20% reduction in NOx emission. Some of the tyre chips were excessively large (150 x 150 mm), which would have dropped to the kiln inlet with firing to either location. (See appendix 7.3).

Therefore, addition of a downdraught combustion chamber should be reserved for firing finely ground fuels with low volatile matter, or small, low density wastes.

4.4. Physical Supports for Firing Wastes

4.4.1. Design Principle

The method for firing wastes discussed above relies on the gas velocity to hold the fuel long enough in the precalciner to allow a high burnout rate. An alternative method is to physically support the fuel in the gas stream to allow it to burn out. In this case burn out would be more controllable since the fuel residence time would be independent of the gas velocity. Then the precalciner type would be less of a consideration for burning lumpy solid fuels.

The principle is to provide a support such as “fingers” to hold the fuel in the gas stream to allow it to burn out.

In the case of large sized fuels such as whole tyres the ‘fingers’ technique has already been trialed in several plants.

4.4.2. Lafarge Experience with Physical Supports ‘Fingers’

‘Finger’ developments:

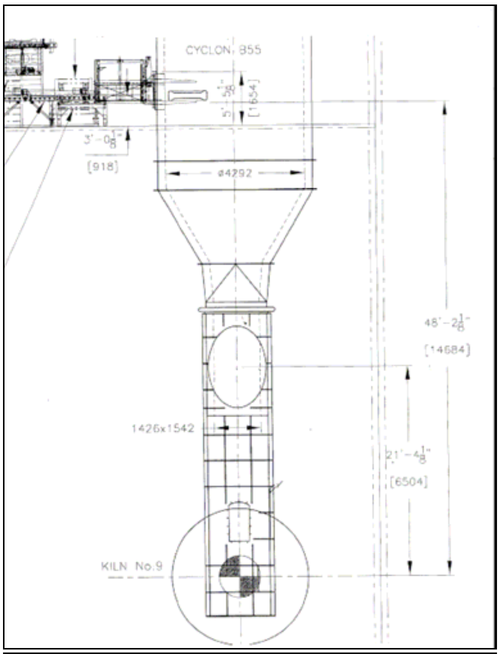
<u>Dunbar:</u> - Precalciner Polysius Riser Duct - Fingers developed in 1996. Abandoned for engineering reasons (no room for 4 sets of fingers)

<u>Cookstown:</u> - Lepol Grate Kiln - Fingers tried in 2001. Abandoned for environmental reasons (high SO2 stack gaseous emissions)

<u>Harleyville</u> – Precalciner Riser Duct. Has been briefly tried in 2003. Not pursued at the moment due to high substitution of whole tyres into the kiln inlet.

<u>Melon</u> – Precalciner FLS Inline Vessel Type (with duct extension) with 3.5 seconds residence time – The most successful trial todate with fuel replacement of up to 10% with a single set of fingers.

<u>FIGURE 4.6 MELON TYRE FINGERS</u>



Melon burns passenger tyres and truck tyres on a set of fingers located in the straight section of the precalciner vessel with an average replacement rate of about 10%. The fingers are manufactured from heat resistant steel of temperature rating 1050 C, with approx 26% chrome and 35% nickel.

Operation at 5% replacement using car tyres (or 2.5% truck tyres), tyres would stay on the fingers for around 50 seconds and almost completely burn. No adverse impact was observed on the process. The CO in the kiln inlet was only affected by occassional spikes.

However, at 10% fuel replacement the car tyres are only on the fingers for 25 seconds and then finish burning in the kiln inlet. In this case CO is increased significantly in the kiln inlet from 500ppm to around 2000ppm.

At the same level of replacement by truck tyres CO can be 6000ppm. In practice the plant control the tyre injection rate to maintain a hot meal S03 less than 4%. At 10% replacement rate a loss in kiln production is experienced arong 1% for passenger tyres and 2.5% for truck tyres. Emission of CO from the preheater was unaffected by the increase in the kiln inlet.

