# Reference Guide for

# Process Performance Engineer

LafargeHolcim Cement Industrial Performance

(Version 12, April 2016)

**LafargeHolcim**
**Cement Industrial Performance**

Edition 12
April 2016

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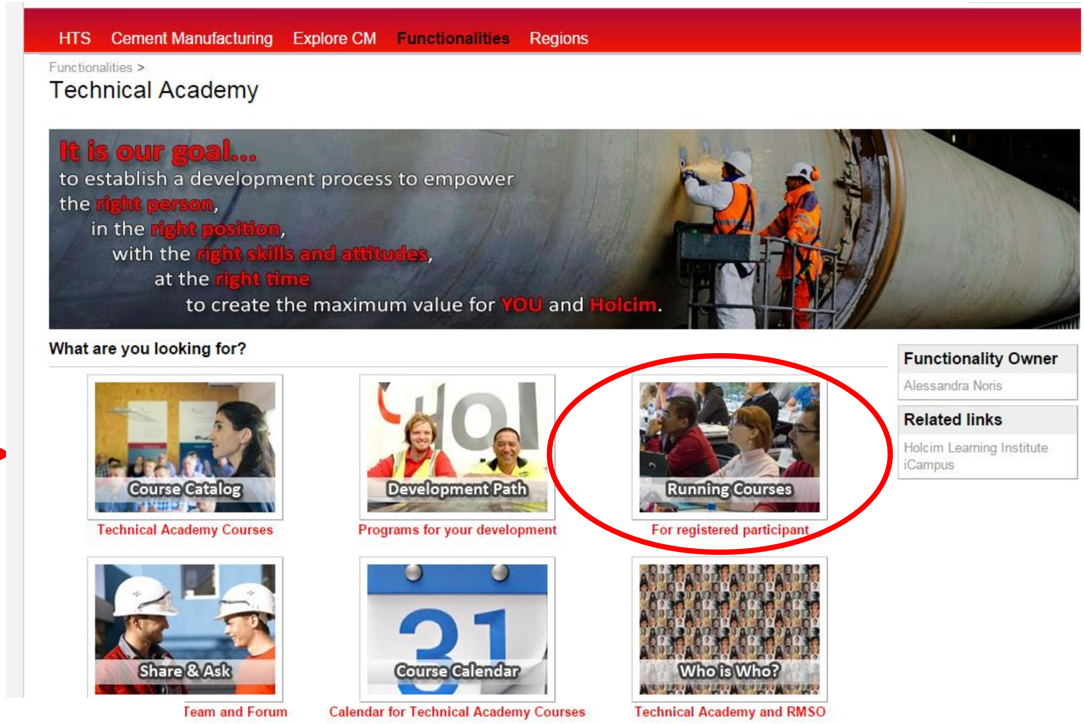
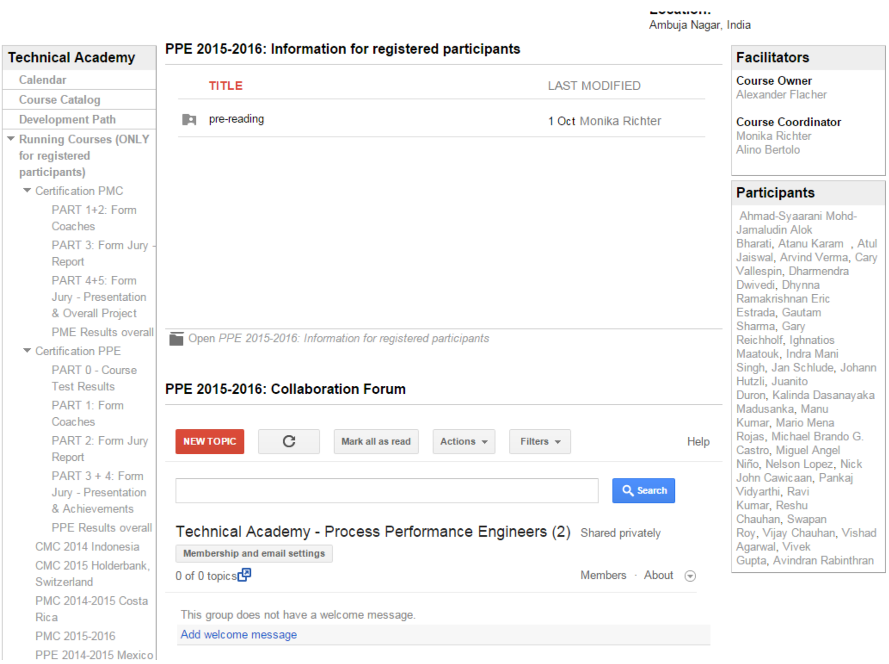
# “Process Performance Engineer Platform” on Google Drive

## Tools and spreadsheets for download



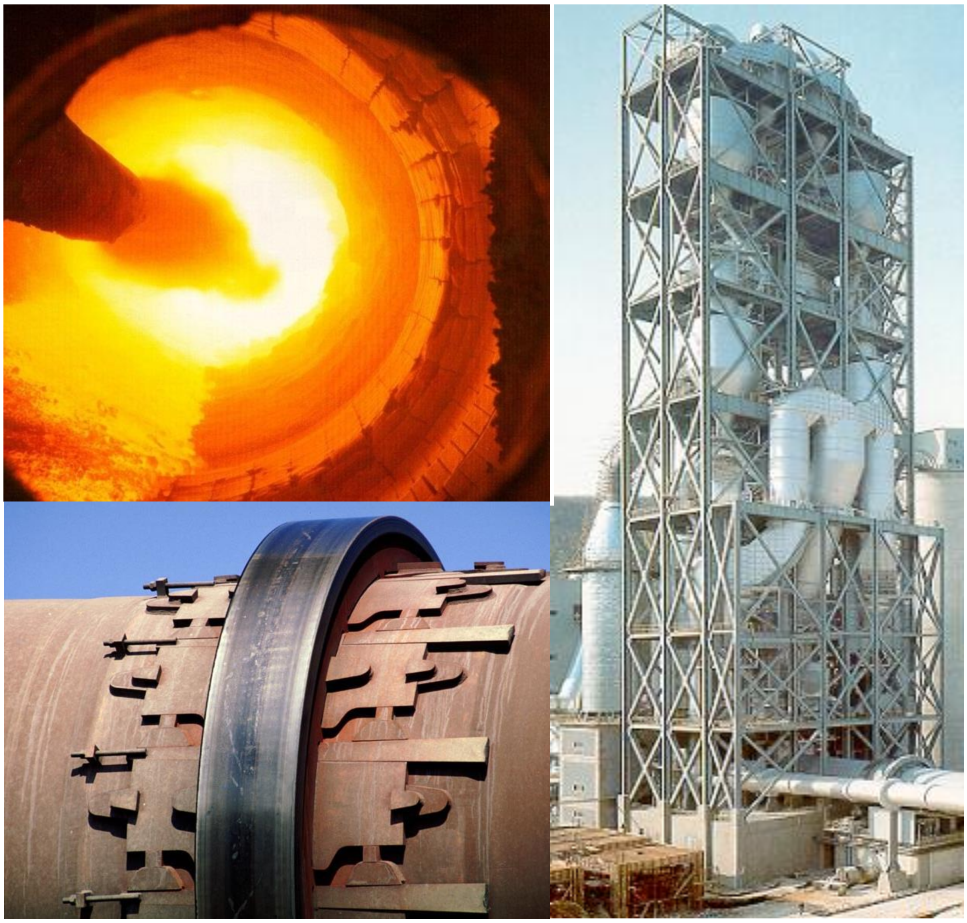


Process Performance Engineer
2015-2016 India



# Reference Guide for

## Thermal Technology



# Contents Thermal Technology

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# Holcim Performance Indicators

## Gross / Net Availability Index

$$\text{Gross Availability Index [\%]} = \frac{\text{Operating time [h]}}{\text{Calendar time [h]}} \cdot 100$$

$$\text{Net Availability Index [\%]} = \frac{\text{Operating time [h]} + \text{Idle time [h]}}{\text{Calendar time [h]}} \cdot 100$$

| | | |
|---|---|---|
| Calendar time | = | Operating time + Idle time + Other downtime |
| | = | Total time in that period |
| Operating time | = | Equipment is operating |
| Idle Time | = | Equipment is not operating but is in a condition for immediate startup |
| Other downtime | = | Equipment is not operating and not in a condition for immediate startup |

## Production Rate Index

$$\text{Production Rate Index [\%]} = \frac{\text{Production Rate [t/d]}}{\text{BDP [t/d]}} \cdot 100$$

BDP (Best demonstrated practice): The best historical production rate (t/d) achieved during the last 24 months before the budget phase.

## Gross / Net Overall Equipment Efficiency (OEE)

$$\text{Gross OEE [\%]} = \frac{\text{Gross Availability Index [\%]} \cdot \text{Production Rate Index [\%]} \cdot \text{Quality Index [−]}}{100}$$

$$\text{Net OEE [\%]} = \frac{\text{Net Availability Index [\%]} \cdot \text{Production Rate Index [\%]} \cdot \text{Quality Index [−]}}{100}$$

For the cement industry with an insignificant level of final product rejects, the Quality Index in the OEE calculation is set to 1.

## Standard Clinker Capacity

$$\text{Standard Clinker Capacity [t/a]} = \text{BDP [t/d]} \cdot 365 \cdot 85\%$$

The Standard Clinker Capacity corresponds to the quantity of clinker that can be produced with a standard target OEE of 85%

Above definitions are based on the HARP (**H**olcim **A**ccounting and **R**eporting **P**rinciples) Manual Release 14. For the most current definition check the HARP Manual on Holcim Portal.

# Holcim Performance Indicators

## Thermal Substitution Rate (TSR)

$$\text{TSR [\%]} = \frac{\text{Alternative Thermal Energy Consumption Kiln System [MJ]}}{\text{Thermal Energy Consumption Kiln System [MJ]}} \cdot 100$$

The Thermal Substitution Rate is the degree of substitution of traditional by alternative fuels, based on thermal energy consumption in the kiln system.

## Thermal Economic Equivalent (TEE)

$$\text{TEE [\%]} = \left[1 - \frac{\text{Actual Cost of Thermal Energy [RC]} \cdot (1 - \text{TSR [−]})}{\text{Actual Cost of Traditional Thermal Energy [RC]}}\right] \cdot 100$$

The Thermal Economic Equivalent (TEE) corresponds to the economic benefit derived from using alternative fuel by showing the relationship between the fuel costs and the theoretical fuel costs if no alternative fuels were used.

Above definitions are based on the HARP (**H**olcim **A**ccounting and **R**eporting **P**rinciples) Manual Release 14. For the most current definition check the HARP Manual on Holcim Portal.

# Combustion Engineering

## Stoichiometric Combustion Air

$$A_{min}[Nm^3/MJ] \approx 0.26$$

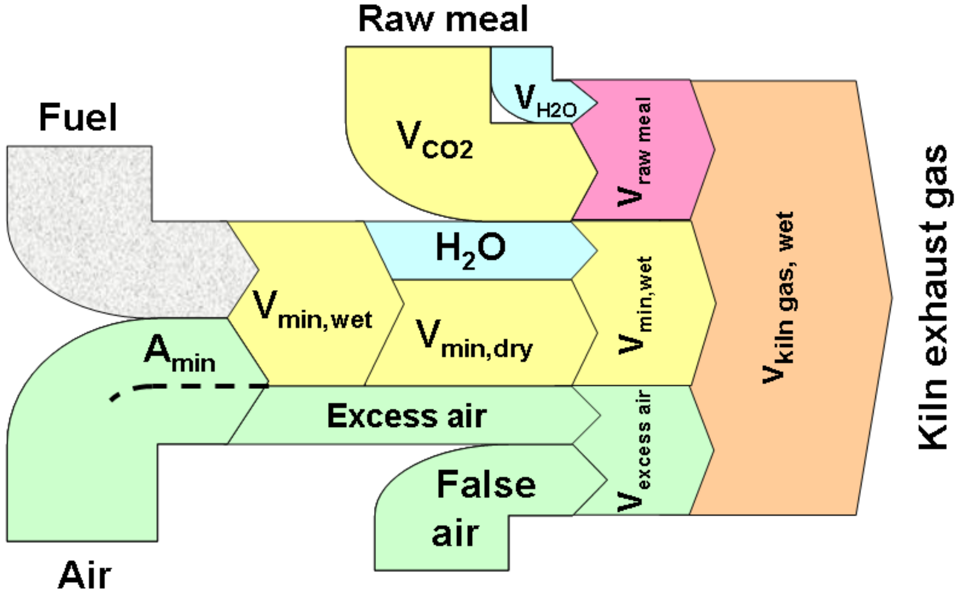
or

| | | |
|---|---|---|
| $A_{min}$ [$Nm^3/kg_{cli}$] | $= 0.26 \cdot q$ [$MJ/kg_{cli}$] | q = Kiln heat consumption [$MJ/kg_{cli}$] |
| $A_{min}$ [$Nm^3/h$] | $= 0.26 \cdot P$ [$MJ/h$] | P = Fuel input [MJ/h] |
| $A_{min}$ [$Nm^3/kg_{fuel}$] | $= 0.26 \cdot NCV$ [$MJ/kg_{fuel}$] | NCV = Net calorific value [$MJ/kg_{fuel}$] |

## Kiln Exhaust Gas

Fuel, raw meal and air contribute to total cement kiln exhaust gas:

$$V_{kiln\ gas} \approx V_{min} + V_{raw\ meal} + V_{excess\ air}$$




→ See next page for the calculation of the components in the schematic.

## Stoichiometric Combustion Gas

For most fuels:

$$V_{min,wet}[Nm^3/MJ] = 0.28$$
$$V_{min,dry}[Nm^3/MJ] = 0.25$$

# Combustion Engineering

## Gas from raw meal

$$V_{raw\ meal} = V_{H2O} + V_{CO2}$$

→ **Gas from raw meal decarbonation**

$$V_{CO2}[Nm^3/kg_{cli}] \approx 0.27$$

→ **Gas from water content in raw meal / slurry**

For **dry** kiln systems only (dry kiln feed):

$$V_{H2O}[Nm^3/kg_{cli}] \approx 0.01$$

For **wet, semi-wet and semi-dry** kiln systems (slurry, granules, cake):

$$V_{H2O}[Nm^3/kg_{cli}] \approx 1.24 \cdot KF \cdot \frac{\%feed\ moisture}{100 - \%feed\ moisture}$$

KF [-] = dry kiln feed/clinker factor ($kg_{kiln\ feed,dry}/kg_{clinker}$)
%feed moisture [%] = % moisture in wet kiln feed

## Excess Air (including False Air)

$$V_{excess\ air} = (V_{min,dry} + V_{CO2}) \cdot \left(\frac{\%O_{2,dry}}{21 - \%O_{2,dry}}\right)$$

→ same units for $V_{excess\ air}$, $V_{min,dry}$, and $V_{CO2}$

$\%O_{2,dry}$ [%] = measured $O_2$ concentration in dry gas

## Gas flow at preheater exit (dry kiln)

Total wet kiln exhaust gas (i.e. after full decarbonation) for a measured $O_2$ concentration $\mathbf{\%O_{2,dry}}$ and specific heat consumption **q**.

$$V_{Kiln\ gas,wet}\left[\frac{Nm^3}{kg_{cli}}\right] = \underbrace{(0.28 + 0.28 \cdot q)}_{\text{from raw meal}} + \underbrace{(0.27 + 0.25 \cdot q)}_{\text{from combustion}} \cdot \underbrace{\left(\frac{\%O_{2,dry}}{21 - \%O_{2,dry}}\right)}_{\text{excess air (based on dry } O_2 \text{ measurement)}}$$

q [$MJ/kg_{cli}$] = specific heat consumption of kiln system

$\%O_{2,dry}$ [%] = measured $O_2$ concentration in dry gas

# Combustion Engineering

## Gas flow at kiln inlet (dry kiln)

At kiln inlet, a fraction of the raw meal is already calcined (%decarb) and only the fuel from the main firing is contributing to the gas flow.

$$V_{\text{Kiln inlet gas,wet}}\left[\frac{Nm^3}{kg_{cli}}\right] = 0.27\cdot\left(1-\frac{\%decarb}{100}\right)+0.28\cdot q\cdot\left(1-\frac{\%PC}{100}\right)+$$
$$+\left\{0.27\cdot\left(1-\frac{\%decarb}{100}\right)+0.25\cdot q\cdot\left(1-\frac{\%PC}{100}\right)\right\}\cdot\left(\frac{\%O_{2,dry}}{21-\%O_{2,dry}}\right)$$

%decarb [%] = decarbonation (= calcination) degree of hot meal at kiln inlet

%PC [%] = thermal energy input at pre-calciner

q [MJ/$kg_{cli}$] = specific heat consumption of kiln system

$\%O_{2,dry}$ [%] = measured $O_2$ concentration (dry) at kiln inlet

## Secondary Air

The Secondary Air is calculated by subtraction of primary air, transport air and false air at kiln outlet from the total combustion air (= Amin + excess air, evaluated by $O_2$ measurement at a position without influence of false air from kiln inlet).

$$V_{\text{secondary air}} = V_{\text{Amin, kiln}} + V_{\text{excess air, kiln}} - V_{\text{primary air,kiln}} - V_{\text{transport air,kiln}} - V_{\text{false air, kiln outlet}}$$

$\rightarrow$ same units for all V

## Tertiary Air

The Tertiary Air is calculated by subtraction of calciner primary and transport air, and the total kiln excess air (= excess air kiln + false air kiln inlet) from the total calciner combustion air (= Amin + excess air calciner, evaluated by $O_2$ measurement at calciner exit).

$$V_{\text{tertiary air}} = V_{\text{Amin, calciner}} + V_{\text{excess air, calciner}} - V_{\text{primary air, calciner}} - V_{\text{transport air, calciner}} - V_{\text{excess air, kiln}} - V_{\text{false air, kiln inlet}}$$

for ILC

$\rightarrow$ $V_{\text{false air, kiln inlet}}$ is typically 0.02 – 0.05 $Nm^3/kg_{cli}$

Obviously, for a SLC, the total excess air from the kiln must be omitted.

$$V_{\text{tertiary air}} = V_{\text{Amin, calciner}} + V_{\text{excess air, calciner}} - V_{\text{primary air, calciner}} - V_{\text{transport air, calciner}}$$

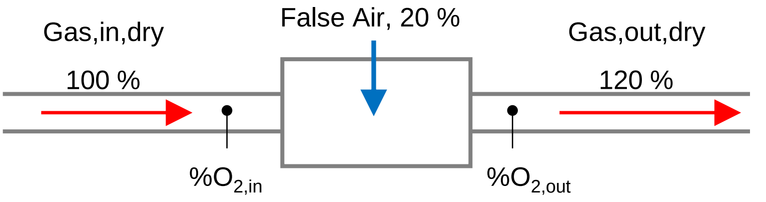
for SLC

$\rightarrow$ same units for all V

# False Air

## False Air intake based on Oxygen measurement

The False Air intake across some equipment (e.g. filter, cyclone, …) can be evaluated by oxygen measurement in the gas flow before and after the equipment.




$$FA[\%] = \frac{V_{FA\ intake}}{V_{Gas,in,dry}} \cdot 100 = \left( \frac{\%O_{2,out} - \%O_{2,in}}{21 - \%O_{2,out}} \right) \cdot 100$$

| | | |
|---|---|---|
| FA [%] | = | additional false air as fraction of flow before false air intake |
| $V_{FA\ intake}$ [$Nm^3/h$] | = | false air intake |
| $V_{Gas,in,dry}$ [$Nm^3/h$] | = | gas flow (dry) before false air intake |
| $\%O_{2,in}$ [%] | = | measured $O_2$ concentration (dry) before intake |
| $\%O_{2,out}$ [%] | = | measured $O_2$ concentration (dry) after intake |

**Important!**

If it is not possible to measure the oxygen before and after the intake at the same time, the two measurements have to be corrected for the $O_2$ variation in the gas flow, e.g. by comparison to the $O_2$ signal at PH exit.

### Typical values for False Air intake

| Location | False Air (% of flow before intake) |
|---|---|
| Bag filter | < 5 |
| Electrostatic precipitator | < 10 |
| Conditioning tower | < 5 |
| Expansion joint | 0 ! |
| Fan | < 2 |
| Damper (butterfly, jalousie, guillotine) | < 2 |
| Preheater cyclone | < 2 |
| Kiln inlet seal | < 1 |

# False Air

## False Air intake based on cross section area of opening

The False Air entering through openings (e.g. hole in a duct, missing top cover, etc.) can be calculated by means of the Bernoulli equation.

$$V_{FA\ intake} \approx \frac{0.75\ A}{\rho_{air,N}} \sqrt{2 \cdot \Delta p \cdot \rho_{air}}$$

| | |
|---|---|
| $V_{FA\ intake}$ [$Nm^3/s$] | = False Air intake |
| A [$m^2$] | = cross section area of opening |
| $\rho_{air,N}$ [$kg/Nm^3$] | = air density at normal conditions = 1.29 $kg/Nm^3$ |
| $\rho_{Air}$ [$kg/m^3$] | = air density at aperture = air density at ambient condition |
| $\Delta p$ [Pa] | = pressure difference measured over aperture |

## False Air intake based on temperature drop

The False Air intake between two gas flow temperature measurements (inlet and outlet) can be calculated by a simplified heat balance (dust in process gas is neglected).

$$FA[\%] = \frac{V_{FA\,intake}}{V_{Gas,wet}} \cdot 100 \approx \frac{T_{Gas,in} - T_{Gas,out} - T_{loss}}{T_{Gas,out} - T_{air}} \cdot 100$$

| | |
|---|---|
| $V_{FA\ intake}$ [$Nm^3/s$] | = False Air intake |
| $V_{Gas,wet}$ [$Nm^3/s$] | = gas flow at inlet |
| $T_{Gas,in}$, $T_{Gas,out}$ [°C] | = inlet and outlet gas temperature |
| $T_{air}$ [°C] | = temperature of air intake ≈ ambient temperature |
| $T_{loss}$ [°C] | = gas temperature drop due to surface area convection and radiation heat loss |

$$T_{loss} = \frac{\dot{Q}_{RC}}{V_{Gas,wet} \cdot c_{p,Gas,wet}} = \frac{A_{surface} \cdot \alpha_{tot} \cdot (T_{surface} - T_{amb})}{V_{Gas,wet} \cdot c_{p,Gas,wet}}$$

| | |
|---|---|
| $Q_C$ [kW] | = total heat loss by convection and radiation |
| $c_{p,Gas,wet}$ [$kJ/Nm^3/°C$] | = specific average heat capacity of gas flow<br>→ see graph in **page 90** for $c_p$-values of gases |
| $A_{surface}$ [$m^2$] | = heat loss surface area |
| $T_{surface}$ [°C] | = surface temperature |
| $T_{ambient}$ [°C] | = ambient temperature |
| $\alpha_{tot}$ [$kW/m^2/°C$] | = total heat transfer coefficient<br>→ approximation: $\alpha_{tot} = (10 + 2 \cdot v_{wind})/1000$<br>$v_{wind}$ [m/s] = wind speed |

# Net and Gross Calorific Value of Fuels

## Net and Gross Calorific Value are related as follows (ASTM D 2015)

$$Q_{net\,af} = Q_{gross\,af} - 24.5 \cdot (H_{af} \cdot 9)$$

$Q_{net\ af}$ = net calorific value as fired [kJ/kg]
$Q_{gross\ af}$ = gross calorific value as fired [kJ/kg]
$H_{af}$ = total hydrogen as fired, includes hydrogen in moisture [%]

If the determination of the total hydrogen content is not possible, the following approximate formulas should be used for coal, petcoke and AFR.

### Coal

$$Q_{net\,af} = Q_{gross\,af} \cdot 0.983 - (15 \cdot VMS_{af}) + 60$$

$Q_{net\ af}$ = net calorific value as fired [kJ/kg]
$Q_{gross\ af}$ = gross calorific value as fired [kJ/kg]
$VMS_{af}$ = volatile matter content as fired [%]

### Petcoke

$$Q_{net\,af} = Q_{gross\,af} \cdot 0.981$$

$Q_{net\ af}$ = net calorific value as fired [kJ/kg]
$Q_{gross\ af}$ = gross calorific value as fired [kJ/kg]

Sampling location: The samples are taken after the coal mill in indirect fired kilns. In direct fired kilns the coal sample is taken at the raw coal bin.

# Net and Gross Calorific Value of Fuels

## AFR

Typical examples: paper, wood, sludge, animal meal, …
(Coal dust, graphite, charcoal or similar high carbon materials are calculated with the formula for coal)

Materials are tested "$Q_{gross\ af}$" (no drying)

$$Q_{net\ af} = Q_{gross\ af} \cdot 0.93 - 24 \cdot H_2O$$

| | |
|---|---|
| $Q_{net\ af}$ | = net calorific value as fired [kJ/kg] |
| $Q_{gross\ af}$ | = gross calorific value as fired [kJ/kg] |
| $H_2O$ | = water/ moisture content as fired [%] |

The water/moisture content in the sample is analyzed with the following methods:

1) ASTM D 5530 Total Moisture of Hazardous Waste Fuel by Karl Fischer Titrimetry
2) ISO 3733 determination of water - Distillation Method

# Gas Conversion, Density, Barometric Pressure

## Gas flow and density conversion from normal to actual

The formula below is used to convert ideal gas from normal conditions (0°C, 1'013 mbar) to actual conditions (T, p).

$$V_{act} = V_{norm} \cdot \left(\frac{1013}{p_x(mbar)}\right) \cdot \left(\frac{T(°C) + 273}{273}\right)$$

$$\rho_{act} = \rho_N \cdot \left(\frac{273}{T(°C) + 273}\right) \cdot \left(\frac{p_x\,(mbar)}{1013}\right)$$

$V_{act}$ = Gas flow at actual conditions ($m^3/s$)

$V_{norm}$ = Gas flow at normal conditions ($Nm^3/s$)

$p_x$ = absolute pressure at actual conditions (mbar) = $p_{measured,relative} + p_{ambient}$

$p_{measured,relative}$ = measured pressure (mbar)

$p_{ambient}$ = ambient pressure (mbar)

T = temperature at actual conditions (°C)

$\rho_N$ = density at normal conditions ($kg/Nm^3$)
(for air = 1.29 $kg/Nm^3$, moisture content can be neglected)

## Density of kiln gas based on $CO_2$, $O_2$, and $H_2O$ content

$$\rho_{N,dry} = \frac{\%O_{2,dry}}{100} \cdot 1.429 + \frac{\%CO_{2,dry}}{100} \cdot 1.964 + \left(1 - \frac{\%O_{2,dry}}{100} - \frac{\%CO_{2,dry}}{100}\right) \cdot 1.257$$

$$\rho_{N,wet} = \rho_{N,dry} \cdot (1 - \frac{\%H_2O}{100}) + \frac{\%H_2O}{100} \cdot 0.804$$

$\rho_{N,dry}$ , $\rho_{N,wet}$ = gas density (dry, wet) at normal conditions ($kg/Nm^3$)

$\%O_{2,dry}$ , $\%CO_{,dry}$ = $O_2$, CO concentration in dry gas (%vol)

$\%H_2O$ = $H_2O$ concentration in wet gas (%vol)

Approximation: Kiln exhaust gas (5% $O_2$, 20% $CO_2$, 10% $H_2O$): $\rho_{N,dry} = 1.4$, $\rho_{N,wet} = 1.35$

## Barometric Pressure

The average barometric pressure at a plant altitude (above sea level) can be calculated using the following approximation formula.

$$p(mbar) = 1013 \cdot \left(1 - \frac{Altitude\,(m)}{44300}\right)^{5.25}$$

p = average barometric pressure (mbar)

Altitude = altitude above sea level (m)

# Gas, Materials and Fuels Properties

## Density of Kiln Exhaust Gas (approx. Calculation)

[kg/Nm3] - Ideal gas at normal conditions

$$\rho_{N,dry} = \frac{\%O_{2,dry}}{100} \cdot 1.429 + \frac{\%CO_{2,dry}}{100} \cdot 1.964 + \left(1 - \frac{\%O_{2,dry}}{100} - \frac{\%CO_{2,dry}}{100}\right) \cdot 1.257$$

$$\rho_{N,wet} = \rho_{N,dry} \cdot \left(1 - \frac{\%H_2O}{100}\right) + \frac{\%H_2O}{100} \cdot 0.804$$

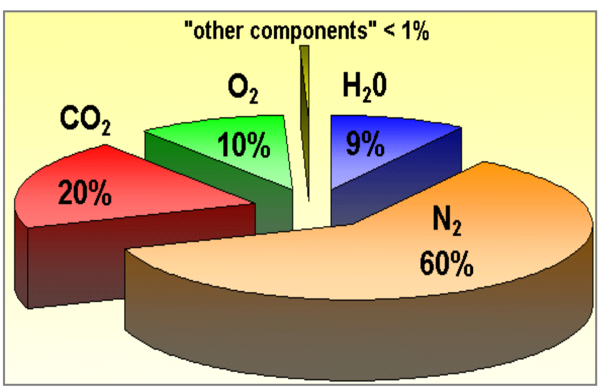
$\rho_{N,dry}$ , $\rho_{N,wet}$ = gas density (dry, wet) at normal conditions ($kg/Nm^3$)

$\%O_{2,dry}$ , $\%CO_{,dry}$ = $O_2$, CO concentration in dry gas (%vol)

$\%H_2O$ = $H_2O$ concentration in wet gas (%vol)

Approximation: Kiln exhaust gas (5% $O_2$, 20% $CO_2$, 10% $H_2O$): $\rho_{N,dry} = 1.4$, $\rho_{N,wet} = 1.35$

## Typical Kiln Exhaust Gas Composition




| Other components | „Typical Value“ |
|---|---|
| ▪ NOx | 0.04 % |
| ▪ $SO_2$ | 0.01 % |
| ▪ VOC² | 0.004 % |
| ▪ CO | 0.04 % |
| ▪ HCl | 0.0006 % |
| + Dust | |

% CO2 = f(fuel, raw mat,…..)

# Rotary Kiln

## Key Figures

| | | |
|---|---|---|
| **Specific kiln volume load:** | **< 2.2 t/d m³** | Suspension preheater kilns |
| | **< 5.5 t/d m³** | Precalciner kilns |

Calculation: Daily clinker production (t/d) divided by kiln volume inside refractory ($m^3$)

| | | |
|---|---|---|
| **Specific burning zone area load:** | **< 180 t/d m²** | Suspension preheater kilns |
| | **< 350 t/d m²** | Precalciner kilns |

Calculation: Daily clinker production (t/d) divided by kiln cross section area at the burning zone inside refractory ($m^2$)

**Specific thermal burning zone load:** **< 6 MW/m²**

Calculation: Total thermal energy input by the kiln burner (MW) divided by kiln cross section area at the burning zone inside refractory ($m^2$)

| | | |
|---|---|---|
| **Gas velocity inside kiln:** | **< 8 m/s** | for new plants (at 5% $O_2$ at kiln inlet) |
| | **< 12 m/s** | for existing plants (at actual $O_2$) |

Calculation: Total gas volume flow at kiln inlet (actual m3/s) divided by the kiln cross section area inside refractory ($m^2$)

| | | |
|---|---|---|
| **Material residence time in kiln:** | **35 - 60 min** | Suspension preheater kilns |
| | **20 - 35 min** | Precalciner kilns |
| **Material filling degree in kiln:** | **4 – 8 %** | typical value |

Calculation: Volume of material in kiln ($m^3$) divided by the kiln volume inside refractory ($m^3$)

**Specific nosering cooling air:** **> 0.33 m³/m s**

Nosering cooling air pressure at nozzle inlet: > 20mbar

Calculation: Nosering cooling airflow ($m^3/s$) divided by the circumferential length of the kiln shell (m)

Nozzles shall be arranged evenly around 360° of the kiln circumference.

# Rotary Kiln

## Material Residence Time in Rotary Kiln

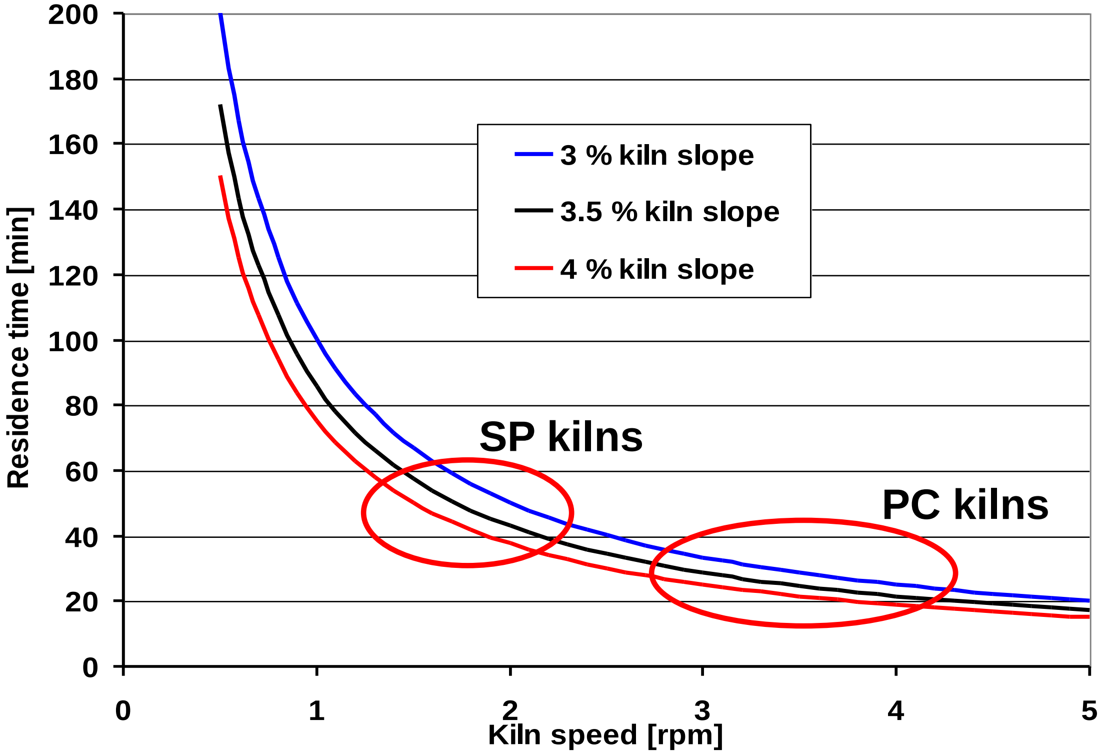
The residence time of the material in a dry rotary kiln can be determined with the formula from Duda Cement Data Book:

$$t = \frac{1.77 \cdot L \cdot \sqrt{\Theta}}{v \cdot (D - 2 \cdot Lining) \cdot rpm} \cdot F$$

| | |
|---|---|
| t | = Material residence time [min] |
| L | = Length of kiln [m] |
| θ | = Angle of repose of material [°], (here 35-40°) |
| ν | = Slope of kiln in degrees [°], (normally 1.7-2.0°) |
| D | = Kiln shell diameter [m] |
| Lining | = Refractory thickness [m] |
| rpm | = Number of kiln revolutions per minute [rpm] |
| F | = Factor, which equals 1, if the kiln has a constant diameter [-] |

| | | |
|---|---|---|
| **Typical Values** | **35 - 60 min** | Suspension preheater kilns |
| | **20 - 35 min** | Precalciner kilns |

For $L/d_{\text{inside lining}} = 16$



# Rotary Kiln

## Kiln Inclination Conversion

The kiln inclination can be indicated both in degrees and in percent. The following formula can be used for conversion:

$$\text{Inclination}\,[°] = \arctan\left(\frac{\text{Inclination}\,[\%]}{100}\right)$$

$$\text{Inclination}\,[\%] = 100 \cdot \tan\left(\text{Inclination}\,[°]\right)$$

With: Inclinations in Degrees and in Percent and mathematical functions
arctan: Arctangent, tan: Tangent

| **Kiln Inclination Conversion Table** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Percent [%]** | **2.00** | **2.18** | **2.50** | **2.62** | **3.00** | **3.06** | **3.50** | **4.00** |
| **Degrees [°]** | **1.15** | **1.25** | **1.43** | **1.50** | **1.72** | **1.75** | **2.00** | **2.29** |

## Material Filling Degree in Kiln

$$FD = K \cdot \frac{\text{Production} \cdot t}{V_{kiln} \cdot 24}$$

FD = Filling degree [%]
K = 1.5 [(d*m$^3$)/(t*min)]
Production = Clinker production [t/d]
$V_{kiln}$ = Kiln volume inside refractory [m$^3$]
t = Material residence time [min]

**Typical value 4 – 8 %**

# Rotary Kiln

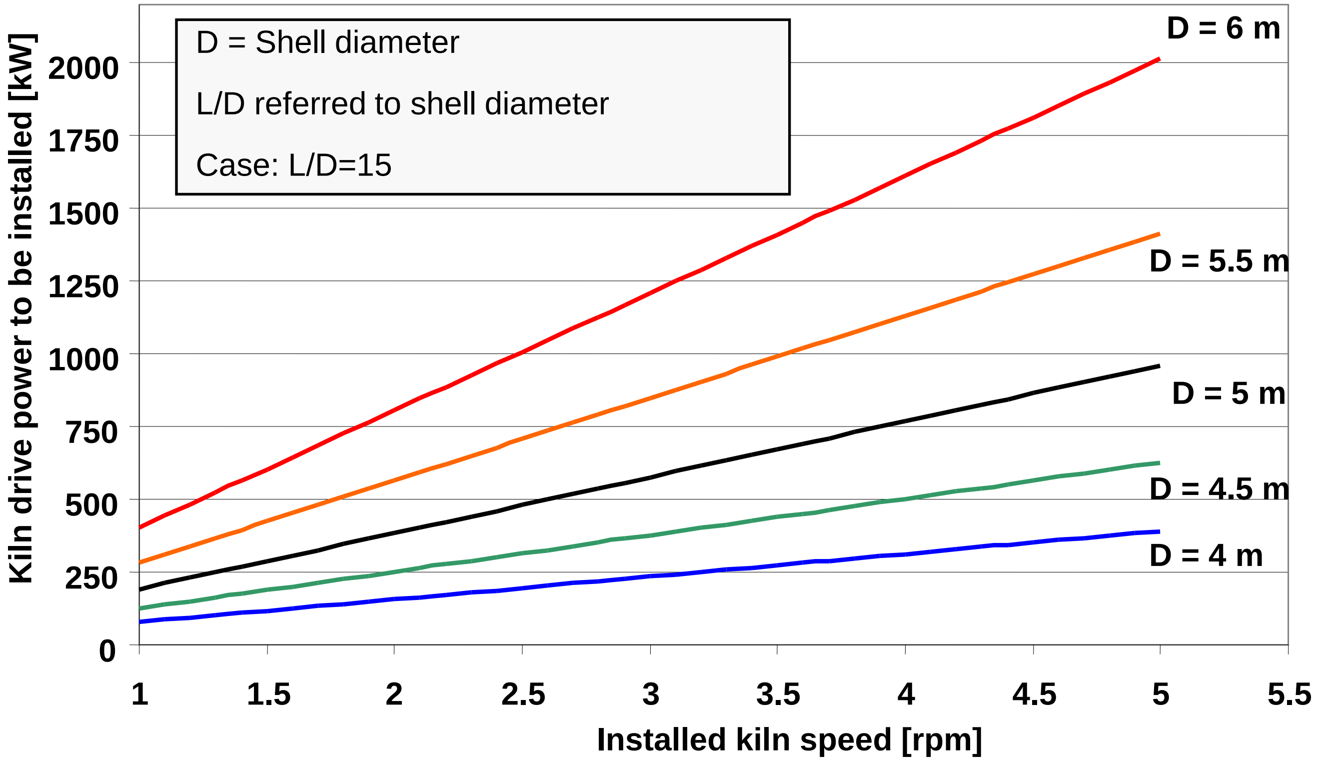
## Required Kiln Drive Power

The required kiln drive power to be installed is:

$$P_{Motor} = n \cdot L \cdot \left(0.0237 \cdot (D - 2 \cdot Lining)^3 + 5.79 \cdot 10^{-5} \cdot D \cdot (25 \cdot D + 750)\right)$$

$P_{motor}$ = Kiln drive power [kW]
n = Maximum kiln speed [rpm]
L = Kiln length [m]
D = Kiln shell diameter [m]
Lining = Refractory thickness [m]

Note: For a kiln of not constant diameter, the above formula is applied to each section and the results added up to the result for the entire kiln.



# Long Wet Kiln Systems

## Wet Kiln Chain Systems

| | | | |
|---|---|---|---|
| **Length of chain system:** | **6 – 10 x kiln diameter** | | |
| **Total chain weight:** | **9 – 12 %**<br>**11 – 20 %** | **weight of daily clinker production (t)** | for < 1000 t/d<br>for > 1000 t/d |
| **Fraction of heat resistant chains:** | **~ 15 %** | of total chain weight | |
| **Chain density: (specific surface)** | **5 – 15 $m^2/m^3$** | (depending on zone, see "Chain Layout" below) | |

Calculation: Surface area of chains ($m^2$) divided by volume of chain section ($m^3$)

### Calculation Sheets and Information Available on Holcim iShare

- Chain System Data: Layout Assessment
- Chain System Material Balance
- Recommended Chain Layout: Summary of "Guidelines Chain Layout"
- Guidelines for Chain Layout on Long Wet Kilns
- Heat Balance Wet Kiln

# Grate Cooler

## Key Figures

| | | |
|---|---|---|
| **Specific grate area load:** | **< 45 t/d m$^2$** | |

Calculation: Daily clinker production (t/d) divided by total active grate surface area (m$^2$).
Note: High grate area load increases the required specific aeration, especially after the recuperation zone.

**Specific grate width load: 1080 t/d m + clinker prod [t/d] x 0.08 m$^{-1}$ +/- 150 t/d m**

Calculation: Daily clinker production (t/d) divided by grate width (m)
Note: High grate width load results in high grate speed. Low values can result in clinker distribution problems at cooler inlet.

| | | |
|---|---|---|
| **Grate speed:** | **10 - 15 str/min** | |

Typical grate speed in strokes / minute for traditional reciprocating grate coolers
(higher speed means higher grate wear)

| | | |
|---|---|---|
| **Installed specific cooling** | **> 2.0 Nm$^3$/kg cli** | For modern coolers |
| **air volume requirement:** | **> 2.3 Nm$^3$/kg cli** | For old type coolers |

Calculation: Installed cooling air volume (Nm$^3$/h) divided by hourly clinker production (kg/h)

| | | |
|---|---|---|
| **Specific cooling** | **1.7 – 1.9 Nm$^3$/kg cli** | For modern coolers |
| **air volume (operation):** | **2.0 – 2.3 Nm$^3$/kg cli** | For old type coolers |

Calculation: Cooling air volume (Nm$^3$/h) divided by hourly clinker production (kg/h)
Note: If clinker end temperature is excessive or problematic, even higher values required.

| | | |
|---|---|---|
| **Typical specific aeration:** | **1.3 – 1.8 m$^3$/m$^2$ s** | For fixed inlet section |
| **(Operation), modern coolers** | **0.8 – 1.4 m$^3$/m$^2$ s** | For recuperation zone |
| | **0.4 – 1.0 m$^3$/m$^2$ s** | For after cooling zone |
| **Typical specific aeration:** | **1.5 – 3.0 m$^3$/m$^2$ s** | For inlet section |
| **(Operation), old type coolers** | **0.8 – 1.4 m$^3$/m$^2$ s** | For recuperation zone |
| | **0.4 – 1.0 m$^3$/m$^2$ s** | For after cooling zone |

Calculation: Actual cooling air flow (m$^3$/s) per respective area of grate / compartment (m$^2$).
Note: Low values are preferred with regard to heat exchange, but require a low specific grate area load.

| | | |
|---|---|---|
| **Recuperation Efficiency:** | **70 – 75 %** | For modern coolers |
| **(normalized)** | **55 – 70 %** | For old type coolers |

Calculation: Actual recuperation efficiency normalized to 0.8 Nm$^3$/kg clinker.
Note: Efficiency depends on the condition and design of the cooler, on clinker granulometry and operating conditions.

# Grate Cooler

**Kiln hood velocity:** **< 5 m/s** For new installations
**< 6 m/s** For existing installations

Calculation: Secondary air (and tertiary air) volume at actual temperature ($m^3/s$) divided by the horizontal cross section ($m^2$) at the cooler roof level.

**Tertiary air take off velocity (only if cooler roof extraction):** **< 5 m/s** For new installations
**< 6 m/s** For existing installations

Calculation: Tertiary air volume at actual temperature ($m^3/s$) divided by the cross section area of the tertiary air duct ($m^2$) at take off point.

**Waste air take off velocity:** **< 5 m/s** For new installations
**< 6 m/s** For existing installations

Calculation: Waste air volume at actual temperature ($m^3/s$) divided by the cross section area of the waste air duct ($m^2$) at take off.

**Tunnel velocity (horizontal air velocity above the clinker bed)** **< 8 m/s**

The tunnel velocity is the horizontal velocity of the air above the clinker bed towards the air extraction locations. It is highest at the location just before the air is extracted via kiln hood, tertiary air duct, waste air duct or middle air duct. Exact calculation of the tunnel velocity is difficult. Rough estimations can be made using cooling air distribution together with cooler drawings and an estimation of air temperature at the respective location (actual m3/h divided by the cross section of the cooler housing inside refractory above the clinker bed).

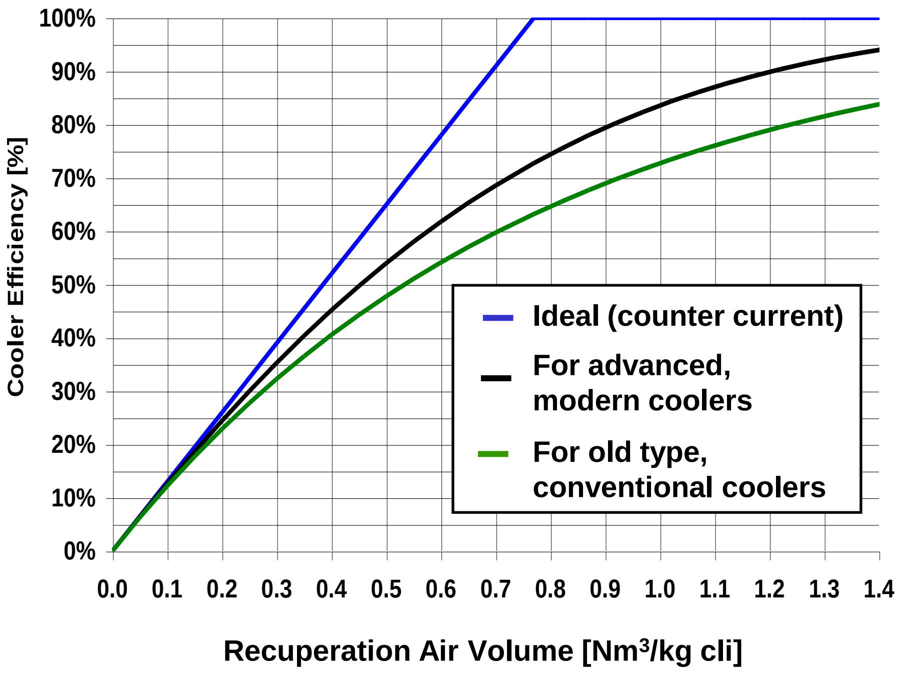
## Normal range of grate cooler process parameter:

| | Modern | | Conventional | | |
|---|---|---|---|---|---|
| Heat Consumption | 3000 | 3500 | 3500 | 5000 | kJ/kg |
| T sec & tert air * | 1070 | 990 | 890 | 610 | °C |
| T sec air | 1230 | 1170 | 940 | - | °C |
| T tert air | 950 | 850 | 850 | - | °C |
| T waste air | 300 | 300 | 240 | 200 | °C |
| Grate speed | 10 - 15 | | 10 - 20 | | min-1 |
| First grate pressure | 80 - 100 | | 45 - 55 | | mbar |
| Specific grate load | 45 - 50 | | 35 - 45 | | t/d m2 |
| Spec. cooling air | 1.8 | | 2.3 | | Nm3/kg |

* TA extraction from kiln hood

# Grate Cooler

## Cooler Recuperation Efficiency Assessment




## Clinker Cooler Recuperation Efficiency

The Clinker Cooler Recuperation Efficiency characterizes the fraction of heat from the hot clinker reintroduced to the kiln system via secondary and tertiary air.

$$\eta = \frac{q_{\text{Secondary Air}} + q_{\text{Tertiary Air}} + q_{\text{Dust Out}} - q_{\text{Dust In}}}{q_{\text{Clinker Hot}}}$$

$\eta$: Recuperation Efficiency [%]

$q_{\text{Secondary Air}}$: Specific Heat Secondary Air [kJ/kg clinker]

$q_{\text{Tertiary Air}}$: Specific Heat Tertiary Air [kJ/kg clinker]

$q_{\text{Dust Out}}$: Specific Heat Clinker Dust at Secondary Air Temperature [kJ/kg clinker]

$q_{\text{Dust In}}$: Specific Heat Clinker Dust at Temperature of Clinker from the Kiln (1450 °C) [kJ/kg clinker]

$q_{\text{Clinker Hot}}$: Specific Heat Hot Clinker from the Kiln (1 kg) [kJ/kg clinker]

# Grate Cooler

## Clinker Cooler Normalized Recuperation Efficiency

In order to be able to compare the performances of different coolers by one number, the efficiency is normalized with regard to the amount of air recuperated of **0.8 Nm3/kg clinker** (typical value for a modern kiln system).

$$\eta_{0.8} \cong \eta \cdot \frac{0.744}{1 - EXP\left[-\frac{v}{0.77} * \left(1 + \frac{v}{2.57}\right)\right]}$$

$\eta_{0.8}$ : Normalized recuperation efficiency [%]

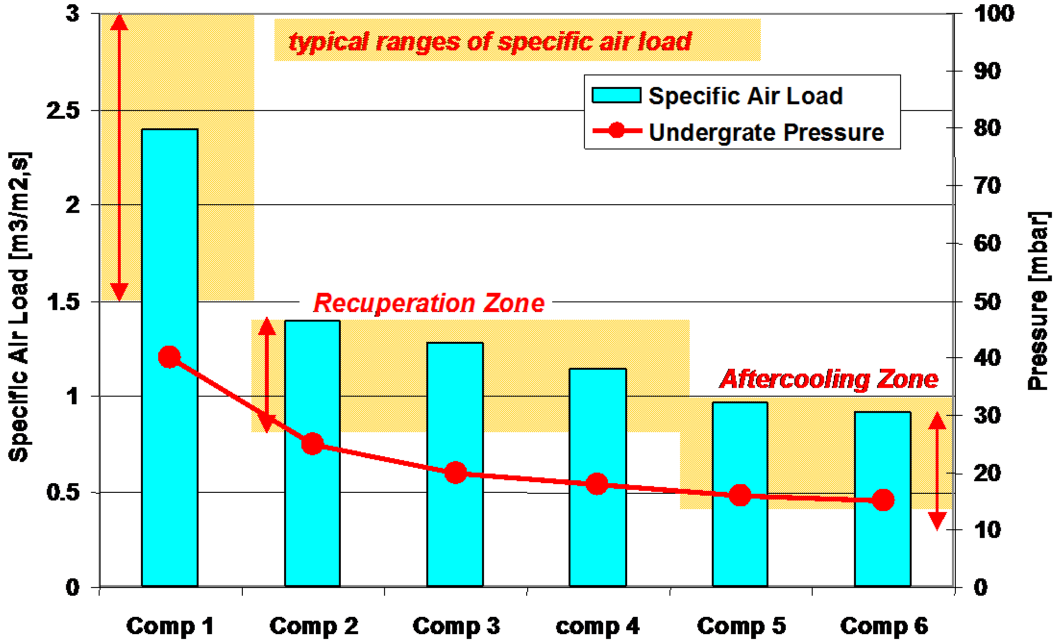
$\eta$ : Recuperation efficiency according to above formula [%]

$v$ : Specific recuperation air volume [Nm3/kg clinker]

# Grate Cooler

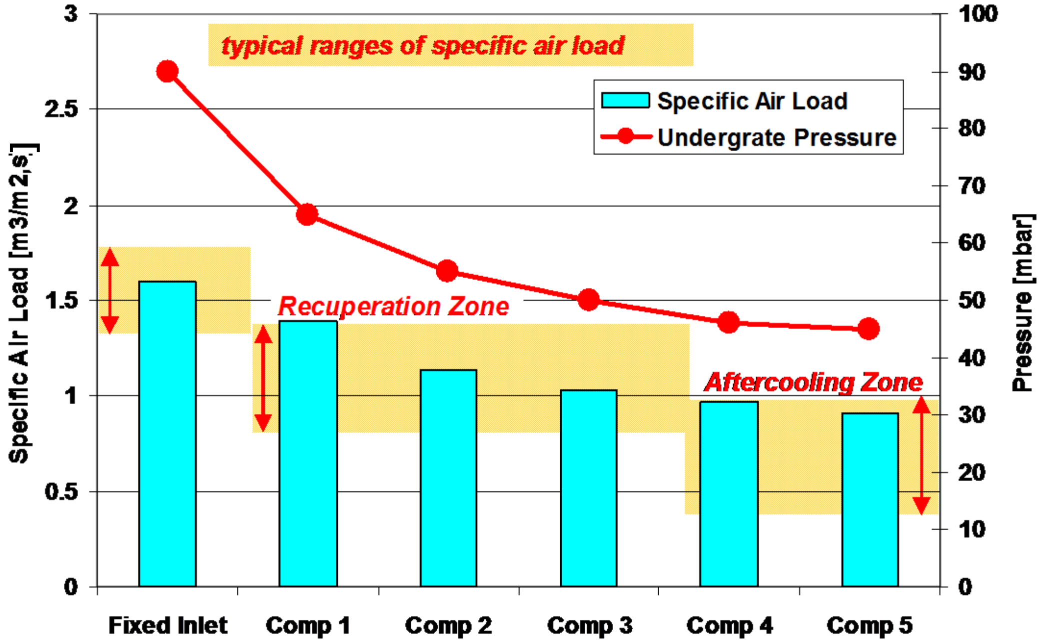
## Grate Cooler Air Distribution for Old Type, Conventional Cooler without Fixed Inlet

The recommended air profile shows a descending pattern from the cooler inlet towards the cooler outlet




## Grate Cooler Air Distribution for Advanced, Modern Cooler with Fixed Inlet

The recommended air profile shows a descending pattern from the cooler inlet towards the cooler outlet



# Grate Cooler

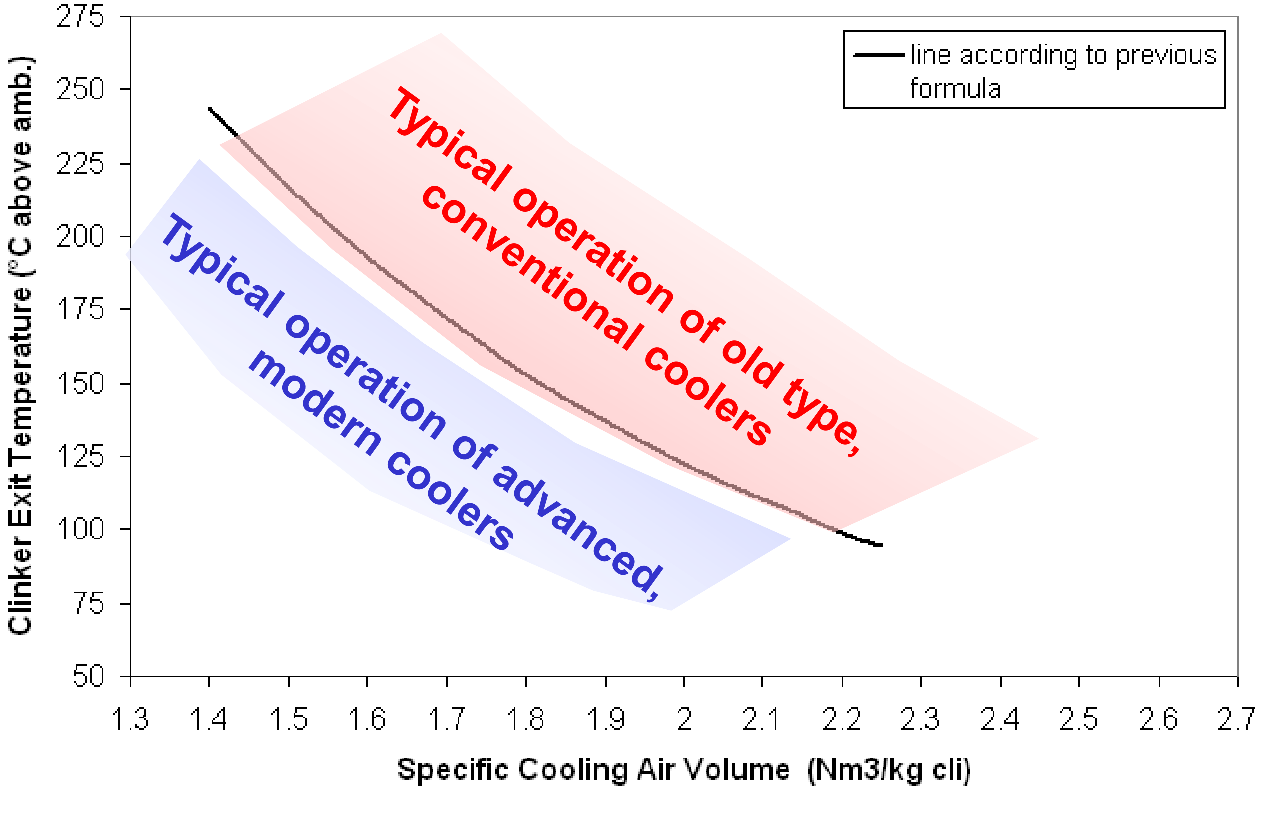
## Clinker Temperature at Cooler Exit

For coolers with moderate efficiency, the achievable clinker temperature at the cooler exit with a given cooling air volume $\mathbf{V_{Air}}$ can be calculated with the following formula. However, this temperature depends strongly on the cooler efficiency. With advanced, modern coolers the temperature is lower compared to the formula; with old type coolers the temperature is higher (see chart below).

$$\frac{T_{Cli,out} - T_{Amb}}{T_{Cli,in} - T_{Amb}} = \exp\left(-\frac{V_{Air}}{0.77}\right)$$

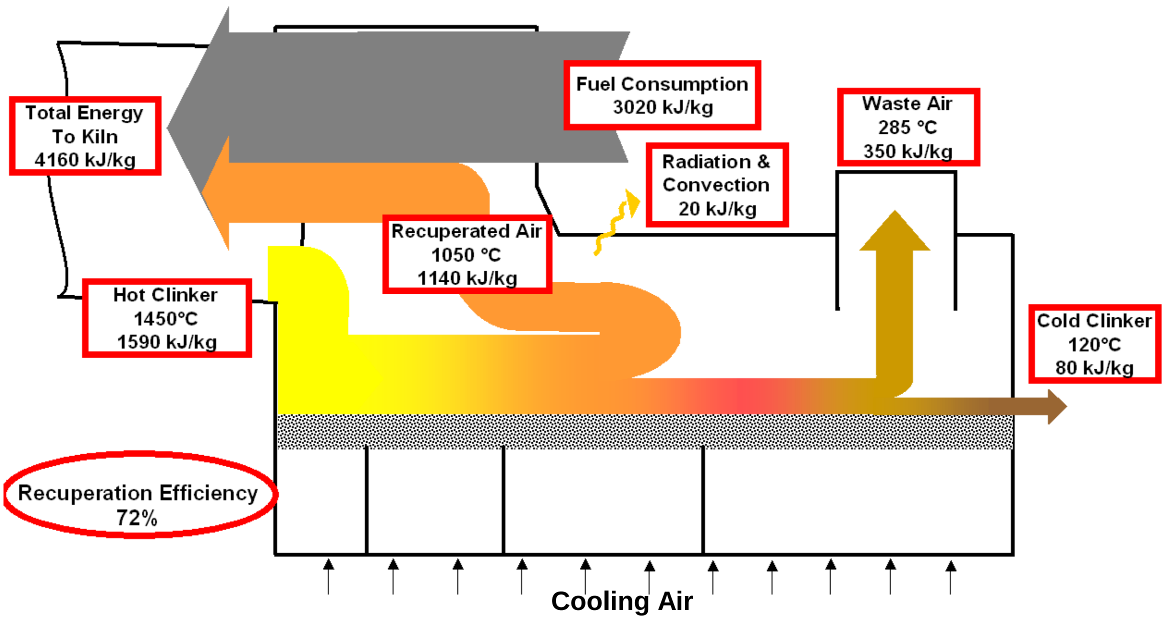
$T_{Cli,out}$ = Temperature of clinker at cooler outlet [°C]
$T_{Cli,\,in}$ = Temperature of clinker at cooler inlet [°C], typically around 1400 °C for grate coolers
$T_{Amb}$ = Ambient temperature [°C]
$V_{Air}$ = Specific cooling air [Nm³/kg cli]

## Clinker End Temperature at Different Cooling Air Flows



# Grate Cooler

## Energy flows in a grate cooler (modern cooler)




## Transport Efficiency of Grate Cooler

The transport efficiency for reciprocating coolers can be calculated as follows:

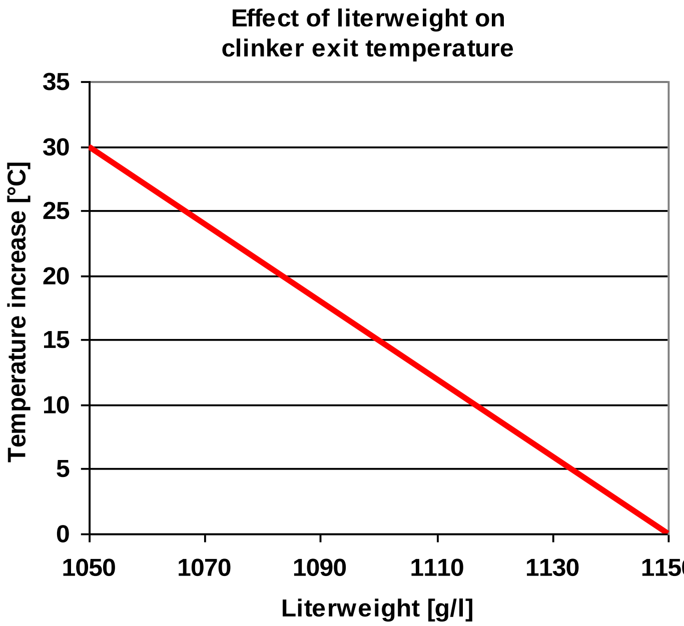
$$\eta_{Transport} = \frac{\mathbf{Production} \cdot \dfrac{1}{\mathbf{Cooler\ Width} \cdot \mathbf{Bed\ Height}}}{\rho_{Cli} \cdot 24 \cdot 3600 \cdot \mathbf{Number\ of\ Strokes} \cdot \dfrac{1}{60} \cdot \mathbf{Stroke\ Length} \cdot \dfrac{1}{1000}}$$

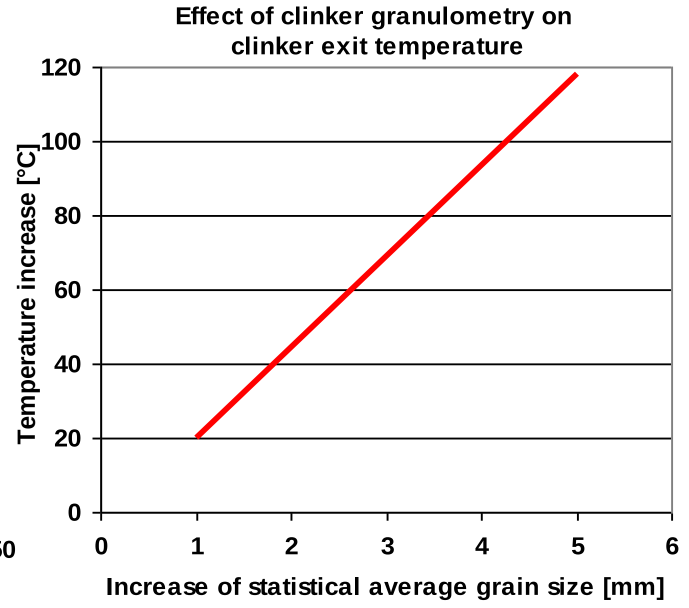
Note: This formula cannot be applied for modern fixed grate coolers such as ETA, Polytrack …

| | |
|---|---|
| $\eta_{Transport}$ | = Transport efficiency of grate [%] |
| Production | = Clinker production [t/d] |
| $\rho_{Cli}$ | = Bulk density of clinker [t/m³], (set to 1.4 t/m³ as a standard) |
| Cooler Width | = Width of grate [m] |
| Stroke Length | = Length of grate stroke [mm] (e.g. 200 mm Polysius, 105 mm IKN) |
| Bed Height | = Height of clinker bed on grate [m] (typically 0.4 - 0.7 m) |
| Grate Speed | = Grate strokes per minute [str/min] (typically 10 -15 str/min) |

# Grate Cooler

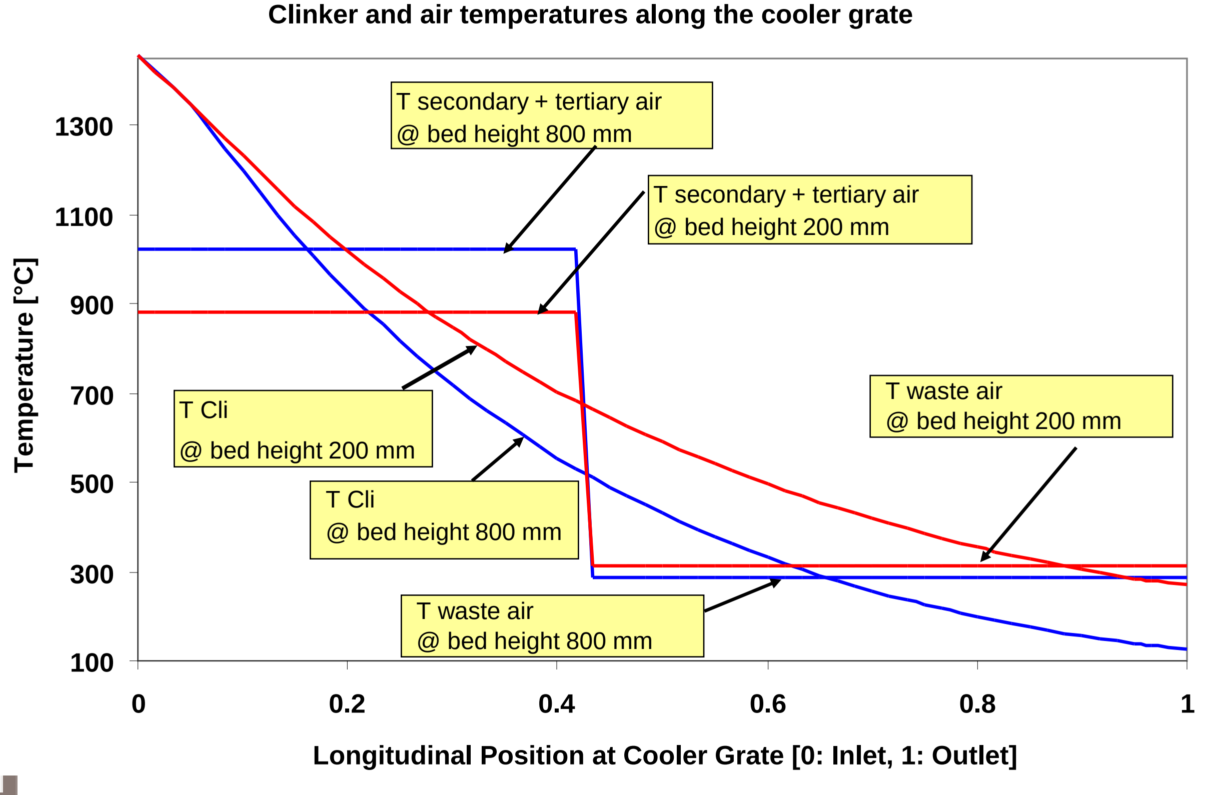
## Effect of Clinker Properties on Cooler Efficiency