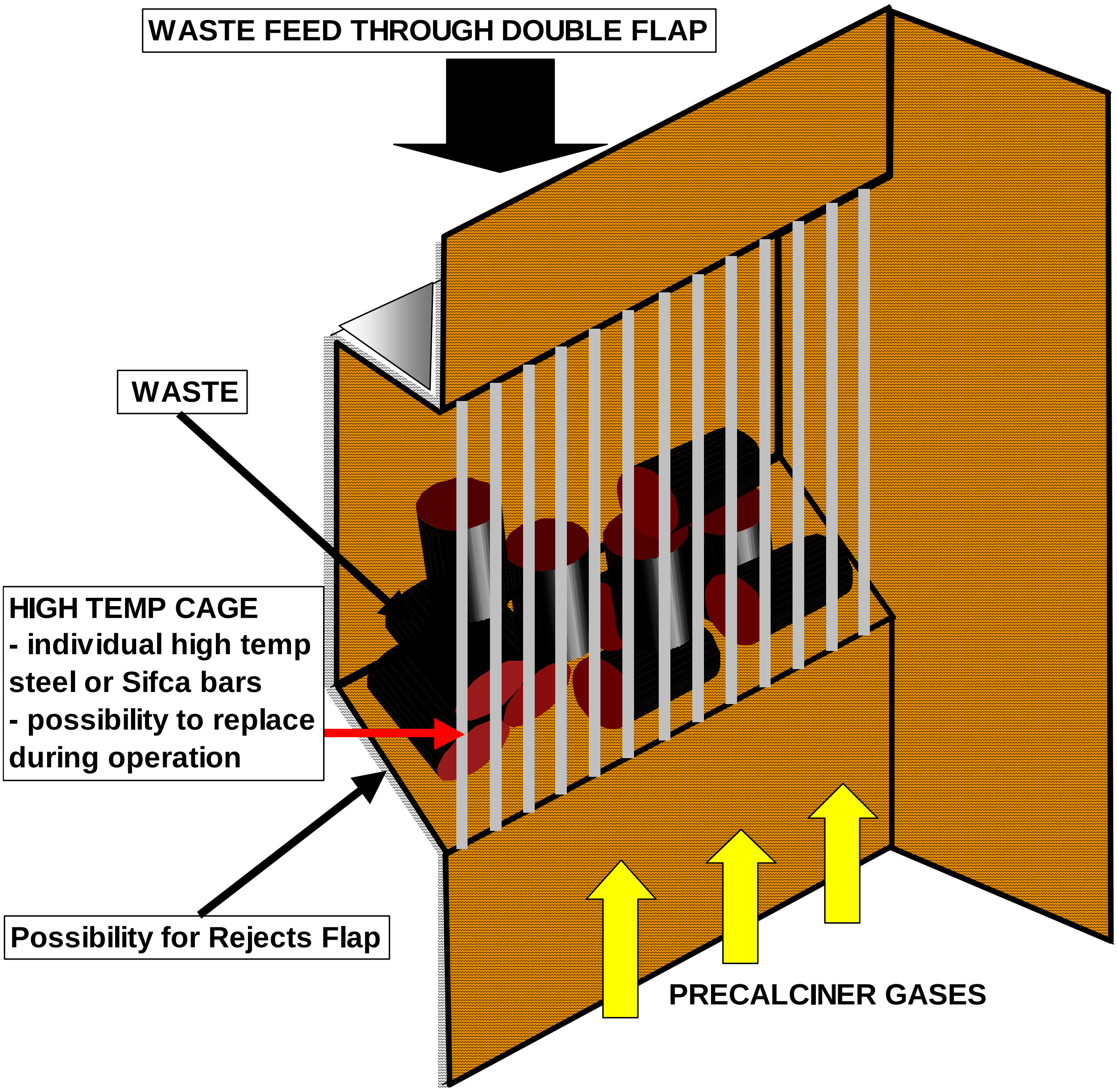
FIGURE 4.7 VIEW FROM THE TOP OF MELON PRECALCINER

Sugar Creek – Precalciner Riser Duct. The plant installed a tyre handling system to introduce tyres into the precalciner. A trial in September 2004 demonstrated that the plant could burn 0.6 tph tyres with out any impact on the volatile cycles. However, the trial had to be stopped due to blockage of the kiln inlet and riser orifice with accumulations of wire from the belting in the tyres.

4.4.3. Physical Supports for Lumpy Fuels – 'Cage'

It could be possible to redesign the fingers system to provide a 'cage', i.e. fingers with smaller gaps between to give the flexibility to burn either whole tyres, baled waste, or loose lumpy wastes. If such a system could be developed it would greatly simplify the application of solid wastes in precalciners. The residence time could be controlled irrespective of the gas velocities and remove the limitation of the precalciner design. Control of the waste feed size would no longer be a critical issue. Such a design placed in the kiln riser could be employed to reduce NOx emissions. The main challenge is to design and develop a reliable system. The concept is shown in figure 4.8 below:

FIGURE 4.8 CONCEPT FOR A 'CAGE' IN PRECALCINER FOR BURNING SOLID WASTES



4.5. Fuel Injection Point

4.5.1. Precalciner Operation Study

Introduction of a waste into the precalciner will involve the selection of the most appropriate position to ensure stable operation and good combustion. To make this selection, it is important to make a detailed study to be able to understand the specific conditions in the precalciner. Firstly a detailed temperature, and ideally oxygen, survey should be made of the precalciner to know where the fuel is burning and whether there is any mal-distribution that needs to be corrected. It is also helpful to conduct a kiln audit to be able to calculate gas volumes and hence velocities through the precalciner and preheater. See Appendix 7.4 Sonadih Precalciner – Modification of Fuel and Meal Injection

4.5.2. Fuel Injection Points

There have been several cases, using coal, where poor fuel and/or meal injection has resulted in severe build up and refractory damage in the precalciner, with significant impact on production level and reliability. In particular, the use of a splitter, in a pneumatic conveying line, to feed fuel to several injection points often results in a poor temperature profile, even when there are only two injection points. Therefore, use of splitters should be avoided.

The injection point for the coal should just below the meal injection to avoid excessive temperatures. In some cases when the distance has been too large rapid refractory failure has occurred. Refractories in the precalciner normally will not withstand more than 1200C on a continuous basis, and there is significant risk of build up if the temperature is more then 1100C.

4.5.3. Meal Injection

Meal injection should use splash boxes, rather than splash plates that can distort and burn out. FLS / Fuller also introduced a chute plus ‘ski jump’ design into some precalciners for meal injection. This design had a tendency not to give the required ‘splash’ and meal dropped out of the precalciner inlet gas duct. In a plant with this design it should be investigated and may need replacement by a splash box.

4.5.4. Guidelines for Selection of Fuel Injection Points

Some general guidelines for changing / adding fuels injection points are shown below for different types of fuels:

Bituminous Coal

- ✓ Lowest possible point in riser – maximise precalciner volume for fuel burnout
- ✓ Fuel injection close to meal injection (typically 0.5m below the splash box) to avoid excessive temperature, localised temperature should be below 1100 C
- ✓ Meal injection using splash box, not splash plate or FLS chute with ski jump

- ✓ Single injection point for single coal dosing – if more than one coal injection point is required install additional coal dosing system.
- **X** Avoid use of splitters in pneumatic conveying lines. There are several cases where split coal injection has caused poor distribution resulting in build up in the precalciner and even refractory damage.
- ✓ Gas velocity in riser > 14m/s to avoid meal / coal short circuiting to kiln
- ✓ Coal Injection velocity 30 m/s

In addition for Petcoke / Anthracite:

- ✓ Hot Spot Combustion Chamber Recommended - Hot spot >1200C increase burnout of low volatile fuel
- ✓ Curtain of meal at walls of Combustion chamber – protection of refractory
- ✓ Special Injection Nozzle desirable

In addition for Solid Waste Fuels injected into the gas stream :

- ✓ Gas velocity at waste fuel injection point > particle terminal velocity, typically for lumpy wastes 30 m/s.
- ✓ Injection of small sized < 5mm or light solid wastes (e.g. fluff or rice husks) larger into ‘hot spot’ downdraught combustion chamber.
- ✓ Wastes >5mm injection into upward rising gas stream in main part of precalciner

5. References

5.1. Bernburg Precalciner Seminar Presentations, Nov 2004 European Cement Research Association

KHD	FLS	Research Institute	Polysius	Research Institute

5.2. Investigation into the Operation of a Cement Works Precalciner Vessel, Sep 2000 Donald Giddings (Cauldon Tyre Chips Precalciner CFD Modeling)

5.3. Preheater and Precalciner Priority Study, Oct 93/Dec 94

5.4. Process Mission Melon, Aug 2003 CTI

5.5. Review of El Melon TDF System, Dec 2004 CTS

5.6. Reducing NOx emissions - FLS

5.7. BREF, Mar 2000 European Commission

5.8. Calciner Measurements – Sugar Creek, Jul 2003 Polysius

6. Appendices

6.1. Lafarge Precalciner Kiln Survey

"Precalciner Study Data.xls"

6.2. Velocities in Precalciners

"Precalciner Velocities.xls"

6.3. Morocco Tyre Injection Trial into RSP and Mixing Chamber, CTEO June 2005

"Tyre chips injection into RSP calciner.doc

6.4. Sonadih Precalciner – Modification of Fuel and Meal Injection, ATC Mar 2005

"Sonadih Precalciner.doc" "Sonadih Precalciner.ppt"