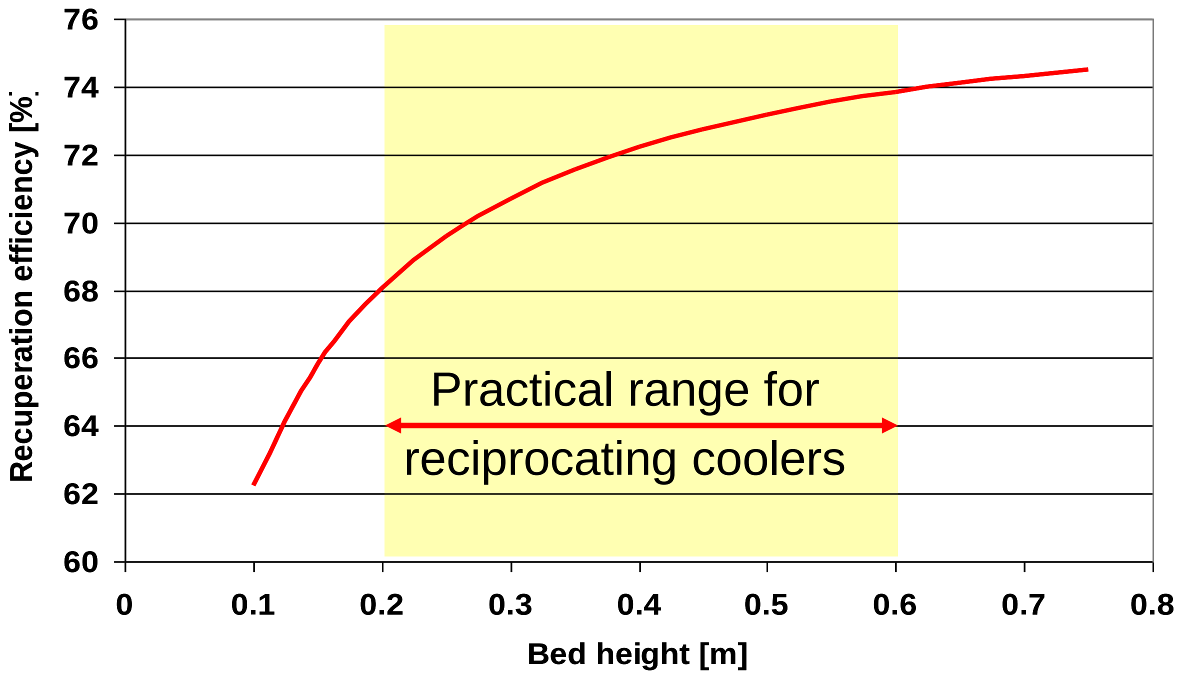

(Information by courtesy of Claudius Peters)

## Effect of Low Clinker Bed on Temperatures

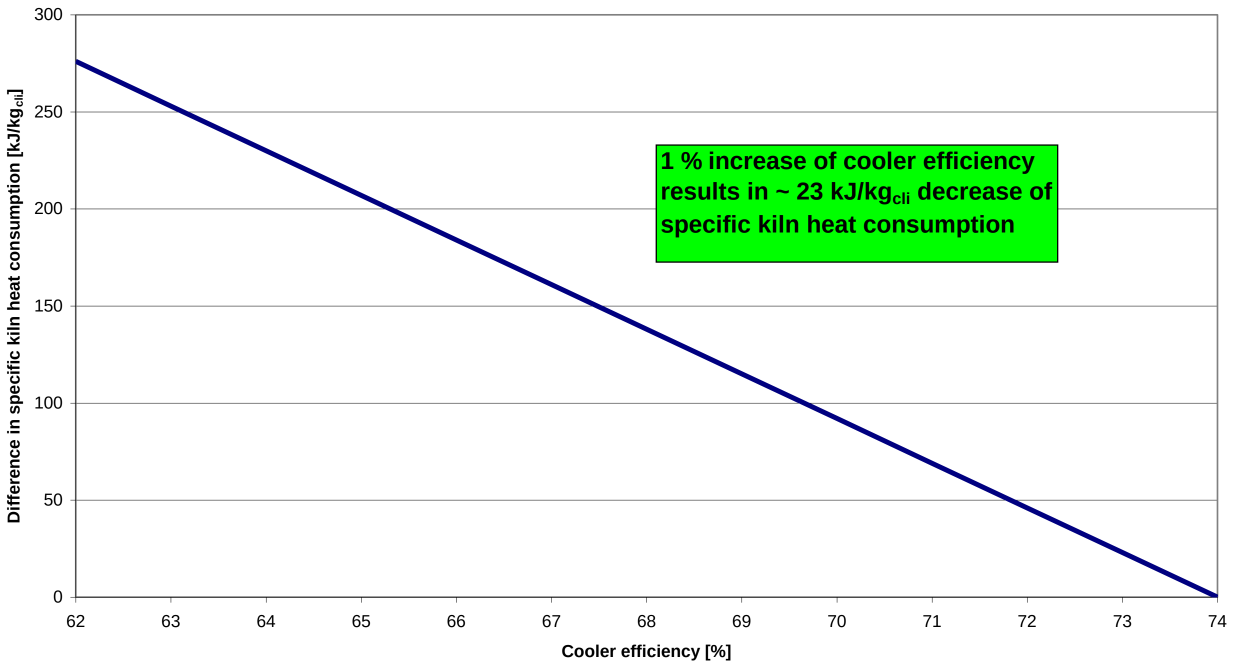


# Grate Cooler

## Effect of Low Clinker Bed on Cooler Efficiency



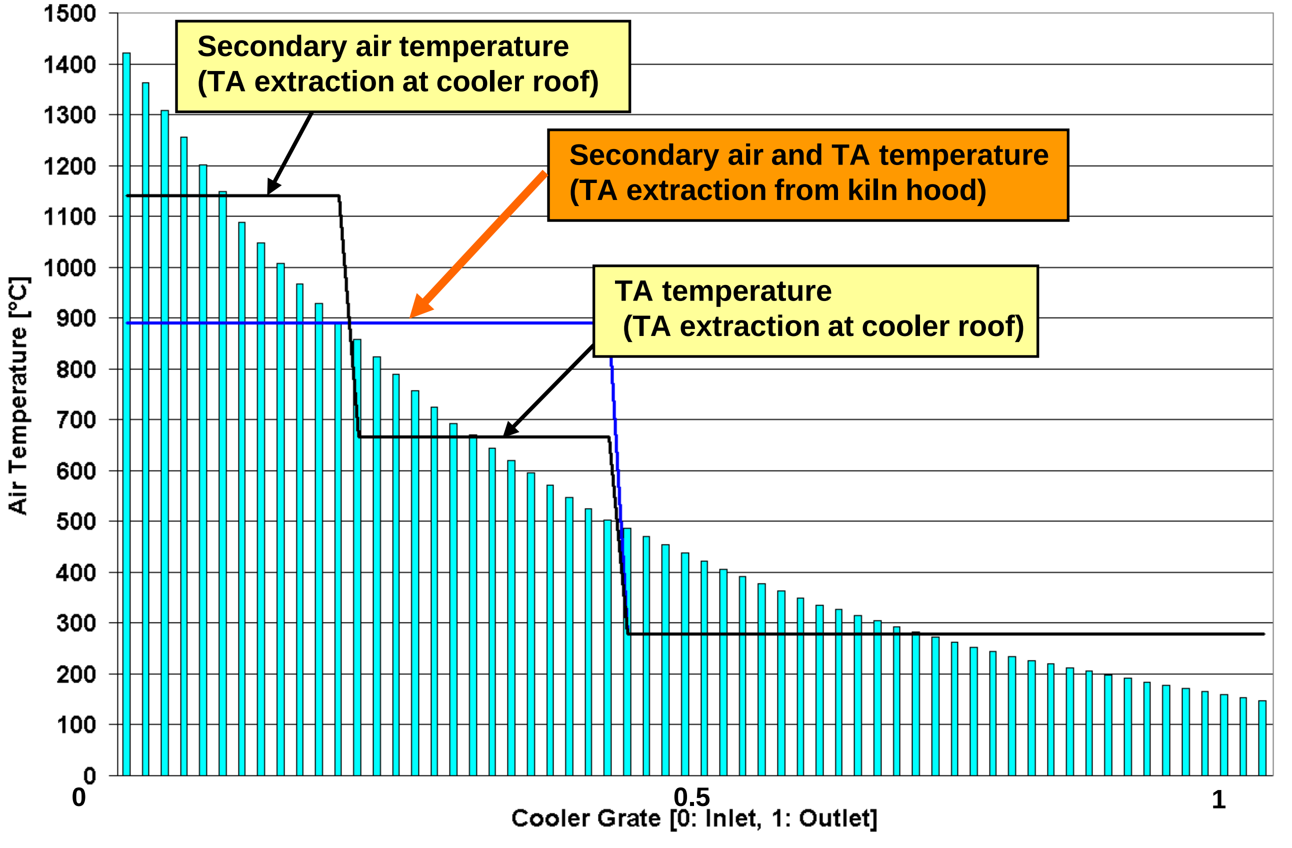

## Effect of Cooler Efficiency on Kiln Heat Consumption



# Grate Cooler

## Tertiary Air Extraction from Kiln Hood vs. Extraction from Cooler Roof

## (typical example with modern cooler)



# Planetary Cooler

## Key Figures

**Specific cooler surface load:** **< 2 t/m² d**

Calculation: Daily clinker production (t/d) divided by total surface area of all cooler tubes ($m^2$)
Note: Use nominal tube length and diameter

**Specific cross section load:** **< 75 t/m² d**

Calculation: Daily clinker production (t/d) divided by total cross section area of all cooler tubes ($m^2$)
Note: Use nominal tube diameter

**Specific volume load:** **< 4.4 t/m³ d**

Calculation: Daily clinker production (t/d) divided by total volume of all cooler tubes ($m^2$)
Note: Use nominal tube length and diameter

**Air velocity through cooler tubes at cooler inlet (close to elbow):** **< 4.5 m/s**

Calculation: Secondary air volume ($m^3/s$) at calculated secondary air temperature (°C) divided by total inner (inside lining) cross section area of all cooler tubes ($m^2$)

**Velocity of air entering to kiln through inlet openings (at elbows):** **< 25 m/s**

Calculation: Secondary air volume ($m^3/s$) at calculated secondary air temperature (°C) divided by total open cross section area of all inlet openings in kiln ($m^2$)

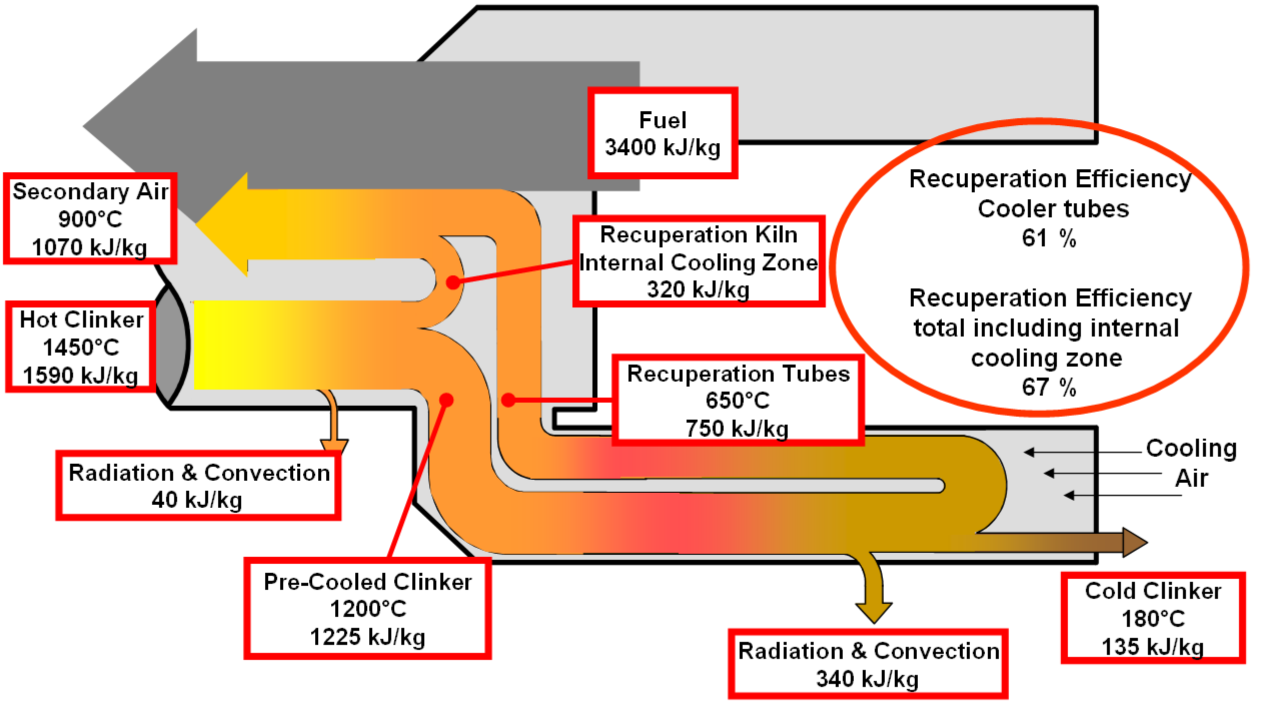
| | | |
|---|---|---|
| **Recuperation efficiency: (normalized)** | **55 – 65 %** | For cooler tube only |
| | **60 – 70 %** | For cooler tube including kiln internal cooling zone |

Calculation: Actual recuperation efficiency normalized to 0.8 $Nm^3/kg$ clinker (equivalent to the normalization for grate coolers).
Note: Efficiency depends on the condition and design of the cooler and its internals and on the design of the kiln internal cooling zone.

| | | |
|---|---|---|
| **Secondary air temperature:** | **~ 730°C** | at 3500 kJ/kg cli |
| | **~ 600°C** | at 5000 kJ/kg cli |
| **Specific cooling air:** | **0,9 Nm3/kg cli** | at 3500 kJ/kg cli |
| | **1,3 Nm3/kg cli** | at 5000 kJ/kg cli |

# Planetary Cooler

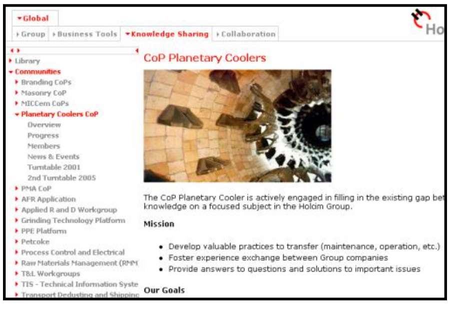
## Energy Flows in a Planetary Cooler




## Information on Holcim Portal

Community of Practice (CoP) Planetary Coolers - Platform for knowledge exchange

**Link:** iShare



# Clinker Granulometry

## Clinker Granulometry

Common Pitfall:

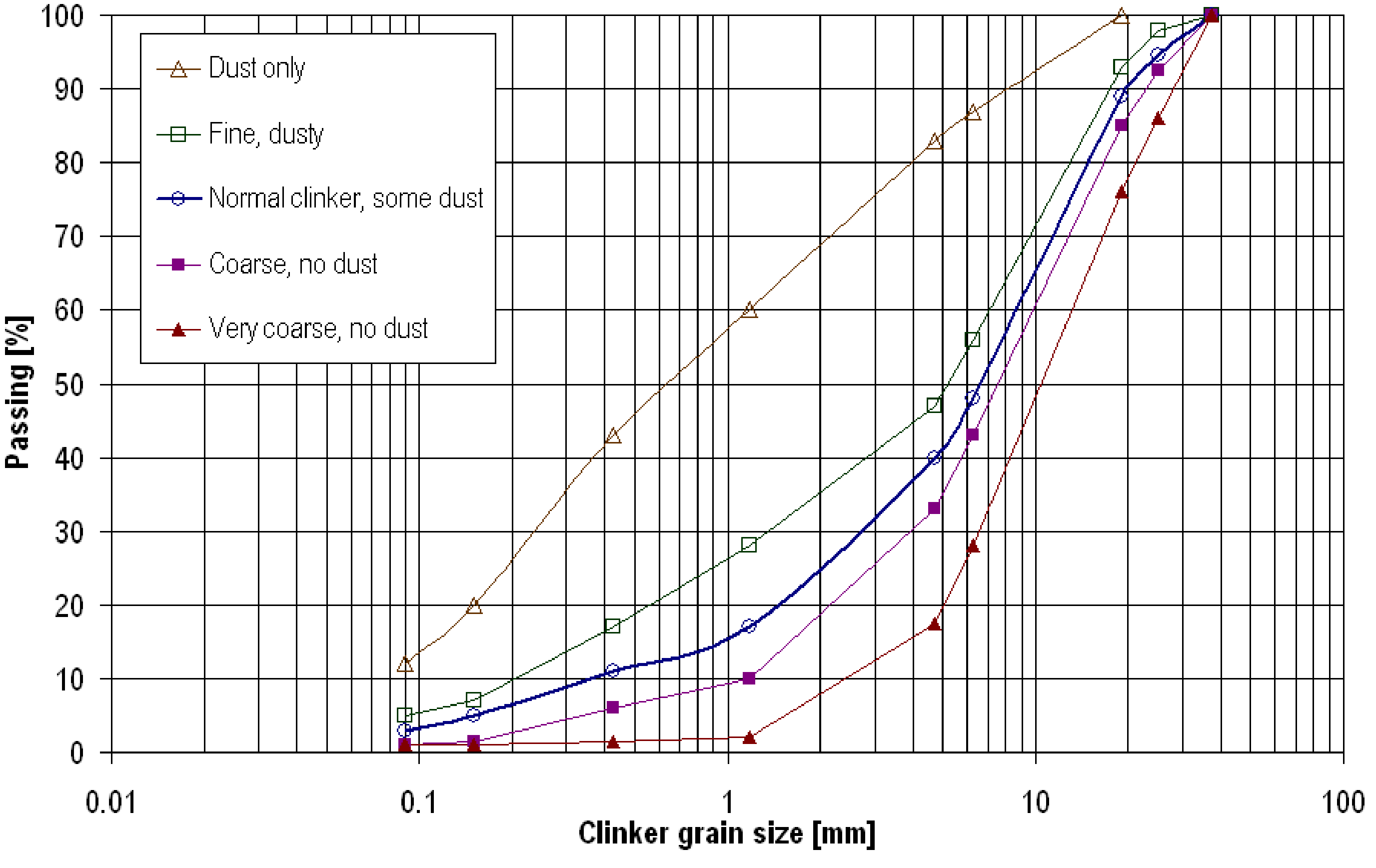
**Sampling is critical** - no sampling from the top of the conveyor (sample not representative because of segregation).

Good sampling points: Transfer points or chutes.

## Guideline for quick check (sieve residue on 1mm)

- **Normal clinker:** **Passing 1mm = 10 – 15%**
- **Fine / very fine clinker:** **Passing 1mm > 25%**

## Guideline for differentiation between fine and coarse clinker



# Suspension Preheater

## Typical Figures

| | | |
|---|---|---|
| **Gas velocities in riser ducts and cyclone dip tubes:** | **10 - 15 m/s** | new installations |
| | **< 20m/s** | existing installations |

Calculation: Kiln gas at operating conditions ($m^3/s$) divided by inner cross section area of riser duct or dip tube ($m^2$). Note: 10 m/s allowed only in case of perfectly working splash boxes

| | | |
|---|---|---|
| **Preheater exit gas temperatures:** | **350 - 380 °C** | 4 stage SP |
| | **310 - 340 °C** | 5 stage SP |
| | **290 - 320 °C** | 6 stage SP |

Typical exit gas temperatures for modern suspension preheater (SP) kilns. For precalciner kilns (PC) exit temperatures are approx. 10°C higher.

| | | |
|---|---|---|
| **Thermal energy consumption [kJ/kg cli]:** | **3'200** | 4 stage SP or PC |
| | **3'100** | 5 stage SP or PC |
| | **3'050** | 6 stage SP or PC |

Guide values for suspension preheater and precalciner kilns at 95% production rate index. Target values in many cases higher mainly due to AFR usage, bypass, Holcim refractory concept and/or lower production.

| | | |
|---|---|---|
| **Oxygen concentration at preheater exit:** | **2.5 - 3.5 % $O_2$ (dry)** | Without AFR |
| | **4.0 - 4.5 % $O_2$ (dry)** | With AFR |

For preheaters without airlift feeding, the airlift may add up to 1% $O_2$

| | | |
|---|---|---|
| **Oxygen concentration at kiln inlet:** | **2 - 3 % $O_2$ (dry)** | Without AFR |
| | **up to 4.5 % $O_2$ (dry)** | With AFR |

For suspension preheater kilns, in case of secondary firing higher $O_2$ values may be required.

| | | |
|---|---|---|
| **Pressure drop across cyclone stage:** | **9 - 14 mbar** | Top stage |
| | **7 - 10 mbar** | Lower stages |

| | | |
|---|---|---|
| **Typical pressure drop over preheater:** | **30 - 45 mbar** | 4 stage SP |
| | **37 - 55 mbar** | 5 stage SP |
| | **44 - 65 mbar** | 6 stage SP |

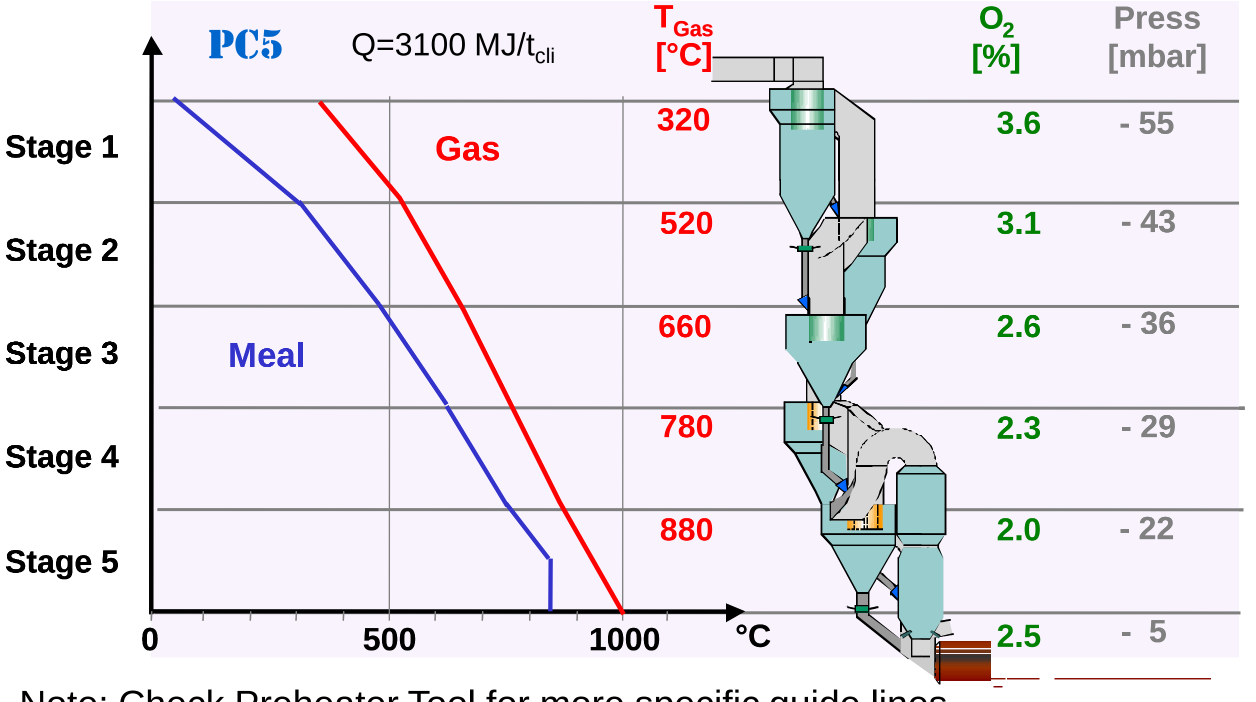
Pressure drop for preheater from inlet to bottom cyclone to outlet of top cyclone. Pressure drop of kiln inlet and calciner NOT included.

| | | |
|---|---|---|
| **Typical separation efficiency of top stage cyclone:** | **90 – 93 %** | (up to 95% for new cyclones and optimum conditions) |

Calculation: Dust loss weigh out relative to the material feed to the top stage.

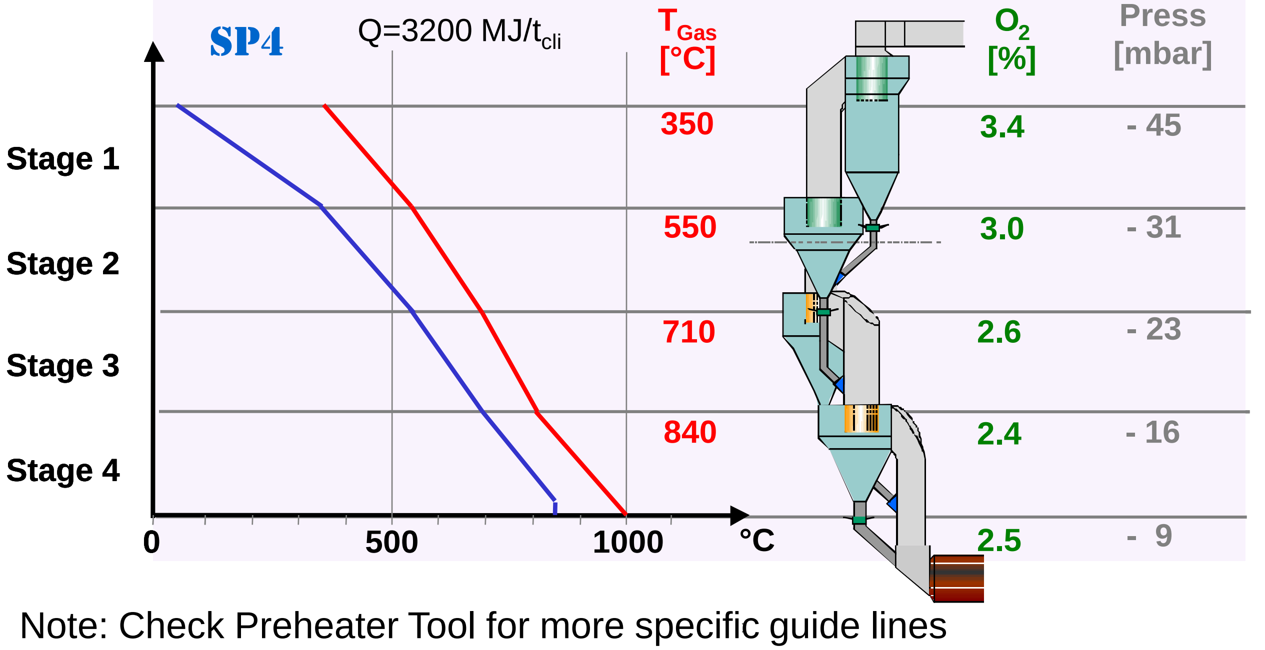
# Suspension Preheater

## Typical Indicators of a 5 Stage Preheater with Precalciner




Note: Check Preheater Tool for more specific guide lines

## Typical Indicators of a 4 Stage Preheater without Precalciner



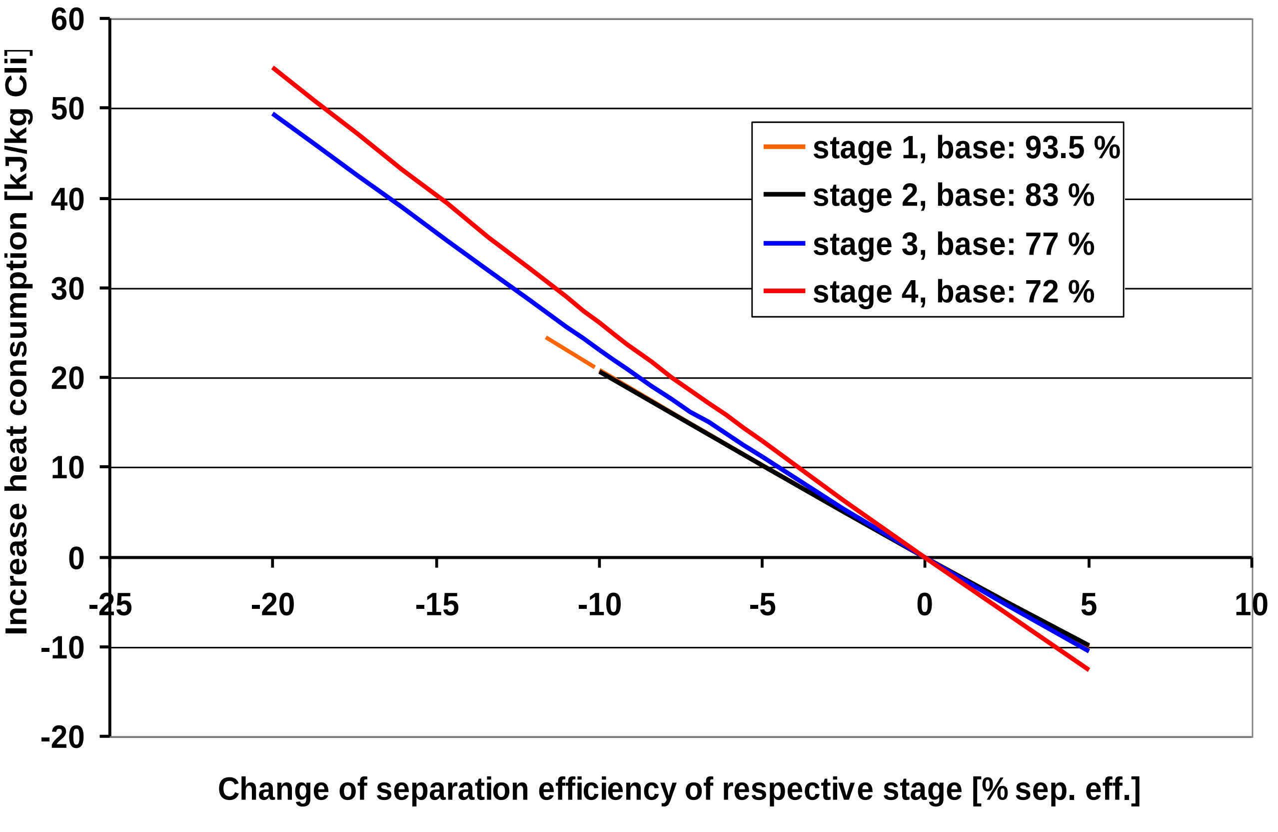

Note: Check Preheater Tool for more specific guide lines

# Suspension Preheater

## Effect of Number of Stages

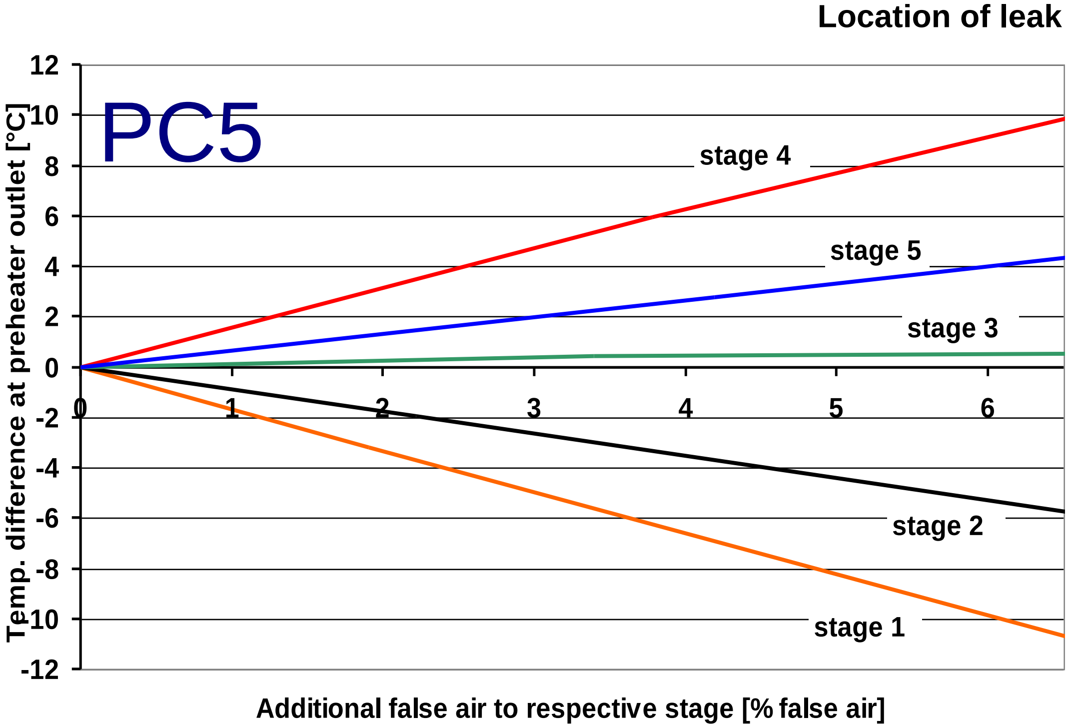
| Control Parameter | units | 4 ➔ 5 stages | 5 ➔ 6 stages |
|---|---|---|---|
| Heat consumption | kJ/kg cli | -80 | -50 |
| Exhaust gas temp | °C | -40 | -20 |
| Exhaus gas flow | Nm3/kg cli | -0.03 | -0.015 |
| SP exit pressure | mbar | + 5 to 8 | + 5 to 8 |
| Drying capacity in raw mill | % H2O | -1.5 | -1.0 |

## Effect of Reduced Cyclone Separation Efficiency

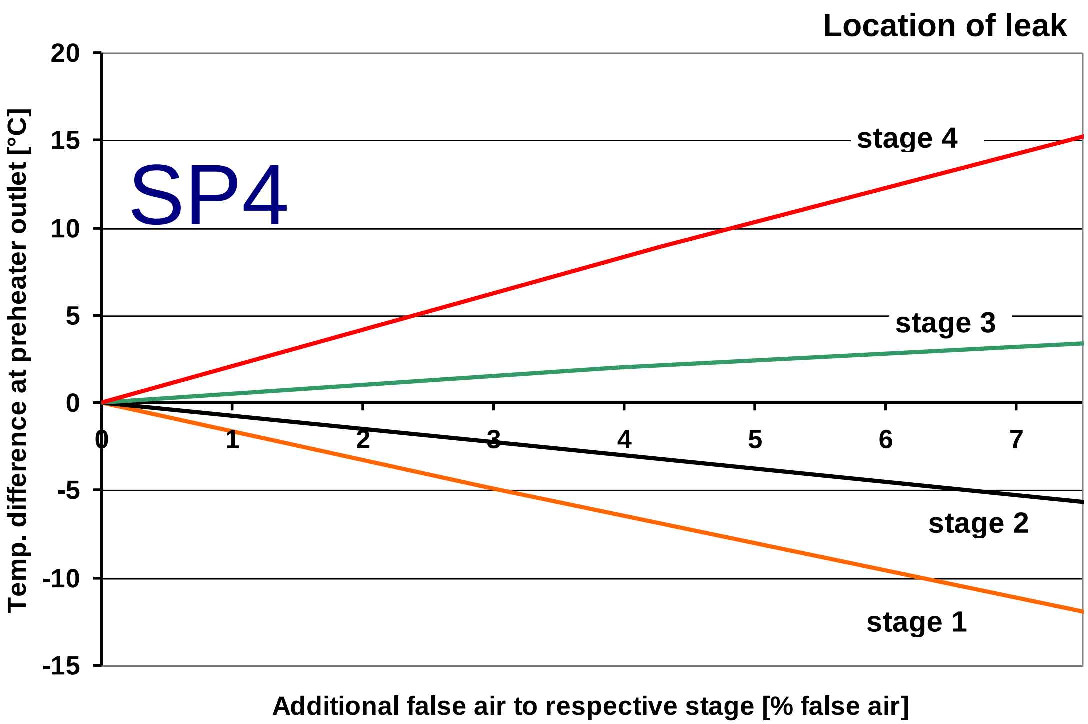


# Suspension Preheater

## Effect of false air on preheater outlet temperature

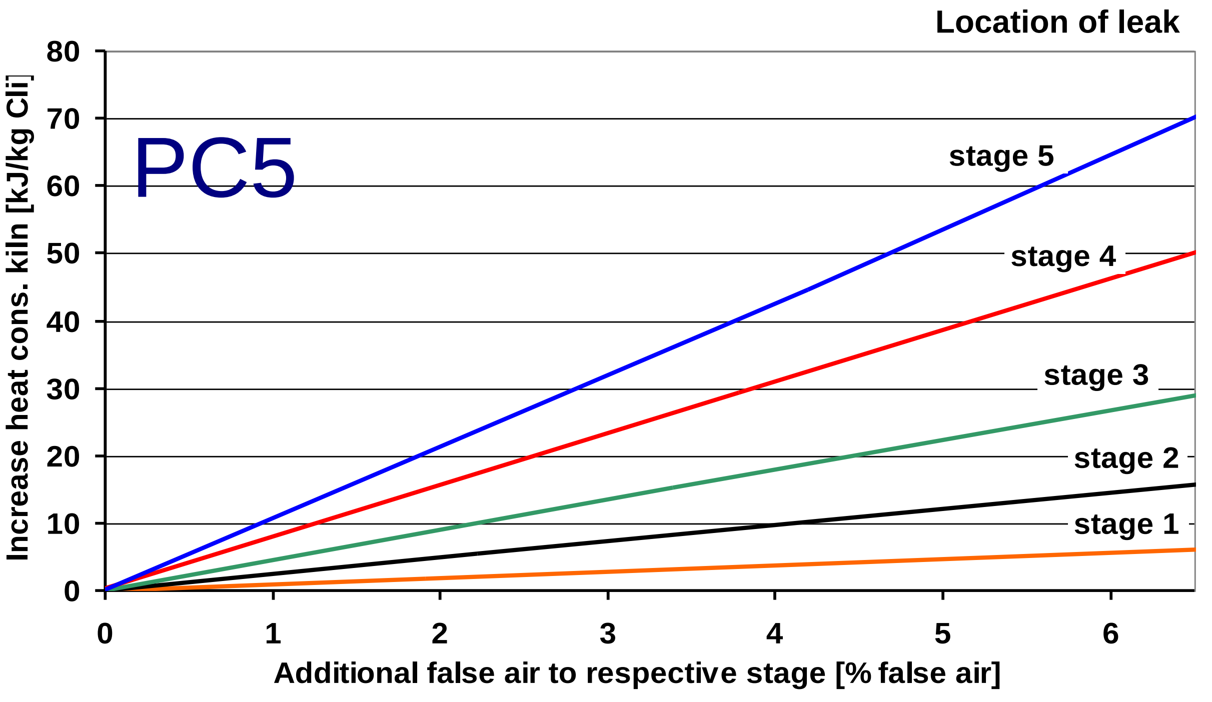



## Effect of false air on preheater outlet temperature

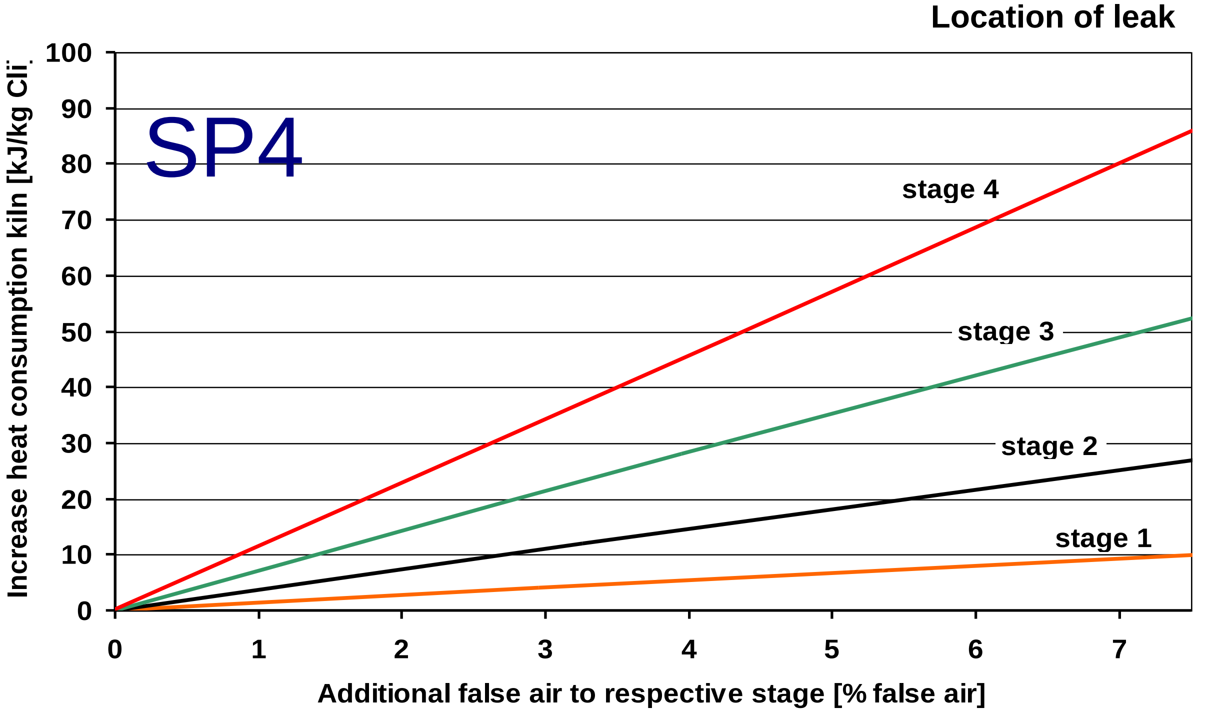


# Suspension Preheater

## Effect of False Air in Preheater on Heat Consumption




## Effect of False Air in Preheater on Heat Consumption



# Precalciner

## Key Figures

**Gas residence time in precalciner (inline):** **5 Seconds** gas residence time at least for new installations (increased AFR use). Existing kilns with < 5 seconds residence time have reduced AFR potential.

Calculation: Volume of precalciner inside lining until inlet of bottom stage cyclone ($m^3$) divided by gas volume flow through precalciner ($m^3/s$) at the calciner exit temperature and pressure. The gas volume at the calciner exit (including all the $CO_2$ released in the calciner) is used. This leads to a smaller retention time number (conservative calculation).

**Gas velocity at calciner orifice:**

| | | |
|---|---|---|
| | **> 25 m/s** | without coarse AFR in PC |
| | **35 – 50 m/s** | with coarse AFR in PC (depending on particle size of AFR) |

Note: At normal fuel split calciner / kiln. Sufficient gas velocity to prevent falling through of meal and solid fuels (e.g. AFR) to kiln inlet.

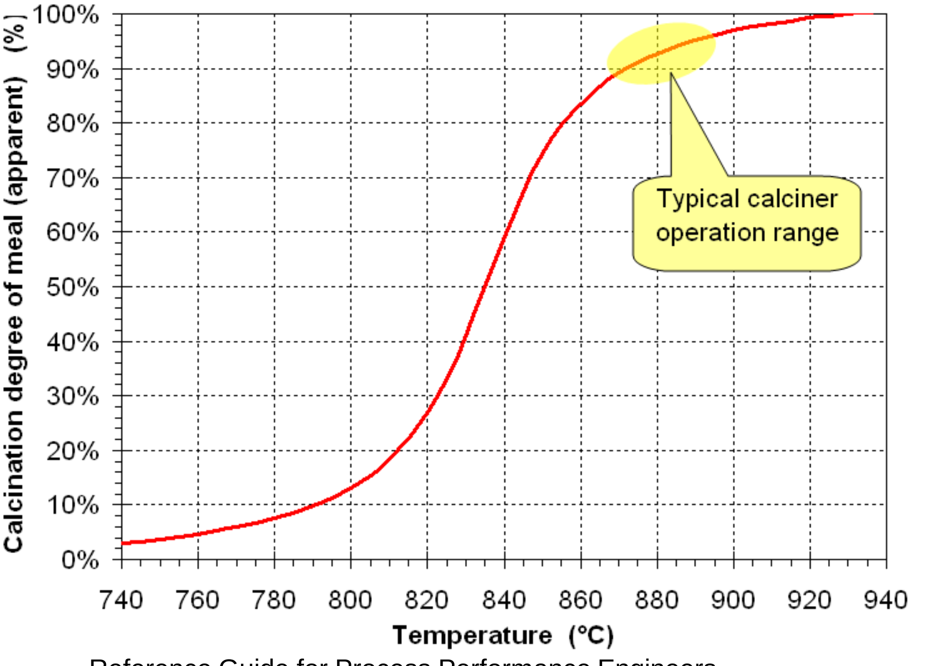
**Air velocity in Tertiary air duct:**

| | | |
|---|---|---|
| | **> 30 m/s** | new installation |
| | **> 25 m/s** | existing installation |

**Fuel ratio :**

| | | |
|---|---|---|
| | **60 - 70%** | for 2-3 stage PC kiln |
| | **55 – 65%** | for ≥ 4 stage PC kiln |

**Typical calcination curve:**



# Precalciner

$$\text{Apparent calcination degree of hot meal [\%]} = \left\{1 - \frac{LOI_{hot\ meal} \cdot (100 - LOI_{feed})}{LOI_{feed} \cdot (100 - LOI_{hot\ meal})}\right\} \cdot 100$$

or (transformation of formula above):

$$\text{Apparent calcination degree of hot meal [\%]} = \left\{\frac{LOI_{feed} - LOI_{hotmeal}}{LOI_{feed} \cdot (1 - LOI_{hotmeal} / 100)}\right\} \cdot 100$$

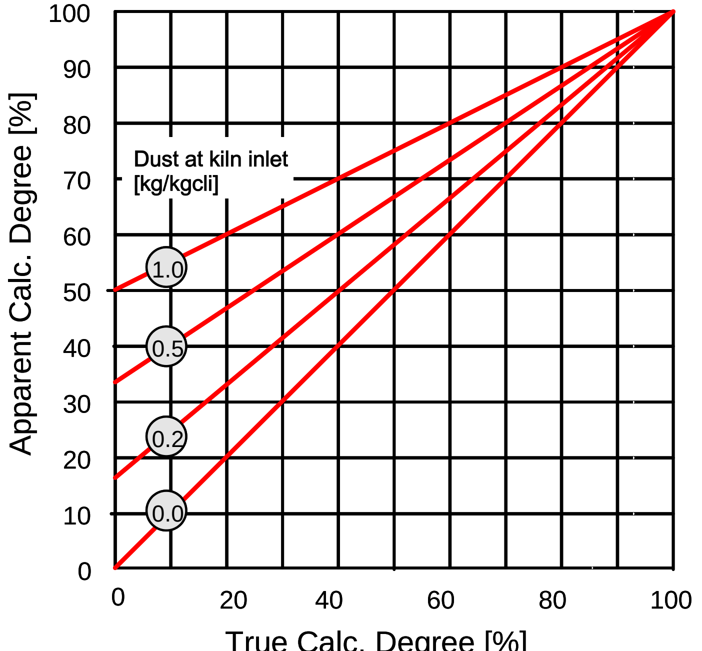
$LOI_{feed}$: Loss on ignition of kiln feed (%)
$LOI_{hot\ meal}$: Loss on ignition of hot meal (%)

| | | |
|---|---|---|
| **Calcination degree of the hot meal (apparent):** | **88 - 94 %*** | for PC systems |
| | **30 - 60 %** | for PH systems with secondary firing |
| | **10 - 40 %** | for PH systems without secondary firing |

*Set-point of circulation degree depending on required kiln stability and tolerable level of temperature peaks (high calcination degree → more stable kiln operation; low calcination degree → less overshooting of calciner temperature).
In case of high TSR in calciner: Calcination degree in lower range to limit temperature peeks.
In case of stable kiln without AFR: Calcination degree up to 94-95% to maximize kiln production.

## Apparent and True Calcination Degree

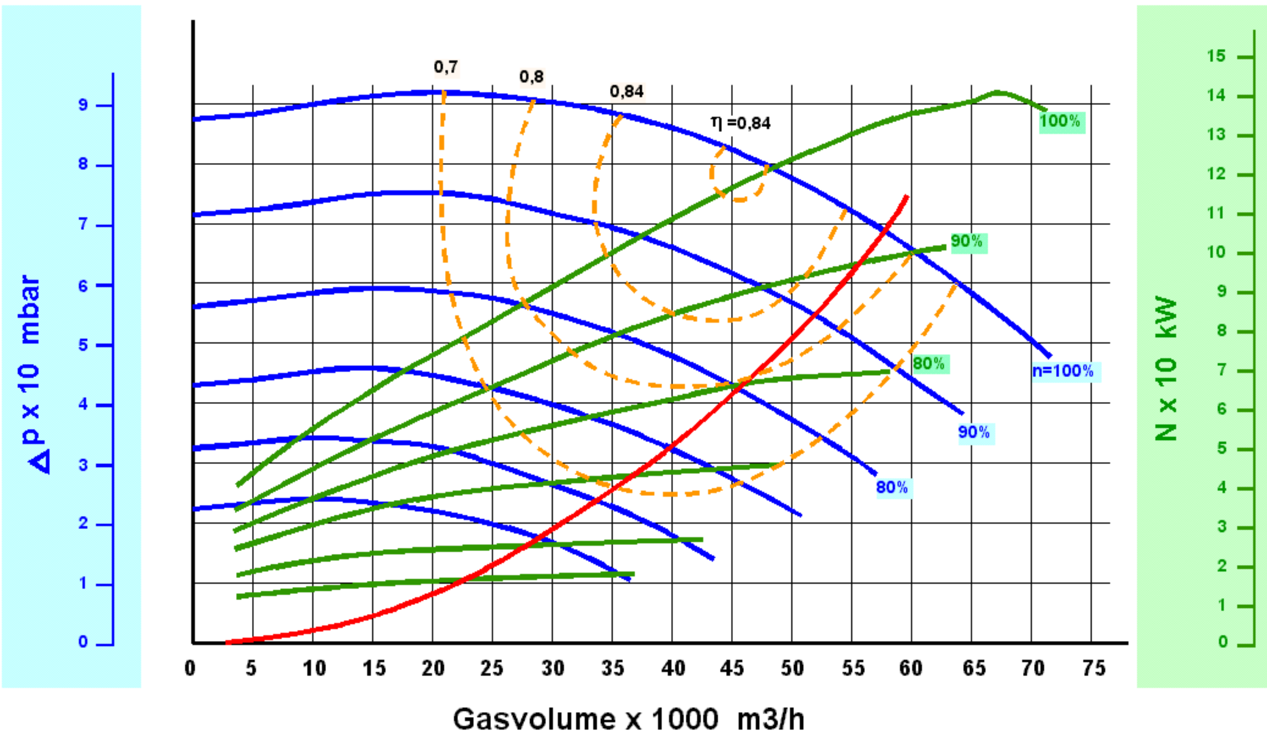
Note: With high dust cycles at kiln inlet the measured apparent decarbonation degree can be much higher than the true decarbonation degree.



# Process Fans

## Typical Characteristic Fan Curve (for VSD Fan)

Pressure increase, power consumption and efficiency in function of gas flow at different fan speed.




System resistance curve

Differential pressure in function of gas flow at different fan speed

Absorbed power in function of gas flow at different fan speed

Fan efficiency

# Process Fans

## Power Requirement at Fan Shaft (dust laden gas)

The required mechanical power can be calculated as:

$$P = \frac{\Delta p \cdot \dot{V}}{10 \cdot \eta} \cdot \left(1 + \frac{C_{dust}}{\rho_{gas}}\right)$$

P = Power requirement at fan shaft (kW)
$\Delta p$: = Static pressure increase across the fan (mbar)
V = Volume flow at fan inlet ($m^3$/sec)
$\eta$ = Fan efficiency (%)
$C_{dust}$ = Dust concentration in the gas stream ($kg/m^3$)
$\rho_{gas}$ = Gas density ($kg/m^3$)

## Total Pressure Increase (rough estimation)

The total pressure increase **p** of a fan can be calculated as:

$$p = \frac{0.6 \cdot \gamma \cdot n^2 \cdot d^2 \cdot \pi^2}{3600}$$

p = Pressure increase (Pa)
$\gamma$ = Gas density ($kg/m^3$)
n = Fan speed (rpm)
d = Impeller diameter (m)

# Process Fans

## Influence of Fan Speed on Volume-flow, Static Pressure and Power Requirement

The volume flow depends on the fan speed as:

$$V_2 = \frac{n_2}{n_1} \cdot V_1$$

$V_1$, $V_2$ = Quantity of gas at speed 1 and speed 2 ($m^3/s$)
$n_1$, $n_2$ = Fan speed 1 and fan speed 2 (rpm)

The static pressure depends on the fan speed as:

$$p_{st,2} = \left(\frac{n_2}{n_1}\right)^2 \cdot p_{st,1}$$

$p_{st,1}$, $p_{st,2}$ = Static pressure at speed 1 and speed 2 (mbar)
$n_1$, $n_2$ = Fan speed 1 and fan speed 2 (rpm)

The power requirement at shaft depends on the fan speed as:

$$P_2 = \left(\frac{n_2}{n_1}\right)^3 \cdot P_1$$

$P_1$, $P_2$ = Power requirement at speed 1 and speed 2 (kW)
$n_1$, $n_2$ = Fan speed 1 and fan speed 2 (rpm)

# Main Burner

## Burner Key Figures (Multi-channel Burner)

| | | |
|---|---|---|
| **Typical specific burner impulsion*:** | **8 – 11 N/MW** | Petcoke / Anthracite |
| | **6 – 8 N/MW** | Coal |
| | **4 – 5 N/MW** | Gas (without Natural Gas) |

* excluding transport air and fuel mass flow
calculation spreadsheet "Burner Check" → Holcim Portal: iShare

**Primary air fan pressure:**

In general high primary air pressures are preferred to reduce the amount of primary air. But the electrical power consumption and requested impulsion needs be considered. Typical range for fans is 250 – 350 mbar. For higher pressures blowers have to be provided.

**Primary air percentage (**typical maximum installed percentage of minimum combustion air):

| | |
|---|---|
| **with fan** | **13 – 15 %** |
| **with blower** | **9 – 14 %** |

**Fuel injection at burner tip:**
The velocity defines the ignition distance of the fuel and is defined by their Volatiles (VM).
A black plume of **0.2m – 0.4m** is desirable to avoid damage of the burner tip.

| | |
|---|---|
| **20 - 25 m/s** | Petcoke, Anthracite |
| **~ 30 m/s** | Coal |
| **30 - 40 m/s** | Lignite / brown coal |
| **30 - 45 m/s** | Solid AFR |

Calculation: Volume of transport air [$m^3/s$] at burner tip (pressure of kiln hood and T= 50°C) divided by the area of the solid fuel injection channel at the burner tip.

## Procedure for Specifying a new Burner

**Step 1:** **Definition of 'Design Thermal Power' of burner:**
- Design Thermal Power = BDP * Real heat cons. * Real main burner fuel ratio

**Step 2:** **Specification: Cleary specify in tender documents and supplier discussions:**
- Design thermal Power [MW]
- Primary air fan flow rate [m3/h] at defined inlet conditions T and p]
- Primary air fan pressure [mbar] + 10% reserve - Plant altitude

# Main Burner

## Burner Adjustment

**Measurements to assess the effect of burner adjustments:**

Changes and effects should be documented systematically.
Check-list for kiln parameters: "Combustion Check" → Holcim iShare
Parameters: Kiln shell temperature profile, hot meal SO3 and LOI, clinker quality (CaOfree, SO3 in cli, Microscopy), O2/CO/NOx at kiln inlet, granulometry of clinker, color of broken clinker cores, Magotteaux test for reducing conditions, back-end temperature.

**Timeframe:**

Wait at least 1 day after each change for stabilization of coating in kiln

**Burner position on kiln:**

Position burner tip (hot kiln) between +0.5m inside and -0.4m outside of rotary kiln; depends on kiln-L/D and temperature profile;
Note: In kilns with planetary coolers, the position of the burner is typically around one kiln diameter inside from the elbow inlet openings to avoid damage and blockage by too hot clinker.

| | |
|---|---|
| Retraction of burner*: | - Shortening of flame<br>- Increase risk of snowman formation<br>- Risk of increase of nose ring temperature |
| Pushing burner into the kiln: | - Lengthening of flame<br>- Risk of increase of back-end temperature<br>- Higher tendency for build-ups on burner pipe („Rhino“) |

* Note: Planetary cooler kilns need longer internal cooling zone

**Alignment of burner position:**

Parallel to kiln axis, in centre of kiln cross-section. Check burner centered by adjusting to same distance from refractory at different points of circumference. You can use a long rod in combination with meter tape.
Alignment can be checked with an inclinometer or by placing a laser in the burner (e.g. AFR channel) and detection of the laser point upwards of the kiln (target is center of kiln inlet section).

**Air channel adjustment:**

Goal: Hot, short and compact flame. No impingement of the flame on refractory and material bed.

**Axial Air**: Ensures mixing of fuel with secondary air. More Axial air/ Higher Pressure will improve mixing → shorter flame

**Radial Air:** More radial air will widen and shorten the flame. Also risk of refractory damage if flame is too wide. Too wide flame with different fuels (high and low reactive) will create 2 flames and elongate the total flame length (similar effect with reduced axial air).

**Central Air:** Stabilization of flame, cooling of central channel and avoiding of build up formation on burner tip.

# Main Burner

## Thermal Power from kiln production and Heat Consumption:

$$P_{thermal} = \frac{Production \cdot q}{24 \cdot 3600} \cdot \%_{Main\ firing}$$

$P_{thermal}$ = Thermal burner power [MW]
Production = Actual clinker production [t/d]
q = Specific heat consumption [kJ/kg$_{cli}$]
$\%_{Main\ firing}$ = Percentage of heat at main burner

## Thermal Power from Fuels (alternative calculation):

$$P_{thermal} = \frac{\sum_{Fuel=1}^{n} (M_{Fuel} \cdot NCV_{Fuel})}{3600}$$

$P_{thermal}$ = Thermal burner power [MW]
$M_{fuel}$ = Fuel mass flow [t/h or Nm$^3$/h], for the fuels 1 to n
$NCV_{Fuel}$ = Net calorific value of the fuel [kJ/kg fuel or MJ/Nm$^3$ fuel] for fuels 1 to n

## Specific Burner Impulsion:

$$G = \frac{\sum_{i} (m_i \cdot v_i)}{P_{thermal}}$$

G = Specific impulsion [N/MW]
$m_i$ = Mass flow of air flow i [kg/s]
$v_i$ = Velocity of air flow i [m/s] calculated with Bernoulli equation (see below)
$P_{thermal}$ = Thermal burner power [MW]

$$v_i \approx \sqrt{\frac{2 \cdot p_{tip,i}}{\rho}}$$

(only approximation)
(NOT for coal or AF channels)

$v_i$ = Velocity at burner tip [m/s]
$P_{tip,i}$ = Pressure at burner tip = approx. pressure before burner -5% [Pa]
$\rho$ = Air density at burner tip at 50°C [kg/m$^3$] (see below)

$$\rho = 1.29 \frac{kg}{m^3} \cdot \frac{P_A}{1013\,mbar} \cdot \frac{273.15\,K}{T_A + 273.15\,K}$$

$P_A$ = Pressure in kiln hood + Ambient Pressure [mbar]
$T_A$ = defined: 50°C [K]

## Approximation of Burner Impulsion:

$$G \approx \frac{PA \cdot v}{300}$$

G = Specific axial impulsion [N/MW]
PA = Primary air ratio [%]
v = Velocity of primary air calculated with Bernoulli equation [m/s]

# Coal and Petcoke: Fineness, Dosing, Transport

## Coal and Petcoke Fineness

| | | |
|---|---|---|
| **Coal:** | **R90<br>R200** | **μm ≤ 0.5 * (% volatiles)<br>μm ≤ 2%** |
| **Petcoke:** | **R90<br>R200** | **μm ≤ 5%, better ≤ 3%<br>μm ≤ 1%** |
| **Anthracite:** | **R90<br>R200** | **μm ≤ 4%, better ≤ 2%<br>μm ≤ 0.5%** |

**Fuel mix:**

$$\text{Residue on } 90\ \mu\text{m} \leq \frac{(\%Coal*0.5*VM)+(\%Petcoke*5)}{100}$$

Example Coal:
Coal with 35% volatiles results in R90μm of 0.5 * 35% = 17.5% R90μm
Example Fuel Mix:
20% coal, 80% petcoke (mass fraction); coal with 35% volatiles.
R90μm upper limit is → [(20*0.5*35) + (80*5)]/100 = 7.5%

**Uniformity of Fineness**: **CoV (R90μ) < 5%**

## Fine Coal Dosing (Details ref to Standard Design Criteria)

| | | |
|---|---|---|
| **Short term fluctuations** | **< ± 1 %** | **within 10s average** |
| **Accuracy (long term)** | **< ± 0.5 %** | **based on set point** |

## Pneumatic Transport

A reduced fuel load enhances the ignition but leads to higher Nox. The shown fuel loads are depending on the fuel volatiles.

| | | | |
|---|---|---|---|
| **Solid fuel load in transport duct:** | **5 - 7 kg/m³** | Lignite, Coal | (VM > 12%) |
| | **3 - 5 kg/m³** | Petcoke | (VM 8-12 %) |
| | **1.5-2 kg/m³** | Anthracite | (VM < 8%) |
| | **2 - 4 kg/m³** | Solid AFR | |

Calculation: Feed rate of solid fuel [kg/s] divided by the transport air flow rate [m³/s]

**Transport velocity:** **28 - 35 m/s (>24 m/s at feeder)**
Calculation: Volume flow of transport air [m³/s] divided by the cross sectional area of the transport duct [m²]

**Transport line:**

- Length: as short as possible **max 80 m**
- Only horizontal and vertical section (no inclining or declining sections)
- Elbow design: Diversion pots preferred over bends
  (Except: First directional change after the dosing should be a normal bend)
- Performance check: Pressure fluctuation near burner **< 5 mbar** and < 10% of average
  (see details in pressure fluctuation tool)

# Petcoke Guidelines (1/3)

**What is different to coal?**

Grinding: Higher fineness (less volatiles) affects mill capacity (different grindability)
Determine mill output by trial (HGI can be misleading, greasing effect)

Burning: Low ash and high CV
Delayed ignition (low reactivity)
High sulfur causes more plugging (kiln inlet, preheater)
Stable and controlled kiln process necessary to minimize sulfur cycles

Clinker quality:More $SO_3$ in clinker (better early strength, reduced gypsum addition)

**What are the limitations ?**

On SP/PC kilns, 2.5% $SO_3$ input and 0.4 A/S have been achieved through an aggressive approach. However, certain factors act against high sulfur incorporation e.g. lump fuel (AFR) or less alkali.

For a first “conservative” approach, go for the $SO_3$ in clinker < 1.5%, and Molar A/S > 0.8

**Petcoke supply:**

Choose quality that fits into the given restrictions for sulfur input and grinding capacity. A more aggressive approach towards petcoke (6-7% S, <40 HGI) provides higher savings.

**Raw coal/petcoke preparation**:

Controlled mixing from two feed hoppers or preblending

**Kiln feed Burnability**:

Good burnability helps (if there is a low-cost possibility to improve it). Mineralizers (F) help to incorporate $SO_3$. However mineralizers so far have been used with simultaneous increase of LSF to improve the clinker quality. Experience at constant LSF is rare.

Assessment methods: Holcim Burnability Model (by HTEC/CM-QPC)

Combinability Temperature (guide value for 100% high sulfur petcoke ) 1450°C, max. 1500°C)

$$CT = 436 + 21 \cdot AIR_{90\mu_{KF}} + 10 \cdot LSF_{cli} + 3 \cdot R_{150\mu_{KF}} + 32 \cdot AR_{cli} - 250 \cdot F_{cli} - 20 \cdot SO_{3_{cli}}$$

| | |
|---|---|
| CT | Combinability temperature, °C |
| $AIR_{90\mu KF}$ | Acid insoluble residue on 90µ of kiln feed, % |
| $LSF_{cli}$ | LSF of clinker, - |
| $R_{150\mu KF}$ | Residue on 150µm of kiln feed, |
| $\%AR_{cli}$ | Alumina ratio of clinker, - |
| $F_{cli}$ | Fluorine content of clinker, % |
| $SO_{3cli}$ | $SO_3$ content of clinker, % |

# Petcoke Guidelines (2/3)

**Kiln**

Burner & flame: Use high momentum burner up to 11 N/MW for compact and short flame. For a given burner / PA fan (with limited operating range), adjust burner for most compact and shortest flame i.e. max. primary air quantity and pressure, max. radial air. In particular retracting burner on grate cooler kilns can have a strong positive impact. For example, one plant retracted the burner by 1.1 m out of the kiln which increased SO3 in clinker from 0.6% to 1.3%. But, retracting a burner can result in hotter kiln outlet and formation of snowman in the cooler.

Cooler: Stable and high secondary air temperature for stable ignition (cooler optimization)

O2/CO: Gas analysis at kiln inlet mandatory (ILC)

Kiln inlet O2 = 2-3 %, CO < 0.05% (< 500 ppm)

(in case of ILC kiln, higher O2 of 4-5% is acceptable; however disadvantage could be lower flame temperature and higher kiln inlet temperature)

Monitoring: Monitor free lime

Monitor kiln shell temperature profile (flame shape)

Granulometry: As a consequence of higher SO3, clinker tends to be finer. If necessary, adjust clinker SR/AR to alleviate finer clinker.

**Precalciner**

Hot flame core for stable ignition ("Hot Spot")

Combustion in pure air better than with kiln gas (precombustion chamber, SLC )

**Retention time**

The following gas retention time guidelines could be used (if not possible, increase petcoke fineness):

| **Fuel** | **ILC [s]** | **SLC, PCC [s]** |
|---|---|---|
| Petcoke | 4 | 3 |
| Bituminous coal | 3 | 2 |
| Lignite | 3.5 | 2.5 |

**Burn out** After calciner, $O_2$ = 2-3%, CO < 0.05 % (< 500 ppm); after PH, 1% higher $O_2$ due to false air). Check out hot meal for combustibles (sparkling)

**Dust curtain** Dust curtain kiln inlet: <20-30% meal from 2nd lowest stage to kiln inlet (splash box!). If no precalciner, dust curtain in riser duct by lowering meal entry points.

# Petcoke Guidelines (3/3)

**Hot meal analysis**

Adequate frequency, usually once/shift (LOI, $SO_3$, $K_2O$). $SO_3$ < 5% (if chlorine < 0.5%)

**Bypass**

An existing bypass alleviates the sulfur cycles, but installation of a new bypass can hardly be justified by the use of petcoke. Fight $SO_3$ cycles by enhanced preheater cleaning.

**Preheater cleaning**

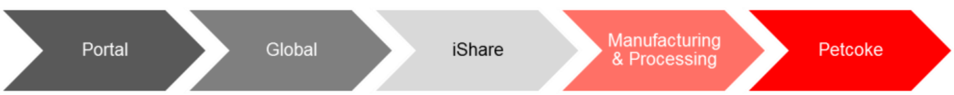
Add poke holes and install air cannons (could be up to 60) where coatings occur. Removal of heavy blockages can also be done with CARDOX blasting on demand. Special attention required for calciner orifice (restriction); if restricted by build-ups, the problem will selfaccelerate rapidly due to lack of $O_2$.

**Recommendation:** Use coating-repellent SiC refractory in the riser duct.

**How to proceed?**

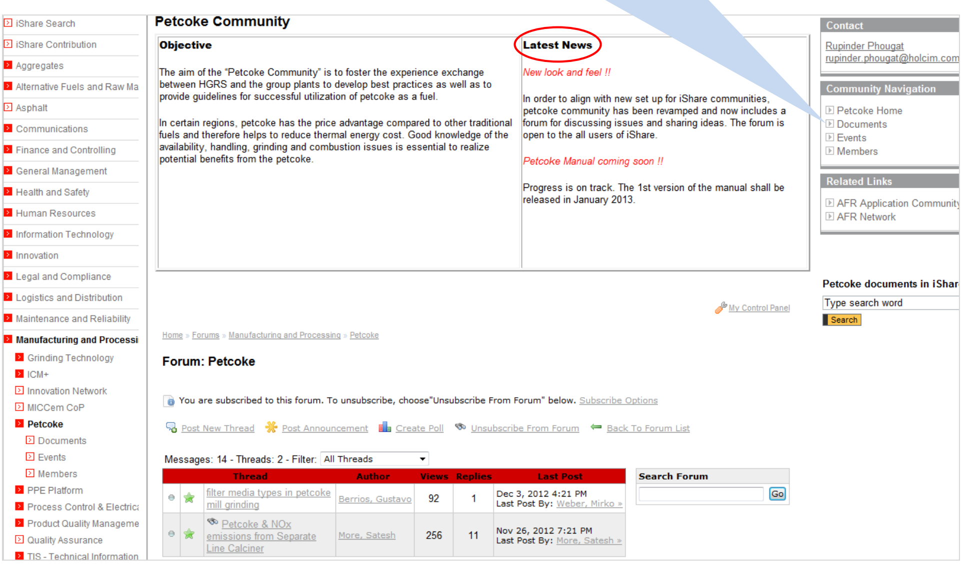
Stepwise increments of petcoke use, based on process and quality data. Depending on results, further stretch the preliminary limits for $SO_3$ input and Alk/$SO_3$ ratio.

## Petcoke Community on iShare




**Documents**

- Firing (field experiences about burning of petcoke)
- Grinding (field experiences about grinding of petcoke)
- Market (information on current market situation)
- Progress (summary of petcoke utilisation in Holcim)
- Tools (collection of guides, spreadsheets, reports, etc.)



# Alkali / Sulfur / Chlorine Balance

**1. Actual Sulfur in Clinker:**
The maximum input of sulfur is limited due to process reasons. The limit depends on the kiln type.

HTEC guide values for maximum sulfur input:

| **Kiln System** | **Max. sulfur input** [%SO3 in cli] | **Min. A/S ratio** [-] |
|---|---|---|
| Long wet kilns (WL) | 1.0 | 0.8 |
| Long dry kilns (DL) | 1.2 | 0.8 |
| Grate preheater kilns (GP) | 1.0 | 0.8 |
| Suspension preheater kilns (SP) | 1.7 | 0.5 |
| Precalciner kilns (PC) | 2.0 | 0.4 |

**2. Alkali / Sulfur - Ratio:**
Balance of sulfur and alkalis
Calculation:

$$\frac{Alk - Cl}{SO_3} = \frac{\frac{K_2O}{94} + \frac{Na_2O}{62} - \frac{Cl}{71}}{\frac{SO_3}{80}}$$

Calculation based on clinker concentrations [%]

$$\%SO_3 = 2.5 \cdot \%S$$

# Alkali / Sulfur / Chlorine Balance

3. **Sulfur Volatility:**

The volatility expresses the amount of sulfur circulation vs. sulfur in clinker.

Calculation:

$$\text{Volatility}\,\varphi = \left(1 - \frac{SO_3\ Cli \big/ (100 - LOI_{Cli})}{SO_3\ HM \big/ (100 - LOI_{HM})}\right)$$

Simplified formula for LOI~ <2%: $$\text{Volatility}\,\varphi = 1 - \frac{SO_3\ Cli}{SO_3\ HM}$$

SO3 cli = SO3 in clinker [%]
SO3 HM = SO3 in Hot meal [%]
LOI Cli / HM = Loss on ignition in clinker / hot meal [%]

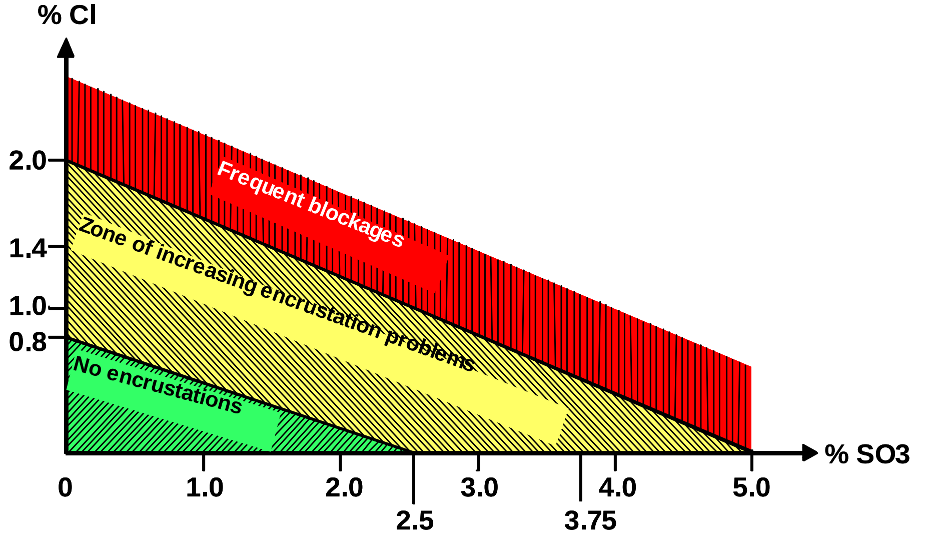
Limits:

| Volatility | Criteria |
|---|---|
| < 0.7 | ok |
| > 0.7 | combustion problem |
| > 0.9 | serious combustion problem |

4. **Hot Meal:**

Applicable to SP and PC kilns only.

Limits: according to graph



# Chlorine Limit

| Kiln system | Cl extraction method | Maximum relevant Cl input [g Cl/ t cli] | Remarks |
|---|---|---|---|
| Any kiln system | without Cl-extraction ("closed loop") | **300** | |
| 4/5 stage SP | discarding filter dust during direct operation | **300- 400** | dep. on available time for direct op. |
| 2 stage SP | same as above | **450** | same as above |
| LEPOL | discarding intermediate grate dust | **600** | |
| SP | 5-10 % Bypass | **300+100 x %Bypass** | applicable for 5-10% bypass |
| Long wet/dry | discarding max. kiln dust (unlimited CKD) | **5000[1]** | unusual, needs extra CKD outlet |

[1] 800 – 1000 g Cl/ t cli is the maximum to get all the dust in the cement

$$100\ g_{Cl}/t_{cli} = 100\,ppm = 0.01\%$$

## Consequences of exceeding the Cl Limit

| Kiln system | Short term [hours] consequences | Long term consequences | Impact on HCl emission |
|---|---|---|---|
| **Suspension preheater / precalciner** | preheater blockages → production loss | corrosion, refractory damage | none (without bypass) |
| **Grate preheater** | high pressure drop in nodule bed → prod. loss | corrosion | medium |
| **Long wet / long dry kiln** | ring formation / material blockage | | HCl emission and risk of dioxin / furan formation |

# AFR

## AFR Families

| LGF Categories | Characteristics | Examples |
|---|---|---|
| Lump fuel incl. whole tires (all 3-dimens. solids >50mm and 2-dimens. foils >200mm) | Heavy material; can not be carried by kiln gases; burns at kiln inlet | Whole tires, coarse shredded tires and plastics |
| Coarse Solids <50mm (3-dimens.) incl. foils <200mm (2-dimens.) | Can be carried by kiln gases (suited for precalciner) | Tire chips, shredded plastics and textiles |
| Fine Solids < 5mm (3-dimens.) incl. foils <50mm (2-dimens.) | Can be carried easily by kiln gases (suited for main firing) | Plastics, impregnated saw dust, animal meal |
| Sludges * | Pumpable with piston pump type PUTZMEISTER | Petroleum sludges |
| Liquids | Can be atomized with compressed air (solid particles in liquid <2-4mm) | Waste oil, solvents |

## Combustion Limits / Maximum Substitution Rates

"Combustion limits" = max. TSR that would be achievable if the burning of the AFR type is limited only by combustion (fuel burn-out) and not by any other factor such as for example chlorine input, flame temperature reduction (main burner only), quality parameters, P2O5 input etc.

- **Liquid AFR:** Not limited by combustion limits
- **Solid AFR:**

| Kiln Type | Feed-point | Max. Substitution Rate Solids [% TSR] (all %TSR values refer to total substitution of the entire fuel used in the kiln) |
|---|---|---|
| Precalciner Kiln (with tertiary air) | 1) Main Firing | • <5mm incl. foils <50mm: max. 10-15% TSR |
| | 2) Precalciner | • <50mm incl. foils <200mm: ① <br>• Sludge: 2-3% ref. to clinker (or max. TSR as above) |
| | 3) Kiln Inlet ① | • Lumps: max. 5-10% TSR |
| Preheater Kiln (no tertiary air) | 1) Main Firing ① | • <5mm incl. foils <50mm: max. 30% TSR |
| | 2) Kiln Inlet ① | • Lumps and solids <50mm (3-dimens.): max. 10-15%TSR<br>• Sludge: 2-3% ref. to clinker (or max. 10-15% TSR) |
| Grate Preheater Kiln (Lepol) | 1) Main Firing | • <5mm incl. foils <50mm: max. 30% TSR |
| | 2) Kiln inlet / Hot Chamber ① | • Lumps and solids <50mm (3-dimens.): max. 10-15%TSR<br>• Sludge: 2-3% ref. to clinker (or max. 10-15% TSR) |
| Long Wet Kiln or Long Dry Kiln | 1) Main Firing | • <5mm incl. foils <50mm: max. 40-50% TSR |
| | 2) Mid Kiln Firing | • Lumps (whole tires or bales); max. 20% TSR, with mixing air max. 30% TSR |

① see LGF-Study

The following PPE Tools help you with the assessment of the current combustion performance and determination of AFR potentials/bottlenecks:

- Combustion Check
- Summary of AFR Potentials and Bottlenecks

# AFR

## AFR Impact Calculation

### Impact factors of AFR according to LGF Study (Low Grade Fuel):

| Influence factor | Impact on heat consumption | | Impact on kiln capacity (tons lost) | | | |
|---|---|---|---|---|---|---|
| | Unit | All kilns | Unit | SP/PC kiln | Grate PH | Long wet |
| **Water** | GJ/t $H_2O$ | **2.15*** | t cli /t $H_2O$ | **2.0** | **1.6** | **0.8** |
| **Ash** | GJ/t ash | **1.1** | t cli /t ash | **0.26** | **0.22** | **0.11** |
| **Additional transp. air (false air)** | GJ/kNm$^3$ | **1 (0.7)**** | t cli /kNm$^3$ | **0.24** | **0.2** | **0.07** |
| **Oxygen level** | % q per % $O_2$ | **1.8** | % cap per %$O_2$ | **5.7***** | **5***** | **4.4***** |

Note: For proper application of above factors consult definitions/explanations in the LGF study

SP: Suspension Preheater, PC: Precalciner Kiln

* When $H_2O$ included in NCV calculation of fuel, when injecting pure water 4.6 GJ/t$H_2O$

** 0.7 GJ/kNm$^3$ applies for Wet kilns only

*** Increase in % of heat consumption / Decrease in % of capacity per increase (%) of Oxygen after last fuel addition. An Increase of the oxygen level in the kiln is often necessary when coarse solid AFR are burned which cause combustion problems or if petcoke is used compared to Coal. A detailed explanation and further details can be found in LFG study (PPE Tools)

"LGF Impacts" calculation spreadsheet → Holcim iShare

Holcim

**LGF IMPACTS** Version 14.12.2001

**Showing Impacts of Water, Ash, Transport Air and Increased O2 Level on Heat Consumption, Kiln Production and Flame Temperature**

**Input Data**

| Basic LGF data | | | Basic Kiln data | | |
|---|---|---|---|---|---|
| LGF type | Impregnated saw dust | | LGF feedpoint | 1 | (1=Main Firing, 2=Secondary Firing, PC or mid kiln) |
| Water content | 30.0% | | Kiln type | 1 | (1=SP, 2=LEPOL, 3=Wet) |
| Ash content | 15.0% | | Total fuel into main firing | 100% | |
| CV net | 15 | GJ/t LGF | Heat consumption | 3.3 | GJ/t cli |
| Transport air or additional false air (from LGF injection) | 0.7 | Nm3/kg LGF | Kiln production | 1800 | t/d |
| O2 increase after combustion of all fuels (to burn LGF) | 0.5 | % O2 (to burn LGF) | Feedrate LGF | 1.65 | t/h |
| O2 increase kiln inlet (to burn LGF; impact only on flame temp.) | 0.5 | % O2 (to burn LGF) | Substitution rate | 10.0% | thermal |
| | | | Ratio LGF/clinker | 0.022 | t LGF/ t cli |

**Results**

| | | Impact on heat consumtion | | | | Impact on flame temperature* (main firing) | | | Impact on production | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Referred to LGF | | Referred to clinker | | Actual quantity | Critical quantity | Red. flame temp. | Loss of production capacity | |
| Influence factor | | [GJ/t LGF] | [% of CV] | [MJ/t cli] | [% of kiln heat cons.] | [kg/kg cli] | [kg/kg cli] | [°C] | [t cli/t LGF] | [% of kiln capacity] |
| Water | 30.0% | 0.65 | 4.3% | 14.2 | 0.43% | 0.007 | 0.11 | -24 | -0.59 | -1.31% |
| Ash | 15.0% | 0.17 | 1.1% | 3.6 | 0.11% | 0.003 | 0.36 | -4 | -0.04 | -0.09% |
| Transport air | 0.7 Nm3/kg LGF | 0.70 | 4.7% | 15.4 | 0.47% | - | - | - | -0.17 | -0.37% |
| O2 increase | 0.5 % O2 | 1.35 | 9.0% | 29.7 | 0.90% | - | - | -40 | -1.30 | -2.85% |
| **Total** | | **2.86** | **19.1%** | **62.9** | **1.91%** | - | **-400 °C** | **-68** | **-2.10** | **-4.61%** |
| | | | | | | | | | | **-83 t/d** |

| Limits for impact on flame temperature* | | | |
|---|---|---|---|
| Critical quantity | H2O | 0.11 | t H2O/ t cli |
| | Ash | 0.36 | t ash/t cli |
| | O2 | 5.00 | % O2 |
| Red temp factor | | -400 | °C |

* Applicable for coal/oil as main fuel

| Factors for impact on production capacity | | |
|---|---|---|
| H2O | 1.98 | t cli/ t H2O |
| Ash | 0.26 | t cli/ t ash |
| False air | 0.24 | t cli/1000 Nm3 FA |
| O2 | 5.70 | %cap / % O2 |

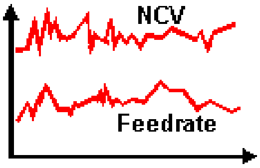
| Factors for impact on heat consumption | | |
|---|---|---|
| H2O | 2.15 | GJ/t H2O |
| Ash | 1.10 | GJ/t Ash |
| False air | 1.00 | GJ/1000 Nm3 |
| O2 | 1.80 | % incr HC/1% O2 |

**Reference:** Low Grade Fuel - Study; HGRS Report Nr. TPT 00/21018/E

# AFR

## Homogeneity / Fluctuation of AFR

The required homogeneity and maximum fluctuation of each AFR stream to the kiln depends on the following factors:




1. Fluctuation of the calorific value in the AFR - short term [minutes]
2. Fluctuation of the mass flow of the AFR into the kiln, given by the quality of the AFR dosing system - short term [minutes]
3. Substitution rate

### Homogeneity / Uniformity Rule (to avoid negative impacts on kiln capacity):

The following "Homogeneity / Uniformity Rule" expresses the required homogeneity and feed-rate stability of a given AFR stream in function of the TSR of that same stream:

**% Uniformity (heat input) < 100% / %TSR**

Definitions:

– % Uniformity (heat input) = % Fluctuation of CV + % Fluctuation of feed-rate

– where the "Fluctuations" are defined as:
% Fluctuation = (maximum - minimum) / (maximum + minimum) *100%

Note: This formula does not apply for whole tires and other slow burning lump fuels

Example of Homogeneity / Uniformity Rule:

The heat value of a given AFR stream is fluctuating between 12 - 13 MJ/kg (= 4% fluctuation) and the feed rate is fluctuating between 3.0 - 3.2 t/h (= 3% fluctuation).

→ Uniformity (fluctuation of heat input) = 4% + 3% = 7%

→ The maximum TSR without impacting production rate is = 100% / 7% = 14% TSR

### How to interpret and apply this rule?

As long as the uniformity rule is respected there will be no sensible negative impacts on kiln operation. If the uniformity is worse it is still possible to operate the kiln but the impacts will become sensible. An increase of $O_2$ is required to avoid CO peaks.

# AFR

## Heavy Metals

Holcim has no official limits or guidelines for HM in AFR.
The following table gives some “Reasonable Limits / Guidelines”:

| Metals | Hg | Tl | Cd | Be | Cr | As | Sb | Sn | Co | Pb | Ni | Cu | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Limits / guidelines [mg/kg] [ppm] | 5 | 50 | 50 | 50 | 250 | 400 | 500 | 500 | 500 | 800 | 1000 | 1000 | 1000 |

As a general guideline, the level of HM in clinker should not be increased significantly by the use of AFR.

Common ranges of HM in clinker:

“Holcim Heavy Metal Database” (iShare)

Definition of local HM limits:

HM balance followed by PRECI-software modeling to predict HM impacts on clinker, dust and emission (iShare)

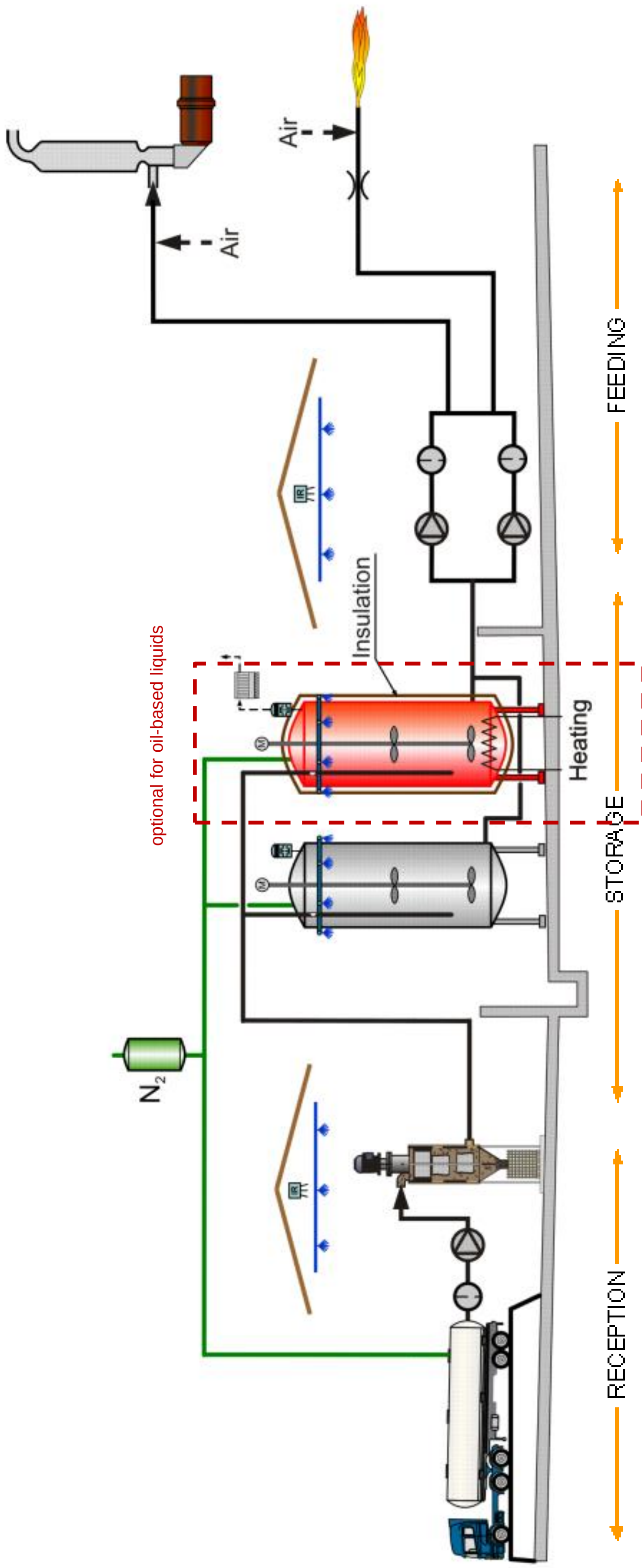
Most important and critical elements:

- Mercury (Hg): Volatile (emission)
- Thallium (Tl): Volatile (enrichment in the outer dust cycle)
- Cadmium (Cd): Volatile (enrichment in the outer dust cycle)
- Chromium (Cr): Cr VI in cement (health problems handling wet / fresh concrete)

# Liquid AFR Handling

## Standard Flow Diagram Liquid AF

For further details refer to Technical AFR Handling Manual (Part A)



# Liquid AFR Handling

**Intake Filter Screen selection** The filter screen size depends on the smallest cross section in the pipe system (normally injection nozzle)

- Filter Screen Opening: 1/3 of the injection nozzle's smallest sectional area
- Basket filter size: > 30 l (use of automatic cleaning filter preferred

**Pipe System**

- Product velocity: > 1 m/s

**Pump selection:**

| | |
|---|---|
| • Unloading pump: | Centrifugal pump with open wheel, Capacity > 40 $m^3/h$ |
| • Dosing pump for solvents: | Double diaphragm pump with PTFE diaphragm |
| • Dosing pump for other: applications | Eccentric screw pole pump |

**Twin fluid atomizing nozzle :**

| | |
|---|---|
| • Liquid pressure at nozzle: | 2 – 5 bar |
| • Compressed air at nozzle: | 3 – 6 bar |
| • Air/Fuel ratio | 0.08 – 0.12 $kg_{air}/kg_{liquid}$ |

**Safety**

Liquids with flash point **< 55°C** require special safety measures !

For further details refer to documents available on the Holcim Portal:

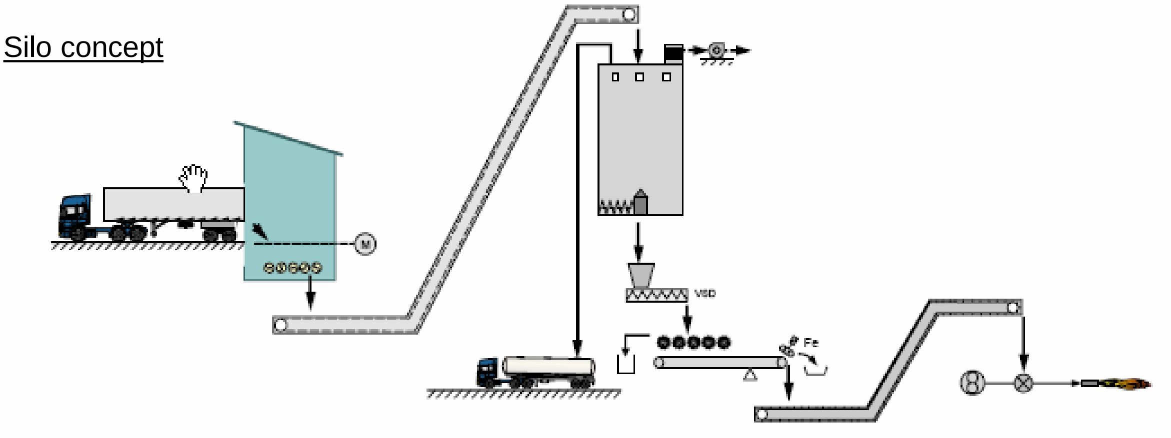
- Technical AFR Manual: Explosion Protection
- Technical AFR Manual: Fire Detection and Protection
- AFR Design Safety Criteria

# Solid AFR Handling

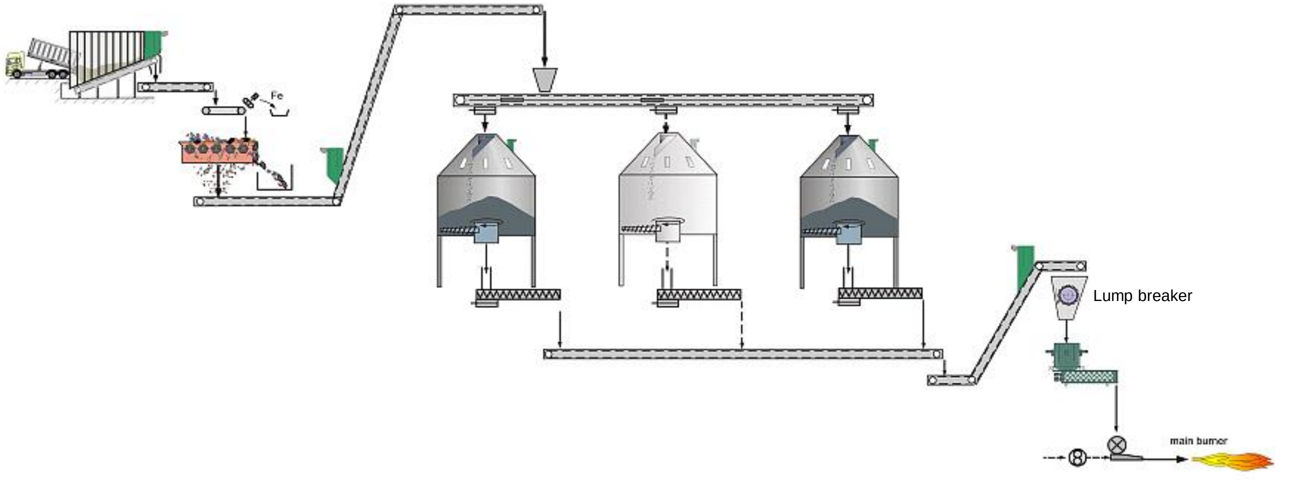
## Standard Flow Diagrams

### Main burner firing

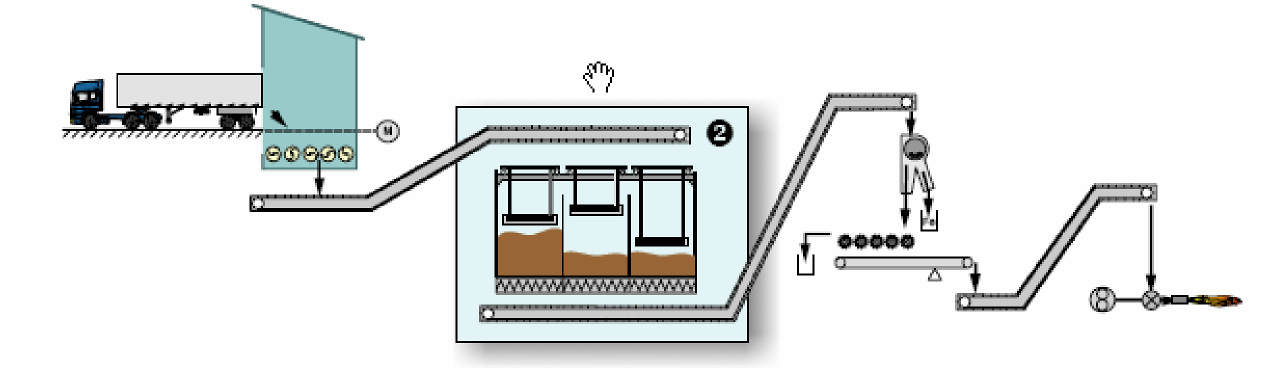
Silo concept




Multiple silo concept for FLUFF



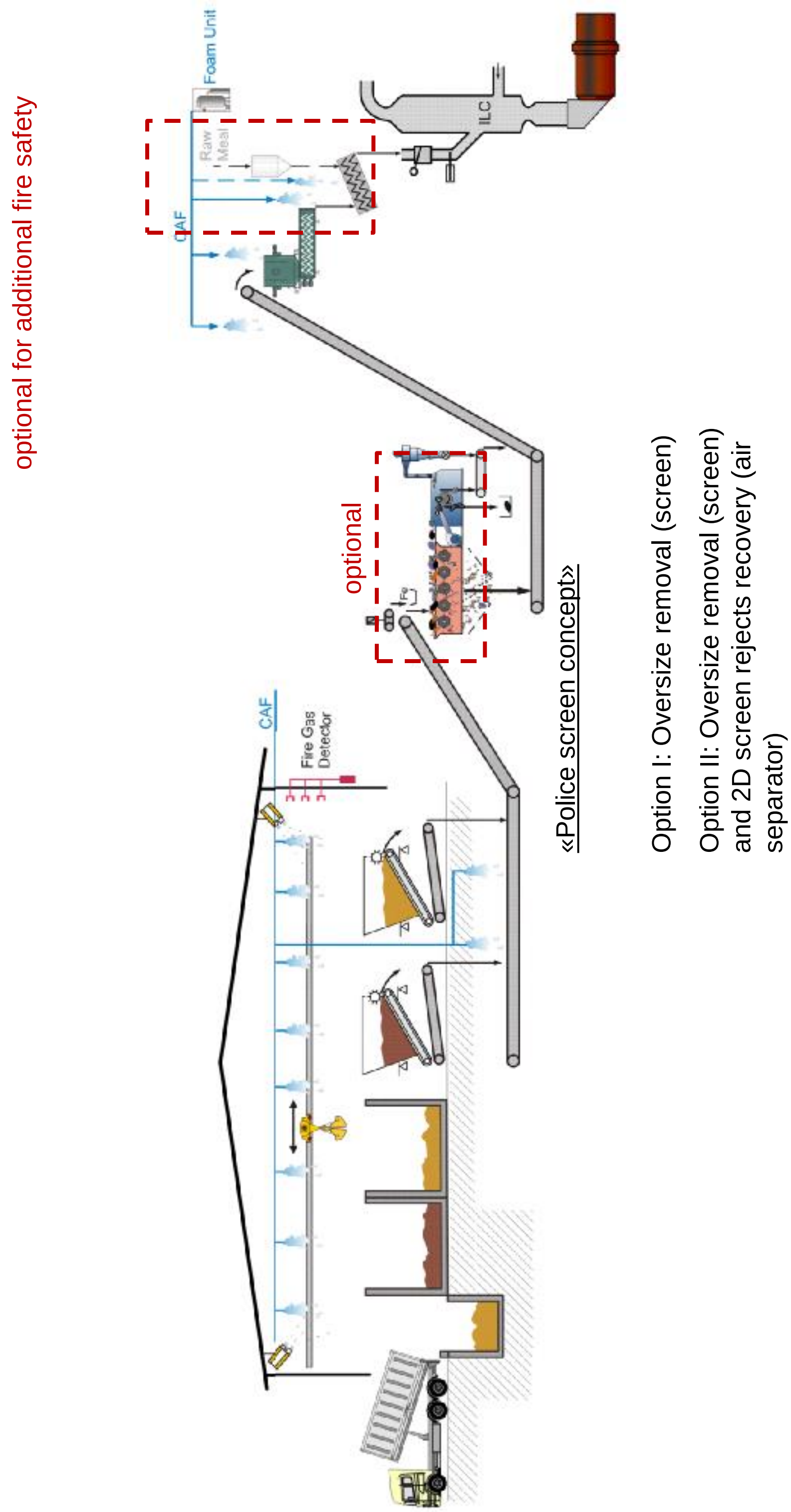

Storage Box concept (Top Reclaiming)



# Solid AFR Handling

## Standard Flow Diagrams

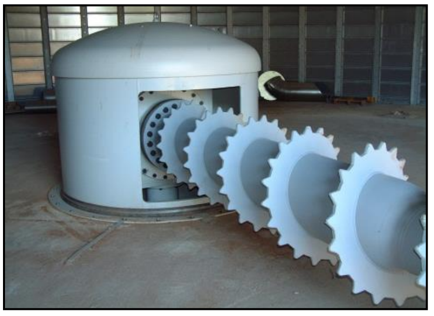
### Precalciner / Secondary firing



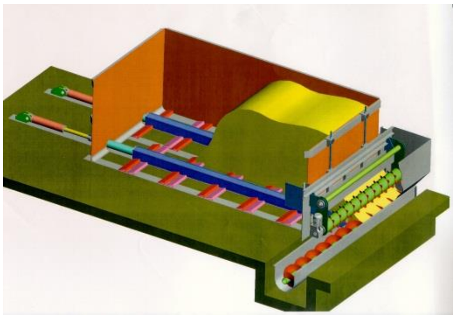
# Solid AFR Handling

## Extraction Systems (Bulk density < 1 t/m³, product low to medium abrasive)

| Storage size< 4000m³ | Storage size< 300m3 |
| --- | --- |



Extraction screw for flat bottom silos

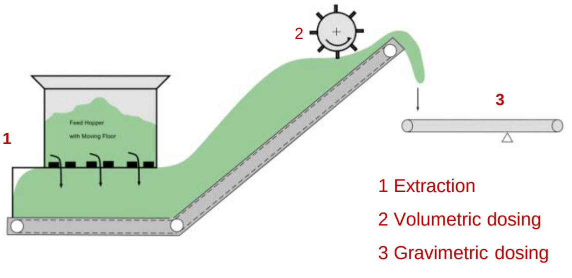


Push floor hopper with extraction screw

## Dosing System (Bulk density < 1 t/m³, product low to medium abrasive)

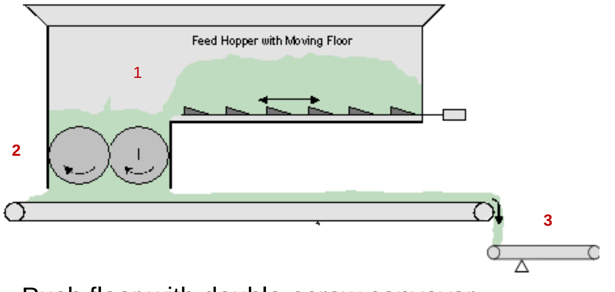
Storage size< 300m3

**Coarse AFR**



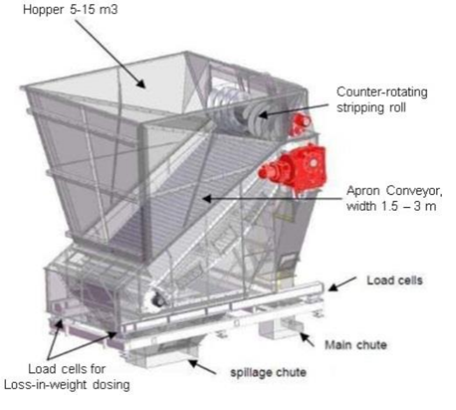

Inclined chain belt conveyor with stripping roll

**Fine AFR (< 50 mm, no longish strips)**

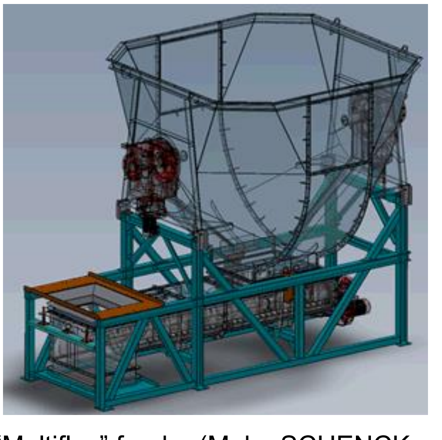



Push floor with double-screw conveyor

| Storage size< 20 m3 | Storage size < 20 m3 |
| --- | --- |




Inclined apron feeder with stripping roll supported on loads cells

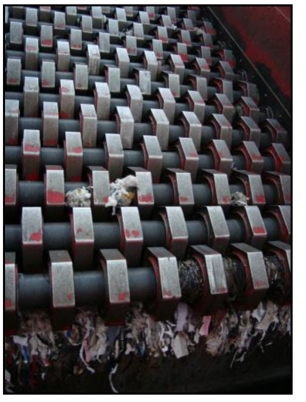


“Multiflex” feeder (Make:SCHENCK

# Solid AFR Handling

## Product Sizing Systems

Disc screen (conventional design)



Disc screen with static spacers

Star screen

Trommel screen

## Screen type selection guidelines

| | |
|---|---|
| • Trommel screen: | Suitable for CSS and other granular material / no longish strips<br>Cut size < 25mm possible |
| • Disc screen: | Suitable for FLUFF (e.g. police screen), with static spacers suitable for longish strips<br>Cut size > 25 mm |
| • Star screen | Suitable for fine FLUFF (e.g. police screen) |

## Cut size guidelines

| | |
|---|---|
| • Main burner | FLUFF: 40 mm<br>CSS: 15 mm (impregnated saw dust) |
| • Calciner | FLUFF/CSS: 100 -150 mm |

# Solid AFR Handling

## Rotary valve selection criteria

- Blow through valve preferred for sticky material → standard solution
  paddle wheel compartment volume according to transport pipe diameter
- Drop-through valve is preferred for very abrasive material.
- Drop-through valve size shall be 3-times than design volumetric flow rate
- Blow-trough valve size shall be 1.5-times the design volumetric flow rate
- Rotor speed: < 0.4 m/s (VFD recommended for adjusting motor speed)
- Inlet opening: > 0.1 $m^2$
- Pressure resistance: 10 bar

## Flap valve selection criteria

- Actuated double or triple flap valve
- Minimum inlet opening::
  - a) particle size nominal < 50 mm: 500 x 500 mm
  - b) particle size nominal < 200 mm: 800 x 800 mm
  - c) whole tyres: 1'400 x 500 mm
- Automatic safety shut off gate for flap valve, fail-safe closing
- Heat resistant materials to the prevailing temperature

# Solid AFR Handling

## Pneumatic Conveying System Design Criteria

- Pipeline shall be straight and conveying distance shall be as short as possible
- Pipe size shall be constant
- Number of bends in the system should be kept as low as possible as they contribute to overall pressure drop and maintenance requirements (erosive wear).
- Bends shall have long radius (r/D ratio: 10 -15)
- Bend shall have liners.
- The first straight section following a bend shall have wear liners too.
- Loading factor (kg of product / kg of air) should be not more than 4 with
  - FLUFF: 2-4
  - CSS: 1-2 (Impregnated saw dust)
  - AM: 1 (Animal meal)
- Ejector design pressure loss: 150 mbar

## Safety

- Equipment grounding
- Operation speed mechanical equipment < 1m/s (sparks !)
- Bearings not in contact with material (e.g. screw conveyor)
- Automatic safety shut-off gate for flap valve, fail-safe closing
- Fire detection and sprinkler system

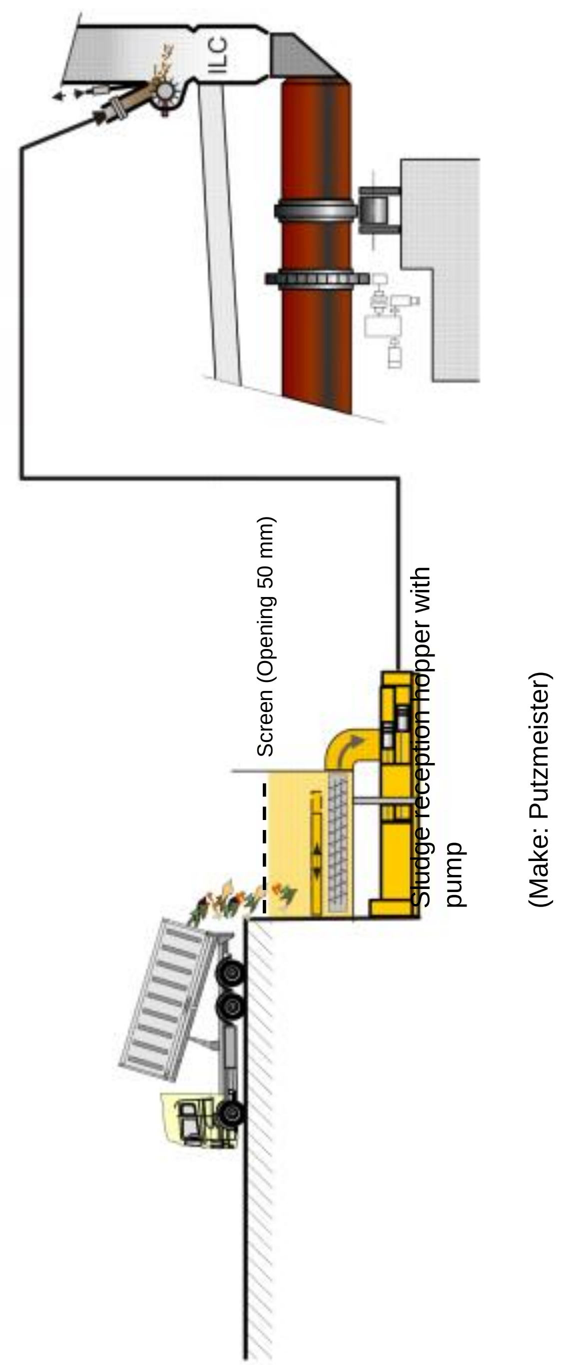
For further details refer to documents available on the Holcim portal.

# Sludge AFR Handling

## Standard Flow Diagram ready-to-burn Sludge AF

**Feed concepts**

- Low viscous liquids:
  Pneumatic atomizing nozzles
- High viscous liquids:
  Mechanical sludge rotor with shut-off valve (as shown)

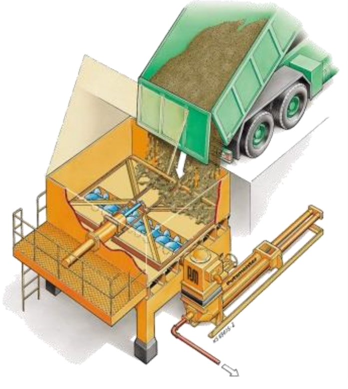


# Sludge AFR Handling

## Sludge Handling Concept

### Hopper concept

Storage size : 40 -100 m3



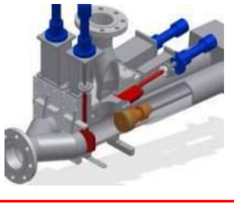
### Silo concept

Storage size > 100 m3§

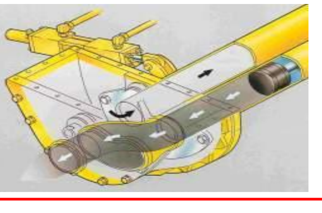
### Typical sludge pump specifications

- Pressure: up to 100 bar (short term pressure peaks up to 130 bar)
- Flow rate: 0.2 – 500 $m^3/h$ (Holcim standard applications: < 30 m3/h)
- Heavy duty design valves
- Boundary injection system (oil) in order to reduce friction between internal pipe surface and material conveyed

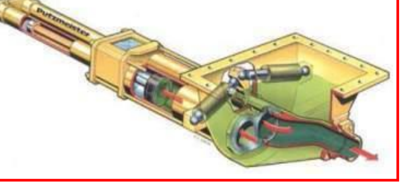
### Valve types



Slide gate valve (Solid Pumps)



Rock valves (Make: Schwing)



S-transfer tube (Make: Putzmeister)

# Sludge AFR Handling

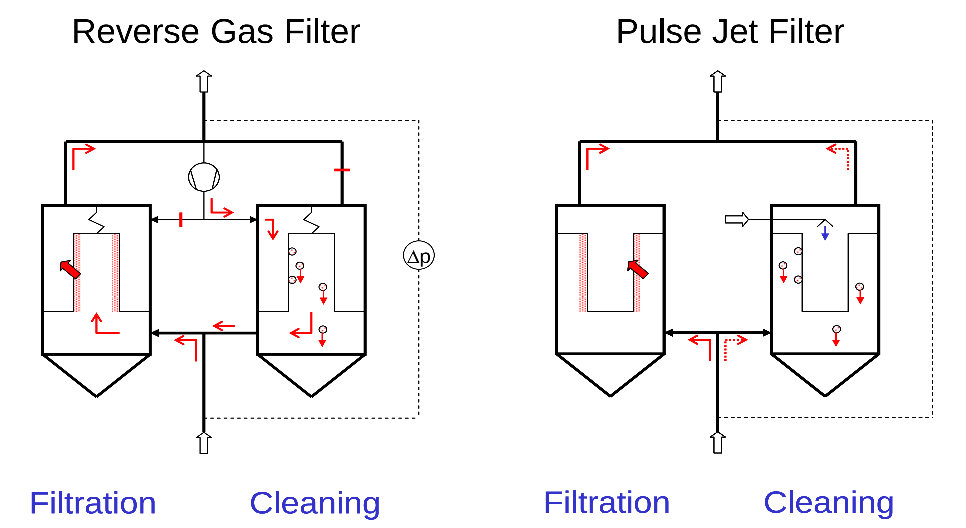
## Typical Sludge AFR specifications

| Material Properties | Typical Values |
|---|---|
| Viscosity at 20°C | approx >1'000 up to 1Mill $mm^2/s$ pumpable by piston pump |
| Dry matter content | 20 – 80 % |
| Solids size after preparation | < 75 mm |
| Flashpoint | > 55°C (oil based)<br>> -20°C (solvent based) |
| pH value | 4 – 9 (standard)<br>1 – 4 (acid tar) |

**Note:**

- AFR sludges can have a wide range of properties. They can show both solid and liquid-like behaviour.
- As a rule of thumb all hand-kneadable product is pumpable even though moisture content is very low (e.g. contaminated soil).
- Tests may be required to determine pumpability.

# Bag Filter




## Air-to-cloth ratio

$$A/C = \frac{V_{act}}{A_{bags,net}}$$

A/C air-to-cloth ratio (specific filter load) [m/min]

$V_{act}$ gas volume at actual conditions [$Am^3$/min]

$A_{bags,net}$ active bag area (not counting shut compartments) [$m^2$]

$= n \cdot \pi \cdot d_{bag} \cdot L_{bag}$

n number of bags (active)

$d_{bag}$ bag diameter [m]

$L_{bag}$ bag length [m]

**Reverse air filters**

| | |
|---|---|
| A/C < 0.6 m/min | no problems expected for existing filters |

**Pulse jet filters**

| | |
|---|---|
| A/C < 1.0 m/min | no problems expected i.e. design criteria for new process filters in normal operation |
| A/C > 1.2 m/min | increased differential pressure expected e.g. for process filter in upset conditions up to 1.5 m/min allowed |
| A/C > 1.5 m/min | inefficient cleaning expected |

# Bag Filter

## Differential Pressure

$$\Delta p \approx \Delta p_0 \cdot \left(\frac{v_F}{v_{F,0}}\right)^{\psi}$$

| | |
|---|---|
| $\Delta p$ | bag filter differential pressure (across tube sheet) e.g. for increased flow in future operation [mbar] |

**Reverse air filters**

| | |
|---|---|
| $\Delta p < 20.0$ mbar | normal operation |

**Pulse jet filters**

| | |
|---|---|
| $\Delta p <$ ~5 mbar | probably overcleaning and low bag life |
| $\Delta p >$ ~12 mbar | probably high A/C-ratio, high dust load, sticky dust or old bags |
| $\Delta p >$ ~20 mbar | cleaning is inefficient, bags can collapse |

| | |
|---|---|
| $\Delta p_0$ | reference diff. pressure e.g. today operation [mbar] |
| $v_F$ | air-to-cloth ratio (specific filter load) e.g. due to increased flow in future operation [m/min] |
| $v_{F,0}$ | reference air-to-cloth ratio e.g. today operation [m/min] |
| $\psi$ | differential pressure exponent e.g. of today's bags or new bags in future [-] |

| | |
|---|---|
| $\psi < 1.2$ | new bags, high permeability |
| $\psi > 1.6$ | old bags, low permeability |
| $\psi > 2.0$ | can velocity problem |

# Environment

## Water Dew Point

The water dew point temperature in a gas stream can be calculated as

$$T_{DP} = \left( \frac{336.48}{5.3362 - \sqrt{17.045 + \ln\left(\frac{\%W}{100} \cdot \frac{p}{1000}\right)}} - 179 \right)$$

$T_{DP}$ = dew point temperature (°C)
%W = gas humidity (Vol %)
p = $p_{measurement,relative} + p_{ambient}$ (mbar)

## Acid Dew Point

The acid dew point temperature for $SO_2$ / $SO_3$ in a gas stream can be calculated as:

$$T_{Acid} = \left( \frac{1000}{1.7842 + 0.0269 \cdot L_W - 0.1029 \cdot L_S + 0.0329 \cdot L_W \cdot L_S} - 273 \right)$$

$T_{Acid}$ = Acid dew point temperature (°C)

$$L_W = \log\left(\%W \cdot p \cdot 10^{-5}\right)$$

where: %W = water content (Vol-%)
p = $p_{measurement,relative} + p_{ambient}$ (mbar)

$$L_S = \log\left(\frac{Conc_{SO3}}{\rho_{N,SO3}} \cdot p \cdot 10^{-9}\right)$$

where: $Conc_{SO3}$ = Sulfur trioxide concentration in gas (mg/Nm3 dry)
= approx. 1-3% from measured SO2
$\rho_{N,SO3}$ = Normalized gas density of $SO_3$ (= 3.57 kg/Nm³ dry)
p = $p_{measurement,relative} + p_{ambient}$ (mbar)

# Environment

## Cooling Water Injection for Gas Cooling

The required amount of cooling water for gas cooling can be estimated as (Rule of thumb):

$$M_W = 0.6 \cdot V_{N,wet} \cdot \Delta T$$

$M_W$ = Amount of cooling water (g/h)
$V_{N,wet}$ = Wet gas volume at normal conditions (Nm3/h)
$\Delta T$ = Inlet minus outlet gas temperature (°C)

# Selective Non Catalytic Reduction (SNCR)

## NOx Reduction Rate [%]

$$NOx\ Reduction = \frac{C_{NOx(\emptyset)} - C_{NOx}}{C_{NOx(\emptyset)}} \cdot 100$$

$C_{NOx(\emptyset)}$ = NOx concentration raw gas before injection location (upstream) or at stack w/o injection

$C_{NOx}$ = NOx concentration with SNCR injection after injection location (downstream)

## Molar Ratio (referred to raw gas NOx) [mol/mol]

$$Molar\ Ratio = \frac{mol_{NHy}}{mol_{NO_X(\emptyset)}}$$

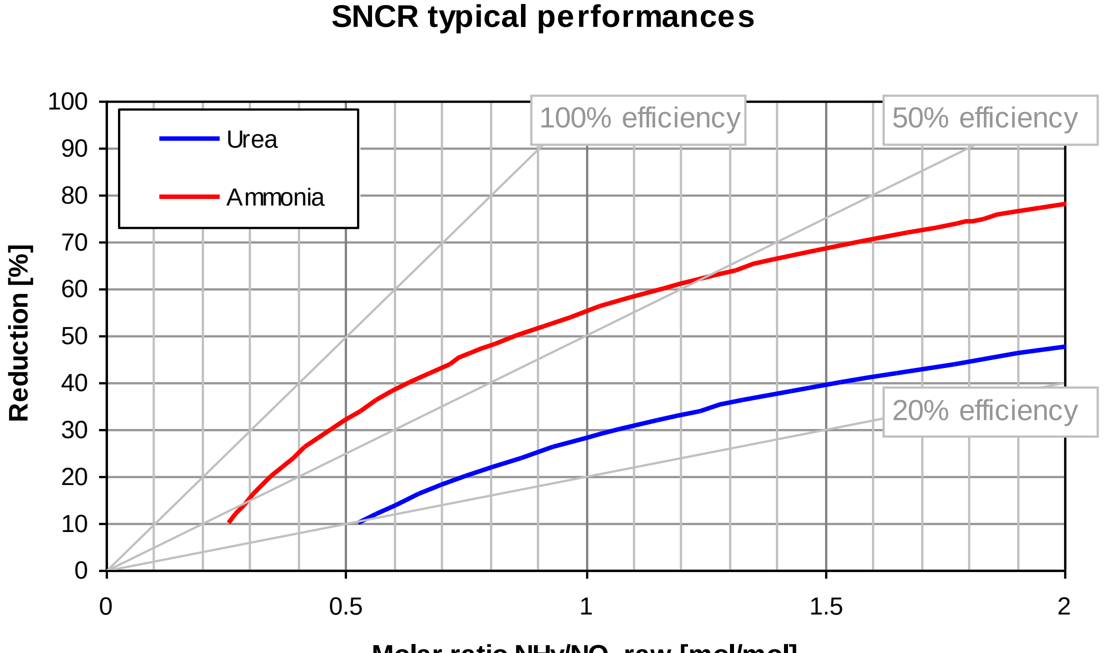
$mol_{NHy}$ = moles of reaction relevant component NHy of injected reagent (1mol of urea contains 2 moles of NHy)

$mol_{NOx(\emptyset)}$ = moles of NOx in raw gas before injection location (upstream) or at stack w/o injection

## SNCR (reagent) Efficiency [%]

$$Efficiency = \frac{\text{NOx Reduction Rate}}{\text{Molar Ratio}} = \frac{mol_{\Delta NOx}}{mol_{NH_Y}} \cdot 100$$

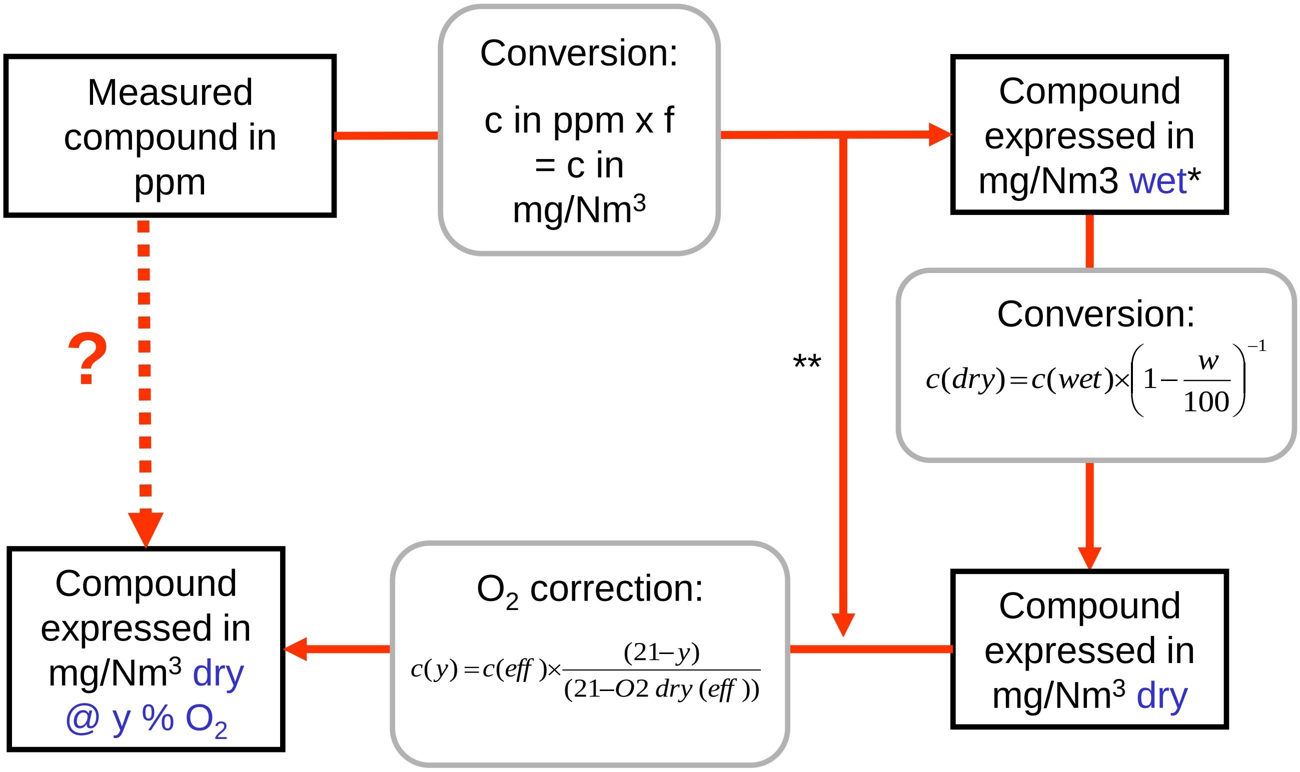
$mol_{\Delta NOx}$ = moles of NOx reduced by injected reagent




**Guide values**

- Efficiency ~ 55% at Molar Ratio of 1-1,2 (Ammonia)
  ~ 30% at Molar Ratio of 1-1,2 (Urea)
- Molar Ratios < 1.2 : NH3 slip not expected

# Emission Concentration Conversions




c Concentration
w Water content of gas (Vol %)
* Wet according to measurement principle (in situ, hot extractive,…)
** If measured on dry basis

NOx emissions normally indicated as mg $NO_2$/Nm³ dry, even though at the stack 95 -98% of the NOx is in form of NO (→ use f=2.05).

VOC emissions are usually expressed as carbon (mgC/Nm3)
(table: propane calibration → f=1.61)

See next page for the calculation of the factor f

**Examples Factor f**
for normal conditions of
0ºC and 1013mbar

| | |
|---|---|
| $NH_3$ | 0.76 |
| $H_2O$ | 0.80 |
| CO | 1.25 |
| NO | 1.34 |
| $NO_2$ | 2.05 |
| $SO_2$ | 2.86 |
| HCl | 1.63 |
| VOC | 1.61 |
| $SO_3$ | 3.57 |

# Emission Concentration Conversions

## wet → dry

$$c(dry) = c(wet) \times \left(1 - \frac{w}{100}\right)^{-1}$$

c(dry): dry concentration mg/Nm3
c(wet): wet concentration mg/Nm3
w: water content of gas Vol%

## oxygen reference x% → 10%

$$C_{10} = C_x \times \left(\frac{21-10}{21-x}\right)$$

$C_{10}$: concentration mg/Nm3 @ 10% Oxygen
$C_x$: concentration mg/Nm3 @ X% Oxygen

## ppm → mg/Nm3

$$c\left[\frac{mg}{Nm^3}\right] = f \bullet c[ppm]$$

with

$$f = \frac{MW\left[\frac{kg}{kmol}\right]}{22.41\left[\frac{Nm^3}{kmol}\right]}$$

MW: molecular weight
(see periodic table)
N→ Norm conditions:
0°C, 1013 mbar

### Periodic Table of Elements

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H 1.01 1 | | | | | | | | | | | | | | | | | He 4.00 2 |
| Li 6.94 3 | Be 9.01 4 | | | | | | | | | | | B 10.82 5 | C 12.01 6 | N 14.01 7 | O 16.00 8 | F 19.00 9 | Ne 20.18 10 |
| Na 22.99 11 | Mg 24.32 12 | | | | | | | | | | | Al 26.98 13 | Si 28.09 14 | P 30.98 15 | S 32.07 16 | Cl 35.46 17 | A 39.94 18 |
| K 39.10 19 | Ca 40.08 20 | Sc 44.96 21 | Ti 47.90 22 | V 50.95 23 | Cr 52.01 24 | Mn 54.94 25 | Fe 55.85 26 | Co 58.94 27 | Ni 58.71 28 | Cu 63.54 29 | Zn 65.38 30 | Ga 69.72 31 | Ge 72.60 32 | As 74.91 33 | Se 78.96 34 | Br 79.92 35 | Kr 83.80 36 |
| Rb 85.48 37 | Sr 87.63 38 | Y 88.92 39 | Zr 91.22 40 | Nb 92.91 41 | Mo 95.95 42 | Tc 99.00 43 | Ru 101.1 44 | Rh 102.9 45 | Pd 106.4 46 | Ag 107.9 47 | Cd 112.4 48 | In 114.8 49 | Sn 118.7 50 | Sb 121.8 51 | Te 127.6 52 | I 126.9 53 | Xe 131.3 54 |
| Cs 132.9 55 | Ba 137.6 56 | Lu 175.0 71 | Hf 178.5 72 | Ta 181.0 73 | W 183.9 74 | Re 186.2 75 | Os 190.2 76 | Ir 192.2 77 | Pt 195.1 78 | Au 197.0 79 | Hg 200.6 80 | Tl 204.4 81 | Pb 207.2 82 | Bi 209.0 83 | Po 210.0 84 | At (210) 85 | Rn (222) 86 |
| Fr (223) 87 | Ra 226.1 88 | Lw (260) 103 | Rf (261) 104 | Db (262) 105 | Sg (263) 106 | Bh (262) 107 | Hs (265) 108 | Mt (266) 109 | Ds (269) 110 | Rg (272) 111 | 112 | 113 | 114 | 115 | 116 | 117 | 118 |
| | | La 138.9 57 | Ce 140.1 58 | Pr 140.9 59 | Nd 144.3 60 | Pm 145.0 61 | Sm 150.4 62 | Eu 152.0 63 | Gd 157.3 64 | Tb 158.9 65 | Dy 162.5 66 | Ho 164.9 67 | Er 167.3 68 | Tm 168.9 69 | Yb 173.4 70 | | |
| | | Ac 227.0 89 | Th 232.1 90 | Pa 231.0 91 | U 238.1 92 | Np 237.0 93 | Pu 242.0 94 | Am 243.0 95 | Cm 245.0 96 | Bk 249.0 97 | Cf 249.0 98 | Es 255.0 99 | Fm 255.0 100 | Md 256.0 101 | No 253.0 102 | | |

For further explanations and emission plausibility checks see EMR Manual and Guidelines.

# PC Kiln Operation and Control Set-points

**Stable kiln operation is key to protect personnel and equipment at all times and to minimize production costs by means of:**

- **Reduction of kiln heat consumption**
- **Maximization of production rate**
- **Reduction of unplanned stops**
- **Stabilization of clinker quality***

**The key prerequisites to achieve a stable and efficient kiln operation are:**

1. **Stable kiln feed properties and feed rate**
2. **Stable fuel properties and feed rate**
3. **Stable gas flow rate trough the system**
4. **Optimization of the kiln control parameters**

**Stabilization:**

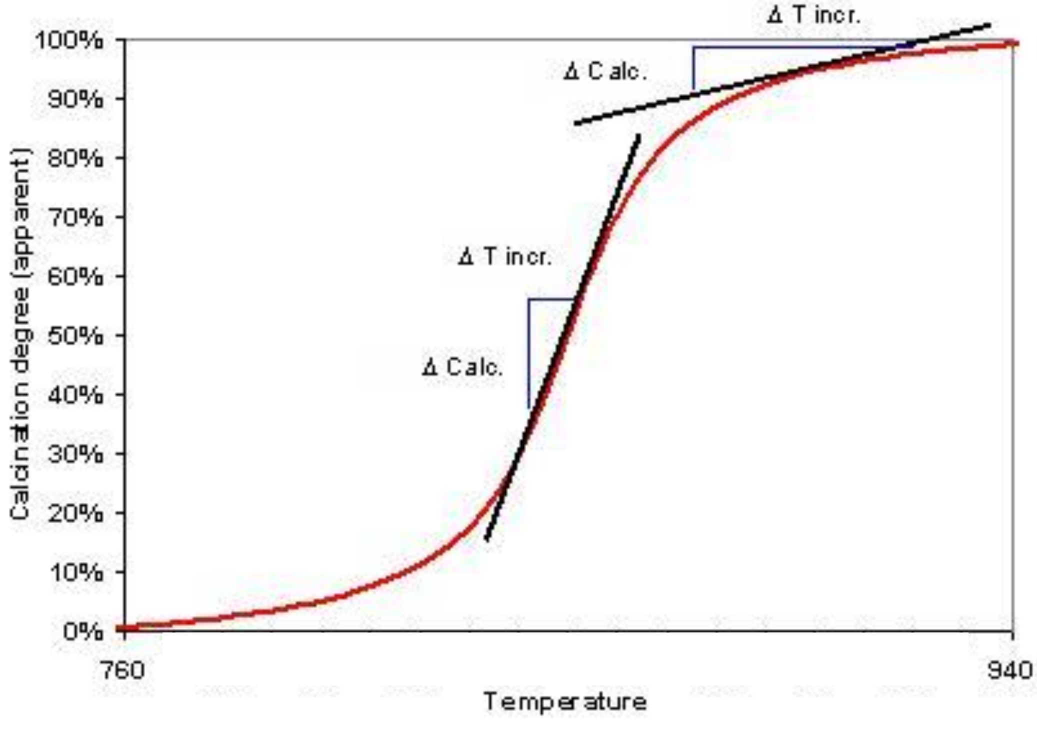
| Parameter | How | Target |
|---|---|---|
| **$O_2$ @ PC exit (or PH exit):** | Minimize the number and magnitude of disturbances of the ID fan flow (e.g. raw meal start and stops, cooling water flow) | Depends by fuel mix |
| **Precalciner temperature** | Reducing gas flow fluctuations<br>Tune PID controller<br>Reduce fluctuation in fuel properties/rate | STD < 5 °C good<br>STD < 2°C excellent |
| **Under Grate Pressure (UGP)** | Tune PID controller<br>Use p under fix inlet as UGP | STD of Secondary Air Temperature < 25 °C good (SAT measured at ToKH) |
| **Kiln feed rate** | Use as last choice to control the process<br>Take care of your feeders | Constant (unless ID fan at max) |
| **Kiln speed** | Adapt to Burning zone conditions | To use as additional support to control BZ |

*** Make use of it in cement grinding department**

# PC Kiln Operation and Control Set-points

## Optimization of the kiln control parameters:

| Parameter | Action | Limit/Constraint |
|---|---|---|
| **Kiln inlet $O_2$** | Find optimum | SO3 in hot meal,<br>NOx formation (flame temp.)<br>PC utilization<br>Reduced number of cyclone blockages. |
| **O2 @ PC exit:** | Reduce | 500ppm < CO < 1000ppm<br>Different legal requirements<br>Kiln inlet $O_2$ < 500ppm in any case<br>Gas speed in riser ducts |
| **Under Grate Pressure** | Increase | Consistent secondary air T increase<br>Stability of operation<br>Design limitations |
| **Precalciner temperature** | Reduce | Burning zone stability<br>Clinker quality |




**Calcination degree (apparent) in hot meal vs. calciner temperature**

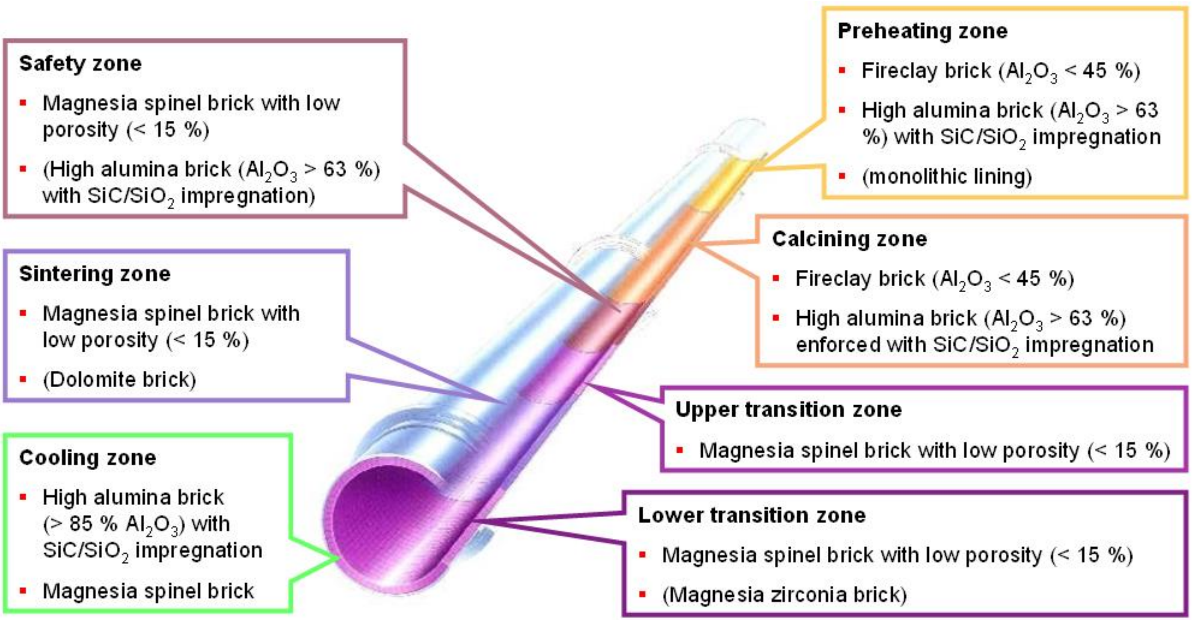
# Refractory

## Holcim Objectives regarding Refractories in Rotary Part

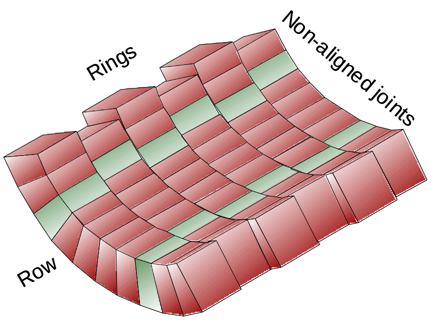
- Specific refractory consumption according or below best practice:
  - < 400 g / t cli for PC kilns
  - < 800 g / t cli for PH kilns
  - < 1200 g / t cli for long kilns

- Kiln lining may not impact availability, not being the cause for any unplanned kiln stop

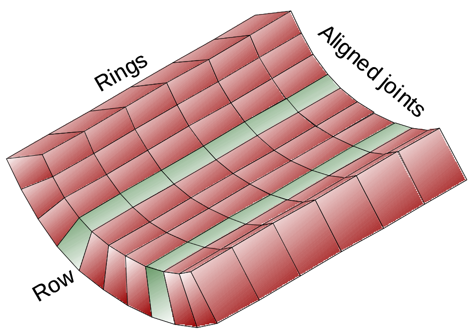
## Standard Refractory Layout for Rotary Part




## Lining Pattern for Rotary Part




Staggered lining preferred



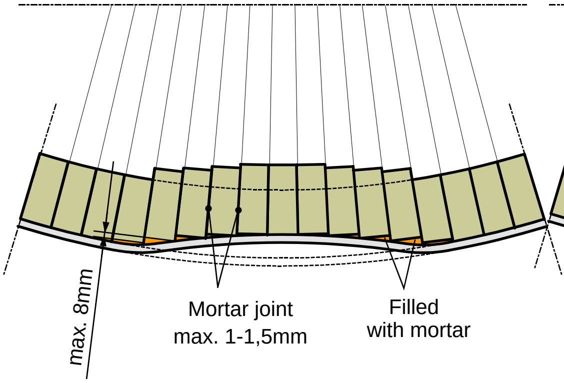

Straight lining acceptable

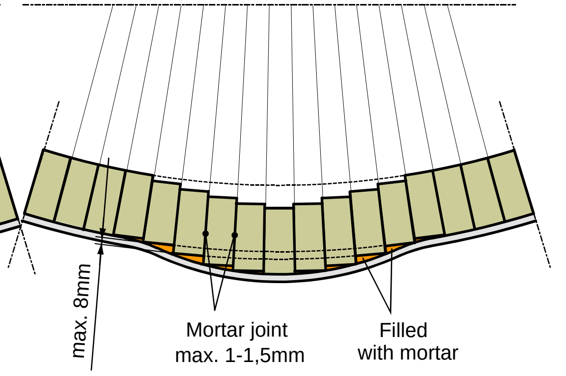
**Note:** More details on iShare: “Refractory Manual 1 – 5”

# Refractory

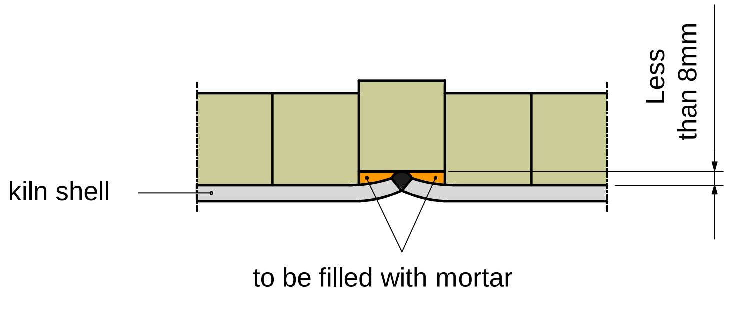
## Usage of Mortar in Rotary Part

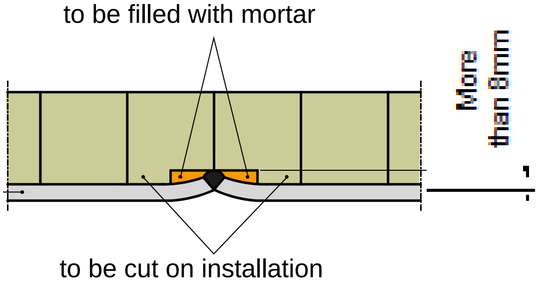
- in kiln tyre areas (0.5 – **1.0** x $D_{kiln}$ up - / downhill of tyre) for increased mechanical flexibility
- in the keying area to avoid usage of metal shims
- in areas of high kiln shell corrosion to achieve a more gastight lining
- in deformed kiln shell sections to increase mechanical flexibility of lining
- different mortars should be used for basic and alumina bricks




- in the area of welding seams (if welding seams are more than 8 mm high, the brick should be cut additionally)



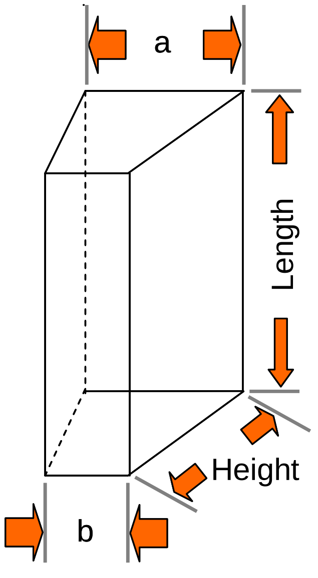



# Refractory

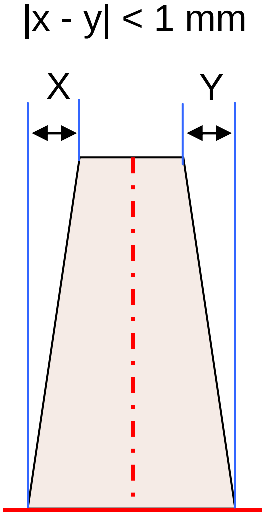
## Main Dimensional Tolerances for Bricks in Rotary Part

| Dimension | Holcim standards (for basic and non-basic bricks) |
|---|---|
| Length (l): | ± 2.0 mm 2)* |
| Brick width (a,b): | ± 1.5 mm 1)* |
| Brick height (h): | ± 1.5 %* |
| Tapering (a-b): | ± 1.0 mm |
| Deviation of symmetry: | (x-y)/2 ≤ 2.0 mm* |
| Parallelism: | ≤ 1.0 mm |
| Side tapering: | ≤ 0.6 mm |
| Warpage: | ≤ 1.0 mm* |

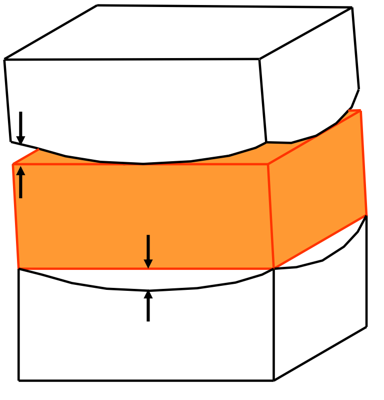
* Translation ZKG, No2 (1989) 57-67
1) referred to the average value of the delivery
2) referred to the specified value of the delivery



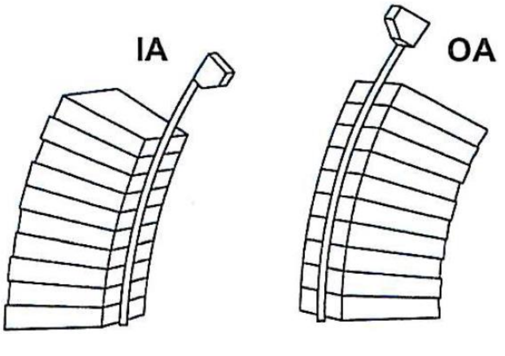

*Brick Dimensions*




*Deviation of Symmetry*



*Warpage*




Stack test of 10 bricks

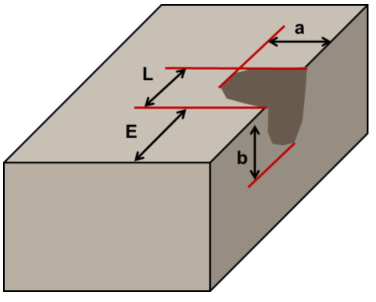
Difference between IA (hot face) minus OA (cold face) should not be more than -4 mm or +6 mm of the theoretical taper of that size of brick

Example (ISO brick 822):
- One brick face side a = 103 mm, side b = 97.3 mm
- Ten stacked bricks would measure; side a (OA) = 1030 mm, side b (IA) = 973 mm
- The allowance of the difference 1030 mm – 973 mm = 57 mm should not be more than -4/+6 mm, i.e. allowable is 53-63 mm

# Refractory

## Typical guide values for admissible Bricks Damages in Rotary Part

- Broken edges




**If**

E ≥ 8 mm ***and***

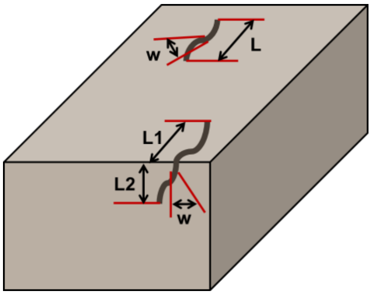
L ≤ 40 mm ***and***

a+b ≤ 20 mm ***and***

≤ 4 numbers of defects (2 on hot- and 2 on cold-face) ***then***

=> **brick can be accepted**

- Cracks




**If**

W > 0.2* mm ***and***

L or (L1+L2) ≤ 50.0 mm ***and***

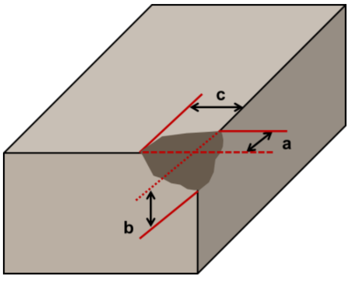
≤ 1 number of defects ***then***

=> **brick can be accepted**

Translation ZKG, No2 (1989) 57-67

* W ≤ 0.2 mm is defined as hair-line crack and can be accepted

- Broken corners



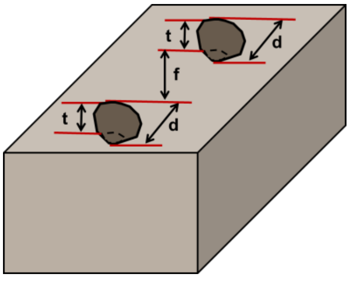

**If**

a + b + c ≤ 60 mm ***and***

≤ 2 number of defects (1 on hot- and 1 on cold-face) ***then***

=> **brick can be accepted**

- Fusion cavities




**If**

d ≤ 8 mm ***and***

t ≤ 8 mm ***and***

≤ 1 number of defects per surface ***then***

=> **brick can be accepted**

# Refractory

## Requirements on Refractory for Main Burner

Anchoring

- Anchor design:
  - Helical or V-form round steel, 6-8 mm diameter, 50-80 mm length (according to refractory thickness)
  - Expansion of the anchorage has to be allowed by plastic caps fitted on the tip
  - Distance between the anchors in the range of in the range of 50-90 mm.
- Anchor material:
  - EN 1.4845 (AISI 310 H) – standard choice
  - EN 1.4862 (INCOLOY alloy DS) – choice for elevated temperatures
  - EN 2.4851 (AISI 601, INCONEL 601) or HAYNES HR-160 for very critical applications (corrosion, temperature)

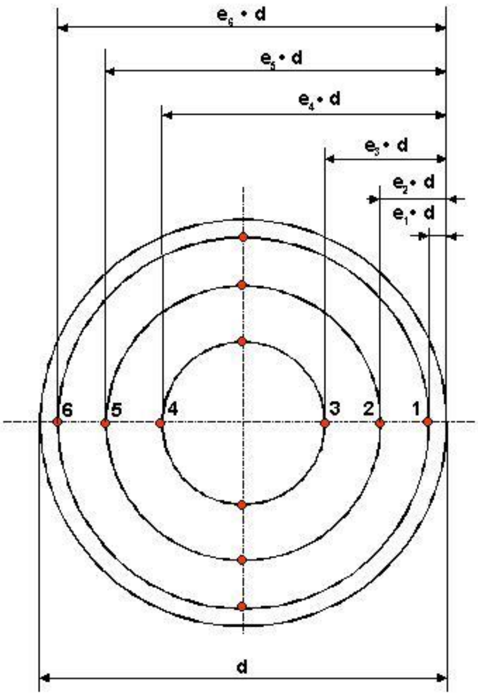
Castable at burner tip

- Castable design:
  - Lining thickness generally 80 mm, however for new burner installations nowadays castable thickness of 100 mm
  - Expansion joints thickness in the range of 6-10 mm, provided by ceramic felt or paper.
  - 3-5 axial expansion joints over burner pipe circumference to be used (no expansion joint @ 6 o'clock position)
  - radial expansion joint every 270 -350 mm on the first meter from the burner tip and every 500 - 800 mm afterwards
  - Vertical burner pipe position is preferred during casting procedure
  - Pre-tempering of the new cast burner pipe is mandatory

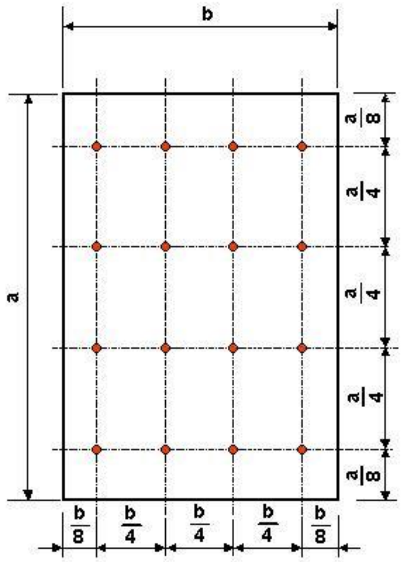
- Castable material:
  - high $Al_2O_3$-containing (> 90 % $Al_2O_3$) low cement castables with low porosity (in case of alkali-attack: < 90 % $Al_2O_3$ with $Zr_2O$ or SiC)
  - examples of proven qualities: Refratechnik: Refracorund 95 LCC / Harbison-Walker: Ultra-Green SR / Calderys: Pliflow T90 / RHI: Comprit 180 H / Resco: Sureflow 93 LC / Höganäs Bjuf: Victor Korund ES QF

# Measuring Points and Flow Measurement

Circular section

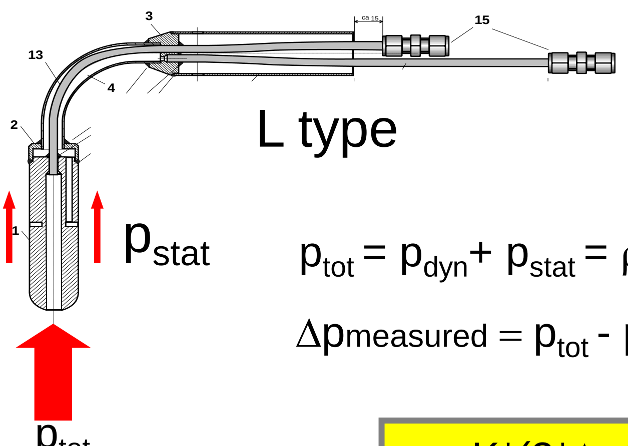


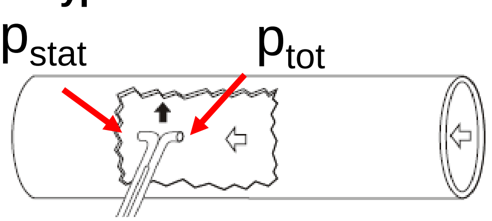

Rectangular section




| Nr. | Measuring points 10 e= | 8 e= | 6 e= | 4 e= |
|---|---|---|---|---|
| 1 | 0.025 | 0.032 | 0.044 | 0.067 |
| 2 | 0.080 | 0.105 | 0.147 | 0.250 |
| 3 | 0.145 | 0.194 | 0.296 | 0.750 |
| 4 | 0.225 | 0.323 | 0.704 | 0.933 |
| 5 | 0.340 | 0.677 | 0.853 | |
| 6 | 0.660 | 0.806 | 0.956 | |
| 7 | 0.775 | 0.895 | | |
| 8 | 0.855 | 0.968 | | |
| 9 | 0.920 | | | |
| 10 | 0.975 | | | |

## Pitot-tube (Prandtl-tube) measurement L and S type:




S type

$$p_{tot} = p_{dyn} + p_{stat} = \rho/2 * v^2 + p_{stat}$$

$$\Delta p_{measured} = p_{tot} - p_{stat} = \rho/2 * v^2$$

$$\boxed{v = K*(2*\Delta p/\rho)^{0.5}}$$

K: Calibration factor based on tube design. Typical K-factor: L type: 1, S-type: 0.84 (KIMO)

# Flow Rate Measurement of Fresh Air Fans

## Calibration of flow rate measurement for fresh air fans (e.g. cooler fans or primary air fans)

Pressure measurement (dp) used for on-line calculation of flow-rate

Measuring points for flow-rate calibration (determination of factor "α")

**Factor "α" should be determined by measuring (the normal range of the nozzle coefficient α for curved inlets is 0.89 – 0.98. In modern designs a typical nozzle coefficient α is 0.95. )**

$$V = A \cdot \alpha \cdot \sqrt{\frac{2 \cdot dp}{\rho}}$$

V = Flow rate [m3/s]

A = Cross section of suction tube [m2]

dp = Pressure difference 'suction tube' to 'ambient' [Pa]

ρ =  Gas density [kg/m3]

α = Correction factor of suction tube [-]

**Note:** More details on iShare: "Air Flow Measurement by Means of the Piezo Ring at the Fan Inlet"

# Gas, Materials and Fuels Properties

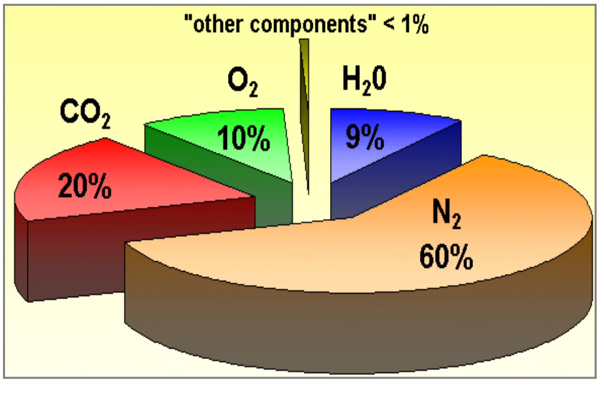
## Density of Kiln Exhaust Gas (Approx. Calculation)

[kg/Nm3] - Ideal gas at normal conditions

$$\rho_{n,dry} = \frac{\%O_{2,dry}}{100} \cdot 1{,}429 + \frac{\%CO_{2,dry}}{100} \cdot 1{,}964 + \left(1 - \frac{\%O_{2,dry}}{100} - \frac{\%CO_{2,dry}}{100}\right) \cdot 1{,}257$$

$$\rho_{n,wet} = \rho_{n,dry} \cdot \left(1 - \frac{\%H_2O}{100}\right) + \frac{\%H_2O}{100} \cdot 0{,}804$$

## Typical Kiln Exhaust Gas Composition




| Other components | „Typical Value“ |
|---|---|
| ▪ NOx | 0.04 % |
| ▪ $SO_2$ | 0.01 % |
| ▪ VOC² | 0.004 % |
| ▪ CO | 0.04 % |
| ▪ HCl | 0.0006 % |
| + Dust | |

% $CO_2$ = f(fuel, raw mat,…..)

# Gas, Materials and Fuels Properties

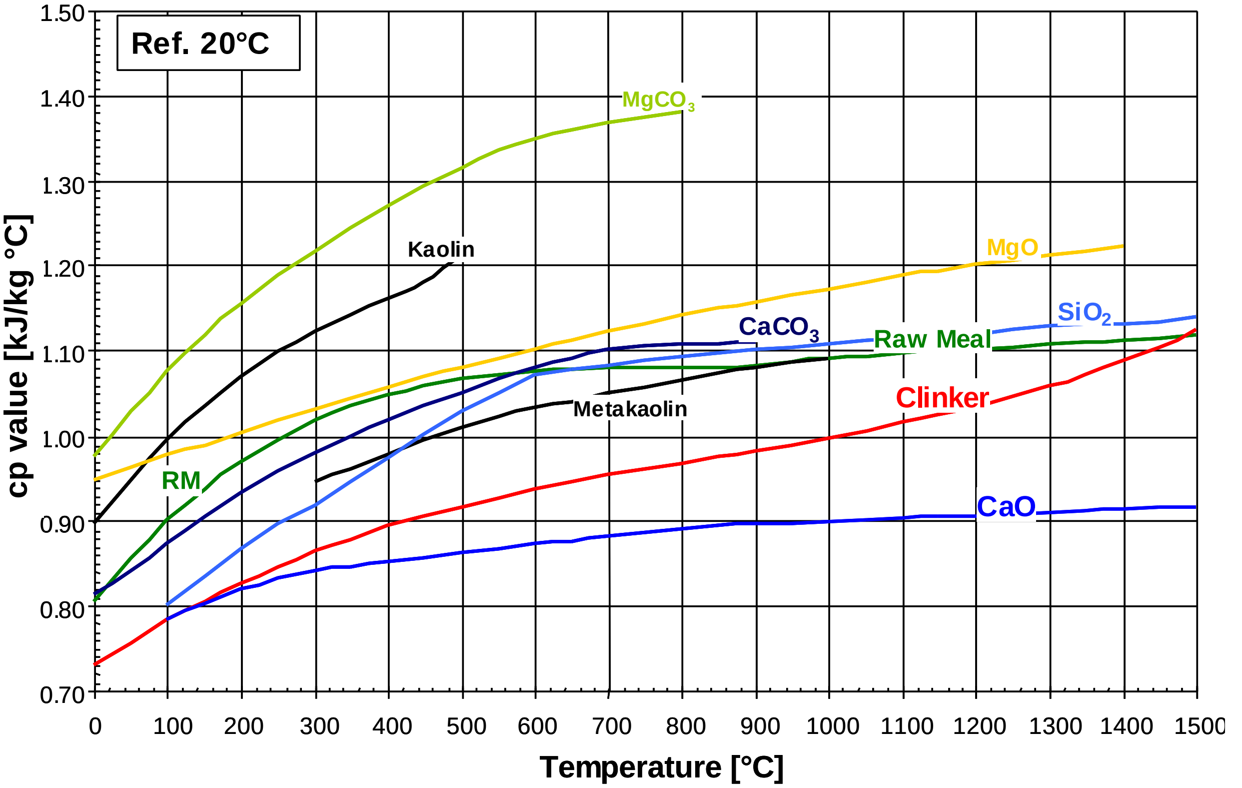
## Sensible Heat $c_p$ of Solids, Liquids and Gases

The following specific heats are **average values** between the temperature T and the **reference temperature of 20°C**. The calculation of the sensible heat difference between two temperatures is as follows:

**Example:** T1 = 200°C , T2 = 100°C , m = Mass [kg]

$$\Delta H_{(200°C-100°C)} = m \cdot \left(c_{p,avg(at\ 200°C)} \cdot (200°C - 20°C) - c_{p,avg(at\ 100°C)} \cdot (100°C - 20°C)\right)$$

### Average Sensible Heat $c_p$ of Solids [kJ/kg °C]




### Sensible Heat of (liquid) Water

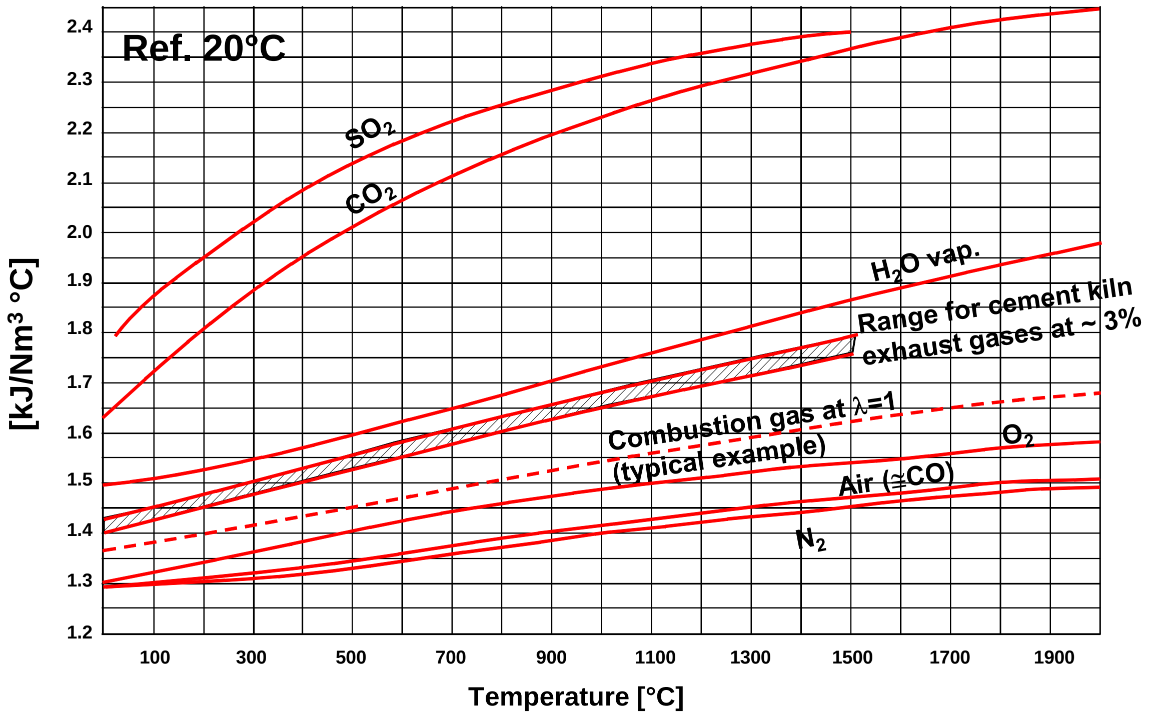
| $C_p$ of liquid water | |
|---|---|
| 0°C | 4,22 kJ/kg °C |
| 50°C | 4,18 kJ/kg °C |
| 100°C | 4,22 kJ/kg °C |

### Heat of Evaporation of Water (h)

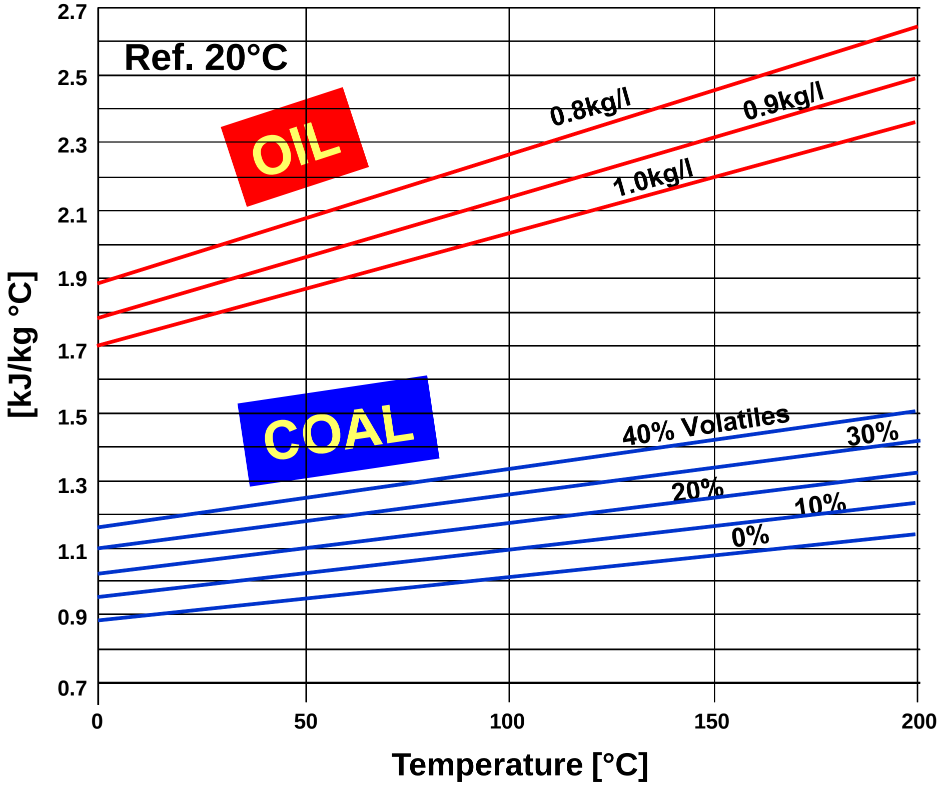
$$h[kJ] = 2450 \left[\frac{kJ}{kg\ H_2O}\right] \cdot m\,[kg]$$

# Gas, Materials and Fuels Properties

## Average Sensible Heat $c_p$ of Gases [kJ/Nm³ °C]




## Average Sensible Heat $c_p$ of Fuels [kJ/Nm³ K]

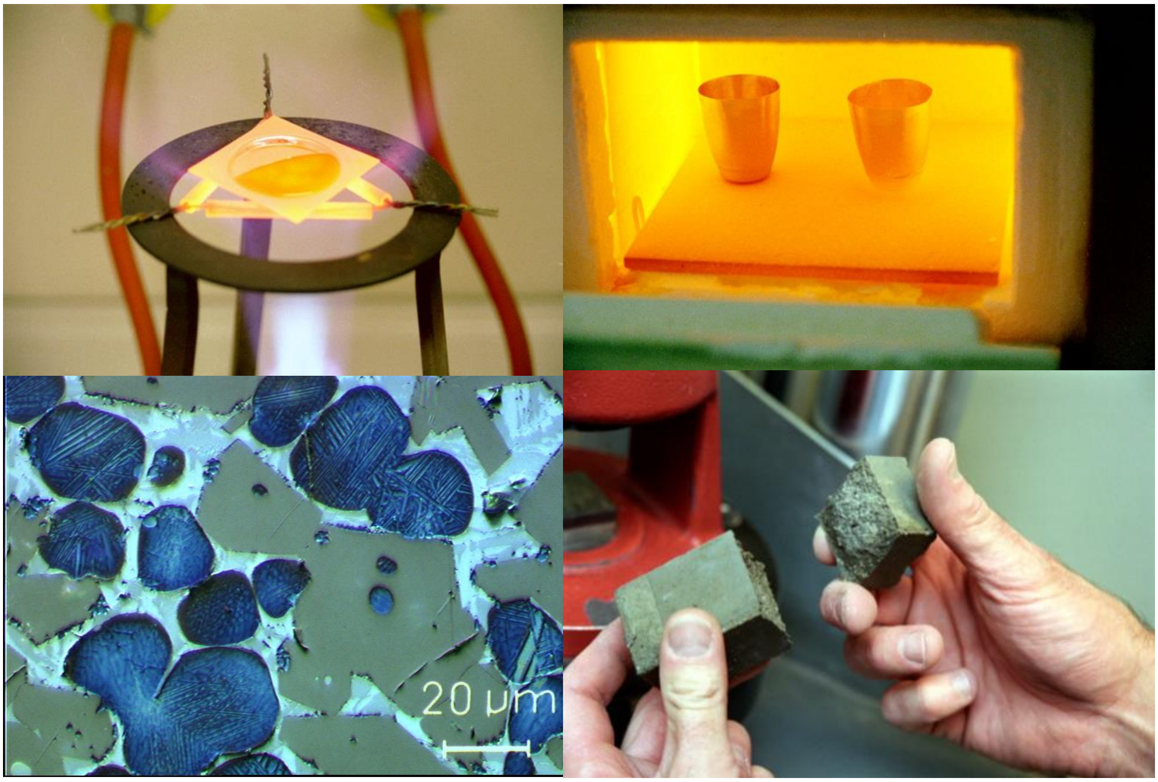


# Own Formulas and Notes

# Own Formulas and Notes

# Reference Guide for

## Materials Technology



# Contents Materials Technology

# Moduli and Quality Parameter

## Lime Saturation (LS)

$$LS = \frac{CaO*100}{2.8*SiO_2 + 1.18*Al_2O_3 + 0.65*Fe_2O_3}$$

Modified for
MgO content < 2.0%

$$LS = \frac{100*(CaO + 0.75*MgO)}{2.8*SiO_2 + 1.18*Al_2O_3 + 0.65*Fe_2O_3}$$

Modified for
MgO content ≥ 2.0%

$$LS = \frac{100*(CaO + 1.5)}{2.8*SiO_2 + 1.18*Al_2O_3 + 0.65*Fe_2O_3}$$

## Silica Ratio (SR)

$$SR = \frac{SiO_2}{Al_2O_3 + Fe_2O_3}$$

## Alumina Ratio (AR)

$$AR = \frac{Al_2O_3}{Fe_2O_3}$$

## Total Alkali

$$Na_2O\text{-equivalent} = Na_2O + 0.658 * K_2O$$

Requirement for „low alkali“ cement ≤ 0.60%

# Moduli and Quality Parameter

## Molar alkali/sulfur ratio

$$Alkali/sulfur = \frac{\frac{K_2O}{94} + \frac{Na_2O}{62} - \frac{Cl}{71}}{\frac{SO_3}{80}}$$

Typical range : 0.8 - 1.7 (Holcim Clinker 2011)

Operational Limits: see “Alk/$SO_3$/CL-Balance” in Thermal Technology Part

The reciprocal value of the molar alkali/sulfur ratio is known as “Sulfatization degree“:

$$Sulfatization\ degree\ [\%] = \left(\frac{\frac{SO_3}{80}}{\frac{K_2O}{94} + \frac{Na_2O}{62}}\right) \cdot 100$$

**Quality aspects of unbalanced alkali/sulfur ratio:**

A/S >> 1: Formation of orthorhombic (reactive) $C_3A$, disturbed setting behaviour

A/S << 1: Reduction of Alite content due to

- Stabilization of belite by $SO_3$
- Formation of (Ca, $SO_4$) minerals, reducing CaO available for Alite formation

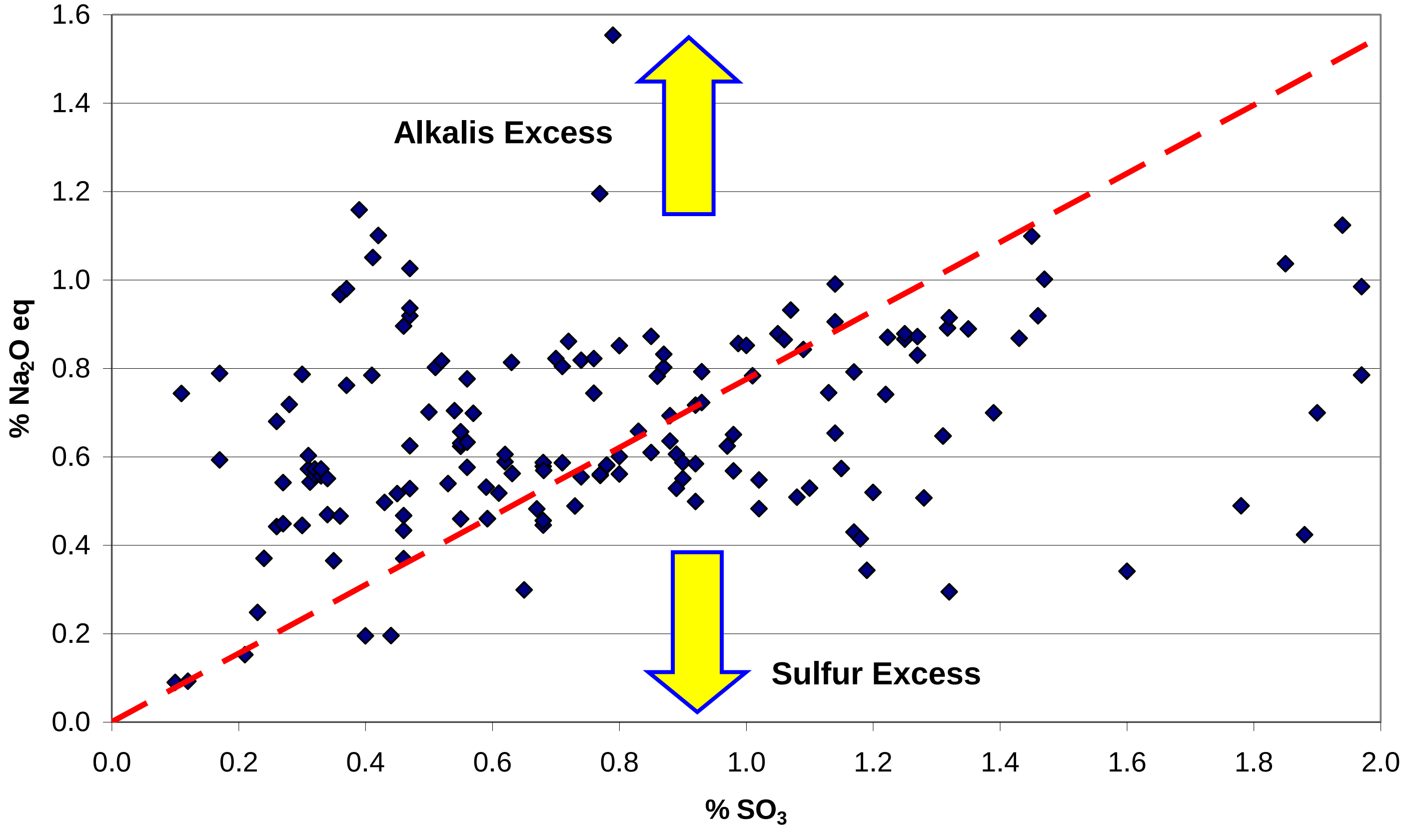
## Degree of precalcination

$$\%\ Precalcination = \left(1 - \frac{P_2(100 - P_1)}{P_1(100 - P_2)}\right) 100$$

P1 = L.o.i. of raw meal P2 = L.o.i. of hot meal

# Moduli and Quality Parameter

## ▪ Alkalis and $SO_3$ in Holcim Clinker (ATR 2009)



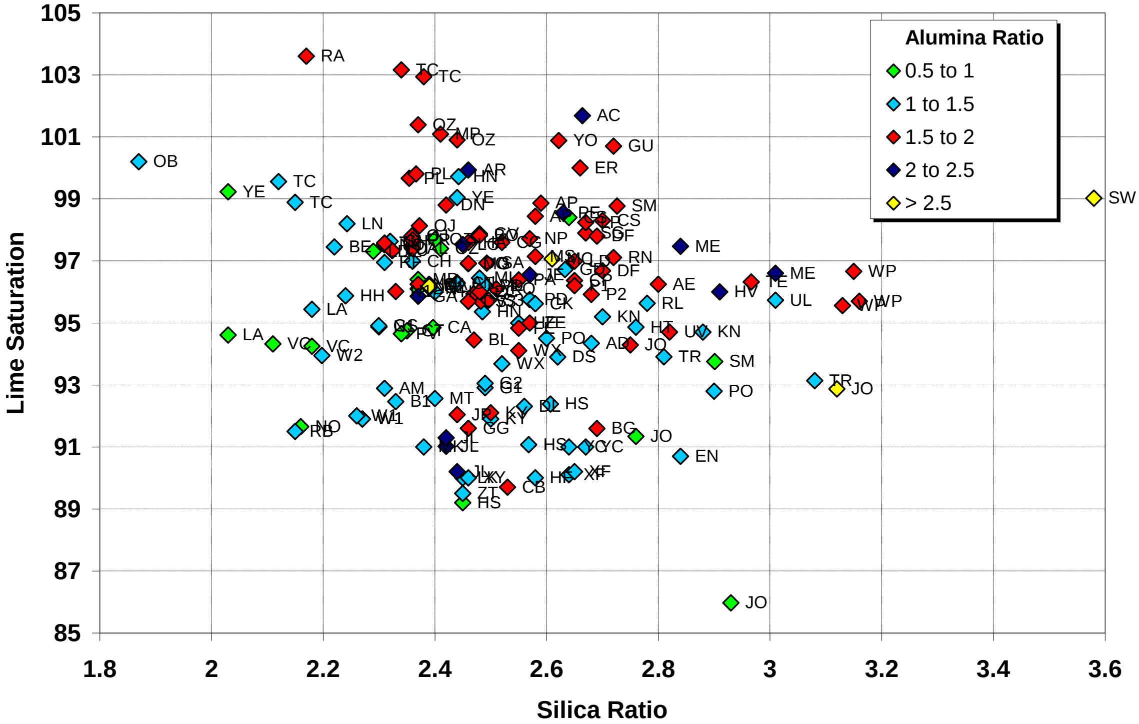

Red line represents molar Alkali / Sulfur ratio = 1

## ▪ Typical Moduli of Holcim Clinker (ATR 2009)

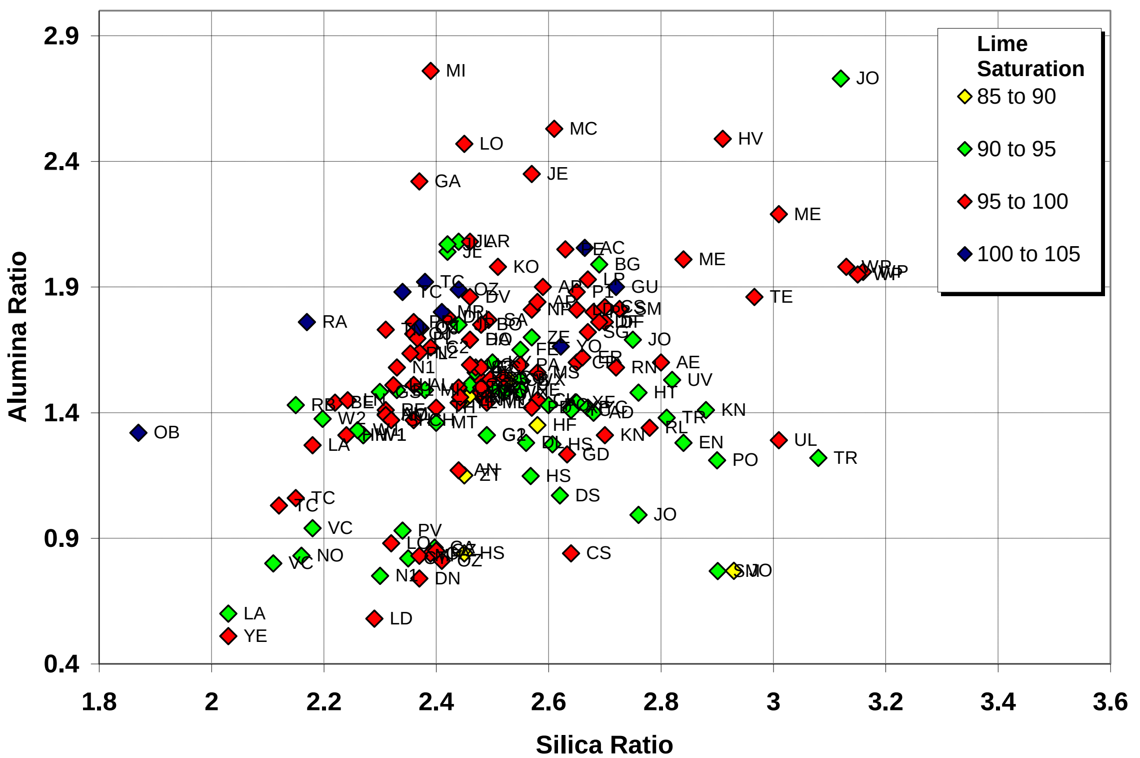
| | Lower Quartile | | Upper Quartile | **Median ATR 2009** |
|---|---|---|---|---|
| **LS** | 93.9 | - | 97.6 | 96.1 |
| **SR** | 2.37 | - | 2.65 | 2.48 |
| **AR** | 1.32 | - | 1.76 | 1.50 |

# Moduli and Quality Parameter

## LS and SR Moduli (ATR 2009)




## AR and SR Moduli (ATR 2009)



# Holcim Burnability Test

The test is based on the isothermal burning for 15 min. at 1400°C of raw meal nodules
It allows the determination of the relative influence of the various material parameter to be ascertained, free from the influence of process technological disturbances

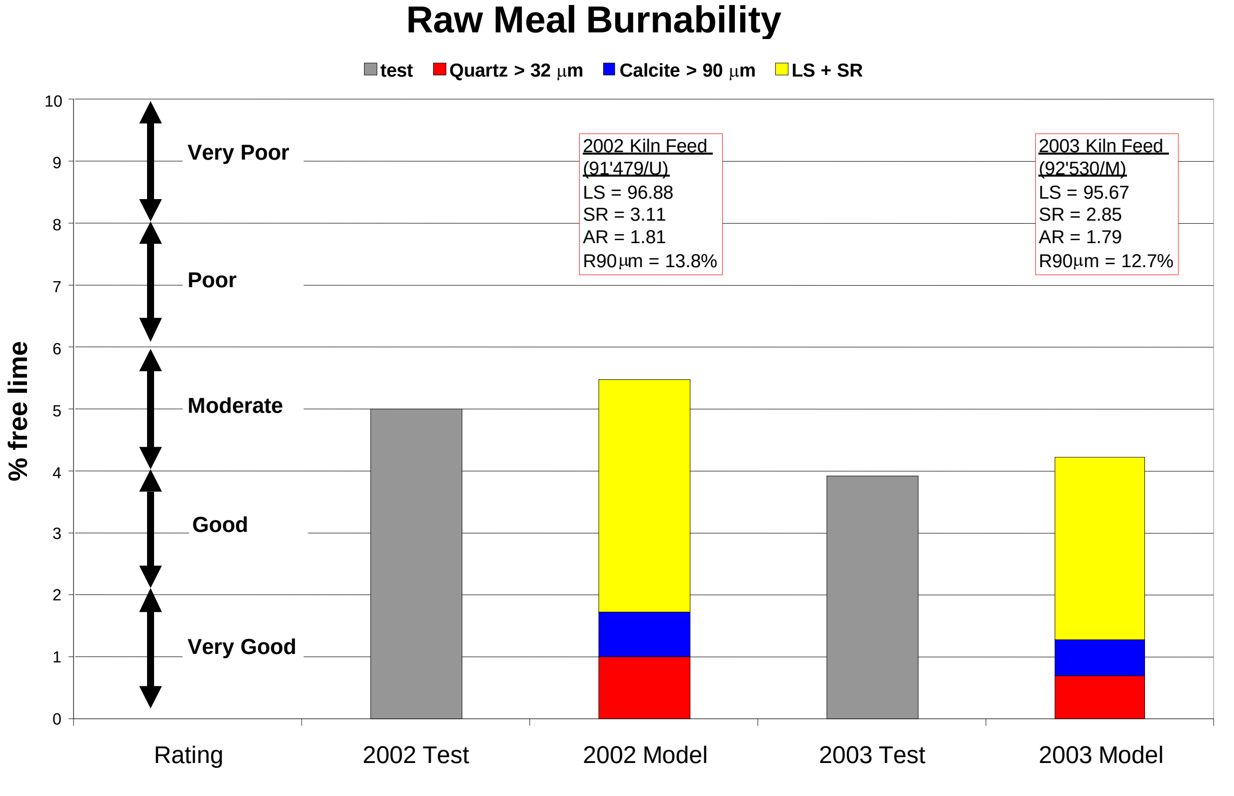
| Evaluation | % Free Lime |
|---|---|
| Very Good | 0 - 2 |
| Good | 2 - 4 |
| Moderate | 4 - 6 |
| Poor | 6 - 8 |
| Very Poor | > 8 |

- ## Physico-chemical Burnability Model

This model allows the calculation of the CaO-free content as expected to result from the burnability test - provided that the lime saturation (LS), the silica ratio (SR), the percentage of coarse calcite (Cc) larger than 90µm, and quartz (Q) lager than 32µm have been previously determined - according to the formula :

$$CaOf = 0.561 \cdot Q{>}32\mu m + 0.166 \cdot Cc{>}90\mu m + 0.356 \cdot LS + 0.804 \cdot SR - 33.886$$

- ## Example for Physico-chemical Burnability Model



# Basic Raw Material Mineralogy

## Classification of Raw Mix Components:

| % CaCO3 | Clay | Designation | Petrographic Design |
|---|---|---|---|
| 95 - 100 | | High-grade Limestone | Limestone, Marble, Chalk, Coral Limestone |
| 85 -95 | | Limestone | Lime Sand, Shell Deposit |
| 75 - 85 | | Marly Limestone | Marly Limestone |
| 65 - 75 | 25 - 35 | Calcareous Marl | Calcareous Marl |
| 35 - 65 | 35 - 65 | Marl | Marl |
| 25 - 35 | 65 - 75 | Clayey Marl | Clayey Marl |
| 15 - 25 | 75 - 85 | Marly Clay | Clay, Loess |
| 5 - 15 | 85 - 95 | Clay | Claystone, Mudstone |
| 0 - 5 | 95 - 100 | High Grade Clay | Siltstone, Shale |

## Mineral Composition of Raw Mixes:

| | | |
|---|---|---|
| Carbonates: | Calcite | $CaCO_3$ |
| | Aragonite | $CaCO_3$ (polymorph to Calcite) |
| | Dolomite | $CaMg(CO_2)_3$ |
| | Magnesite | $MgCO_3$ |
| | Siderite | $FeCO_3$ ($MgCO_3$ and $FeCO_3$ have the same structure) |
| Silicates: | Quartz | $SiO_2$ |
| | Feldspars | e.g. $(K,Na)AlSi_3O_8$ |
| | Micas | e.g. $K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$ |
| | Clay Minerals | e.g. $Al_4[Si_4O_{10}](OH)_8$ |
| | Amphiboles | e.g. $Ca_2Mg_5Si_8O_{22}(OH)_2$ |
| | Pyroxenes | e.g. $Ca_2[SiO_6]$ |
| | Olivines | e.g. $(Mg,Fe)_2[SiO_4]$ |
| Oxide | Hematite | $Fe_2O_3$ |
| | Magnetite | $Fe_3O_4$ |
| Hydroxides | Gibbsite | $Al(OH)_3$ |
| | Goethite | FeOOH |
| Sulfides | Pyrite | $FeS_2$ |
| Sulphates | Gypsum | $CaSO_4$*2 $H_2O$ |
| | Anhydrite | $CaSO_4$ |

# Clinker Liquid Phase & Coating Behavior

## Liquid Phase (LP)

- **1 338 °C** — **AR < 1.38** → **LP = 8.5*$Al_2O_3$-5.22*$Fe_2O_3$+MgO+$K_2O$+$Na_2O$**
  - **AR > 1.38** → **LP = 6.1*$Fe_2O_3$+MgO+$K_2O$+$Na_2O$**
- **1 400 °C** — **MgO < 2 %** → **LP = 2.95*$Al_2O_3$+2.2*$Fe_2O_3$+MgO+$K_2O$+$Na_2O$**

**Guide values:**

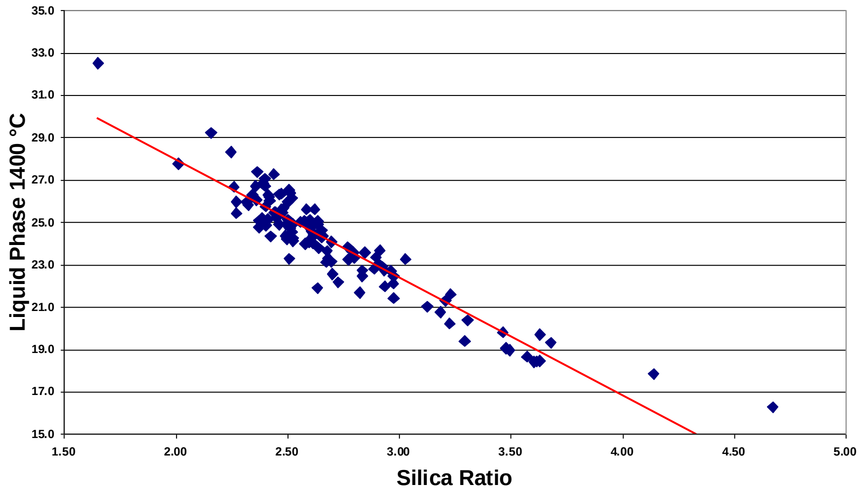
- 23-27% = normal range
- <23% = low amount of liquid phase
- >27% = high amount of liquid phase

- **1 450 °C** — **MgO < 2 %** → **LP = 3.0*$Al_2O_3$+2.25*$Fe_2O_3$+MgO+$K_2O$+$Na_2O$**

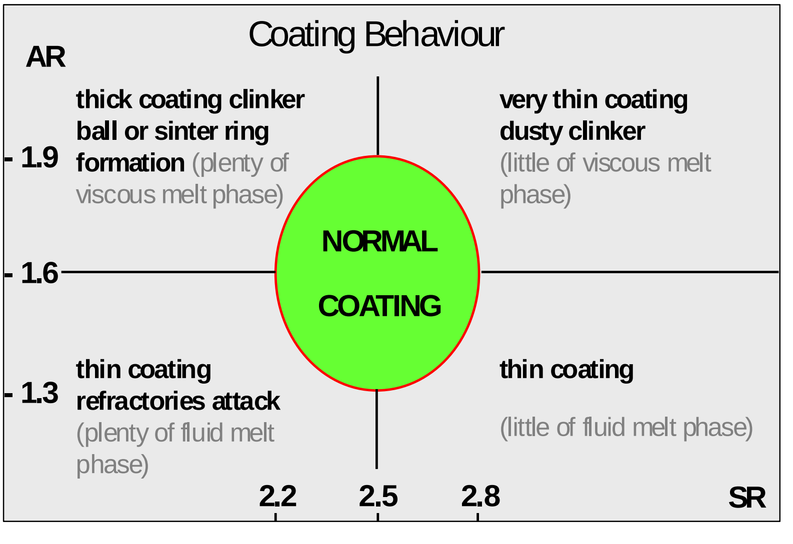
**Calculated according to Lea & Parker (on clinker basis)**

## Correlation of Quantity of Liquid Phase with Silica Ratio

(Data from Holcim industrial clinkers, Product Handbook)




## Coating



# Clinker Minerals

## Typical Ranges of Clinker Phases

| Mineral Name | Chemical formula | Simplified formula | Content in clinker (%) | |
|---|---|---|---|---|
| | | | Normal OPC clinker | Mineralized clinker |
| Alite | $Ca_3SiO_5$ | $C_3S$ | 60 – 70 | 70 – 80 |
| Belite | $Ca_2SiO_4$ | $C_2S$ | 10 – 20 | 0 – 10 |
| Aluminate | $Ca_3Al_2O_6$ | $C_3A$ | 7 – 10 | 7 – 10 |
| Ferrite | $Ca_4Al_2Fe_2O_{10}$ | $C_4AF$ | 7 – 10 | 7 – 10 |
| Free lime | CaO | CaOf | 0.5 – 1.5 | 0.5 – 1.5 |
| Periclase | MgO | M | 0.6 – 1.2 | 0.6 – 1.2 |
| Alkali sulfates | $K_2SO_4$ | | 0.6 – 1.2 | 0.6 – 1.2 |

## Bogue Calculation of Clinker Phase Composition (AR > 0.64)

$C_3S = 4.071*CaO – 7.60*SiO_2 – 6.718*Al_2O_3 – 1.430*Fe_2O_3$

$C_2S = 8.60*SiO_2 + 5.068*Al_2O_3 + 1.079*Fe_2O_3 – 3.071*CaO$
$= 2.867*SiO_2 – 0.754*C_3S$

$C_3A = 2.650*Al_2O_3 – 1.692*Fe_2O_3$

$C_4AF = 3.043*Fe_2O_3$

Corrections: $CaO = CaO_{tot} – CaO_{free}$ For clinker

$CaO = CaO_{tot} – 0.7*SO_3$ For OPC, acc. to ASTM

---

Clinker phases can analytically be quantified by

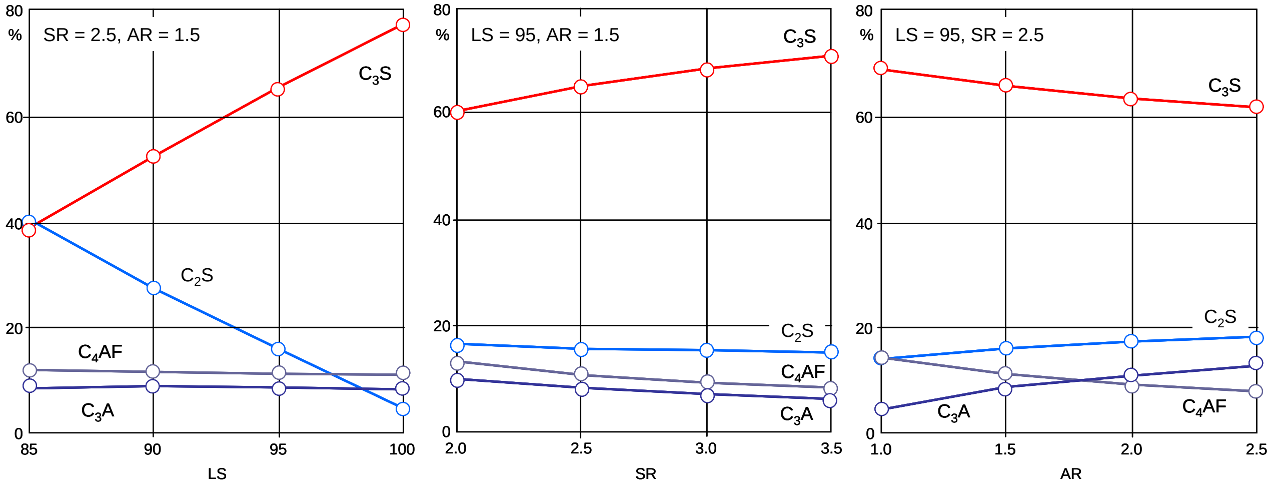
- Microscopy (point counting)
- X-Ray Diffraction (Rietveld quantification)

Compared to these methods, the Bogue calculation shows in general

- Lower values for $C_3S$
- Higher values for $C_2S$
- No clear trend for $C_3A$ and $C_4AF$

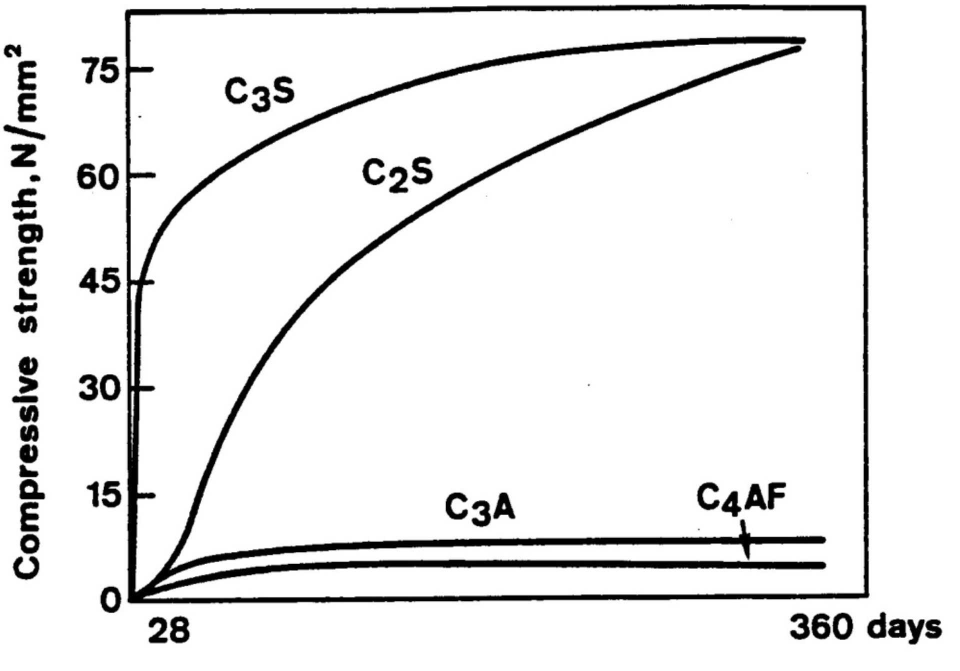
# Clinker Minerals

## Correlation between clinker moduli and main clinker phases



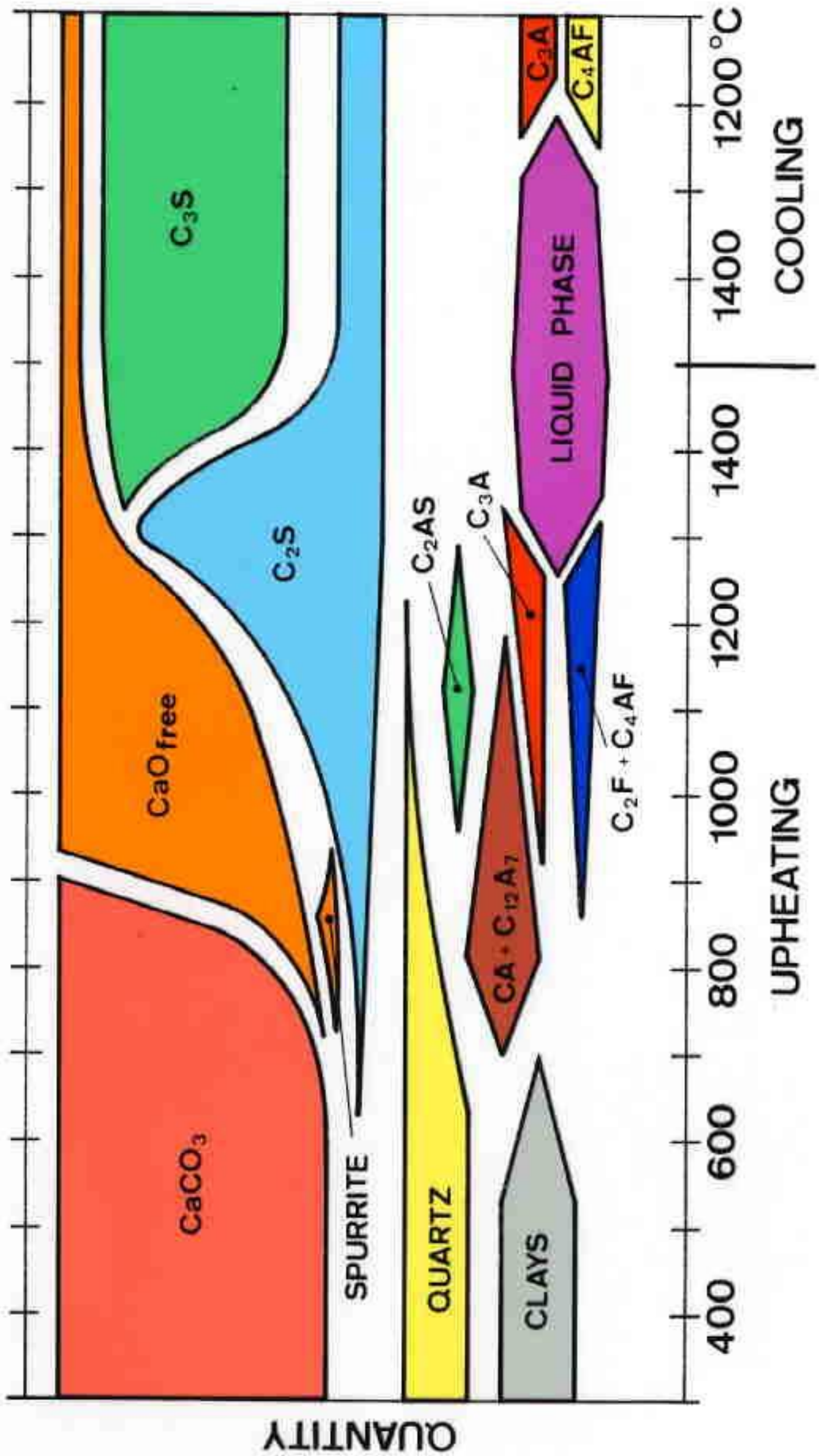

Correlation with **LS** Correlation with **SR** Correlation with **AR**

## Compressive strength development of main clinker minerals



# Clinker Minerals

Quasi Quantitative Variation of Minerals with Temperature



# Significance of Clinker Minerals for Cement Properties and ASTM Cement Types

## Significance of Clinker Minerals for Cement Properties:

- $C_3S$ Contributes to early and late strength (1 d - …)
  Increases heat of hydration
- $C_2S$ Contributes to late strength (28 d - …)
- $C_3A$ Contributes to early strength (1 – 3 d)
  Increases heat of hydration
  Impairs resistance to sulphate attack
- $C_4AF$ Little effect

## Significance of Clinker Minerals for ASTM Cement Types:

- Type I Portland no restrictions regarding clinker minerals
- Type II Portland with moderate sulphate resistance
  (and moderate heat of hydration)
  $C_3A$ max. 8 %
  ($C_3S$ + $C_3A$ max. 58% for moderate heat of hydration)
- Type III Portland with high early strength
  $C_3A$ max. 15%
  ($C_3A$ max. 8% for moderate sulphate resist)
  ($C_3A$ max. 5% for high sulphate resist.)
- Type IV Portland with low heat of hydration
  C3S max. 35%
  C2S min. 40%
  C3A max. 7%
- Type V Portland with high sulphate resistance
  C3A max. 5.0 %
  C4AF + 2 C3A max. 25% or C4AF + 2 C2F max. 25%

# Effect of clinker/cement composition in paste and mortar properties

| Clinker phase | Early strength | Final strength | Setting time | Water demand | Soundness |
|---|---|---|---|---|---|
| Alite | ↑ | ↑ | - | - | - |
| Belite | ↓ | ↑ | - | - | - |
| Aluminate | ↑ | ↓ | ↓ | ↑ | - |
| Ferrite | (↓) | (↑) | - | (↓) | - |
| Free lime | - | - | ↓ | - | negative |
| Alkali sulfates | ↑ | ↓ | (see below) | ↑ | - |
| Periclase | - | - | - | - | negative |

| Minor elements | Early strength | Final strength | Setting time | Water demand | Soundness |
|---|---|---|---|---|---|
| $P_2O_5$ | ↓ | - | (↑) | - | - |
| F | ↑ | ↑ | ↑ | - | - |
| Cl | ↑ | ↓ | ↓ | ↑ | - |

## Effects from Alkali and Sulfur on Cement Properties

<table>
<tr><th>$Na_2O$-Eq [%]</th><th>$SO_3$ [%]</th><th>A/S</th><th>Low alkali</th><th>Early strength</th><th>Late strength</th><th>Setting time</th><th>Efflore-scence</th></tr>
<tr><td rowspan="3">< 0.60</td><td rowspan="3">< 2.0</td><td>> 1</td><td rowspan="3">Yes</td><td>~</td><td>~</td><td>↓</td><td rowspan="3">~</td></tr>
<tr><td>~ 1</td><td rowspan="2">↑</td><td rowspan="2">↓</td><td rowspan="2">↑</td></tr>
<tr><td>< 1</td></tr>
<tr><td rowspan="3">0.6 – 1.0</td><td rowspan="3">< 2.0</td><td>> 1</td><td rowspan="3">No</td><td>~</td><td>~</td><td>↓</td><td rowspan="3">~</td></tr>
<tr><td>~ 1</td><td rowspan="2">↑</td><td rowspan="2">↓</td><td rowspan="2">↑</td></tr>
<tr><td>< 1</td></tr>
<tr><td rowspan="3">1.0 – 1.3</td><td rowspan="3">< 2.0</td><td>> 1</td><td rowspan="3">No</td><td>~</td><td>~</td><td>↓</td><td rowspan="3">~</td></tr>
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<tr><td rowspan="3">< 1.3</td><td rowspan="3">> 2.0</td><td>> 1</td><td rowspan="3">~</td><td rowspan="3">~</td><td rowspan="3">↓?</td><td rowspan="3">~</td><td rowspan="3">↑</td></tr>
<tr><td>~ 1</td></tr>
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</table>

# PQM Quality Indicators

5 quality indicators are used for performance monitoring and calculation of the Product Quality Index

| Index | | Indicator | Target |
|---|---|---|---|
| **Product Quality Index** | 1 | Customer complaints related to product quality issues | Company or plant specific<br>**Ratio actual over target < 1** |
| | 2 | Product performance benchmarking | Company or plant specific<br>**≥ 95% of market reference** |
| | 3 | Compliance to internal product specifications | Group standard<br>**≥ 95%** |
| | 4 | Product uniformity (Coefficient of variation 2d or 3d strength) | Group standard<br>**≤ 7% (2d CoV);**<br>**≤ 5% (3d CoV)** |
| | 5 | Compliance to clinker specifications | Group standard<br>**≥ 90%** |

**Responsible:** **Marketing** **Manufacturing**

- Compliance to internal product specifications:
  - Product specifications are established for each product between marketing and manufacturing. They contain product relevant parameters such as strength, setting time, Cl content, etc.
  - The compliance is the percentage of samples (over one month) that comply with the internal product specifications.
- Product uniformity:
  - Coefficient of variation of early strength (2d or 3d) per product over one month. Aggregation over products: Average weighted with production volumes.
  - Preferably based on production samples ex cement mill.
- Compliance to clinker specifications:
  - Percentage of samples (or clinker volume) over one month that comply with the clinker specifications
  - Based on individual clinker samples (frequency: at least every 4h).
  - Mandatory specifications for free lime (minimum: target -0.5%, maximum: target + 1%) and LS ( target ± 2.5). Further specifications, e.g. for $C_3A$ or alkali, to be added if relevant to meet special product requirements.

Details: See Product Quality Management Manual on the Portal

# Uniformity

## Holcim Uniformity Targets

| | | Short term<br>Avg of daily stdev; Impact on Kiln performance | Long term<br>Stdev of daily avg; Impact on product quality |
|---|---|---|---|
| Kiln feed (or clinker) | **LS** | **< 1.2** | **< 1.0** |
| | **SR** | < 0.04 | < 0.03 |
| | **AR** | < 0.04 | < 0.03 |
| Raw meal (tentative) | **LS** | < 3.6 (*) | < 1.0 |

(*) For plants with pre-blending systems

## Example: Calculation of uniformity

| Clinker Lime Saturation | | | | |
|---|---|---|---|---|
| **Date** | **Hour** | **LS** | **Stdev*** | **Avg**** |
| 01.01.10 | 02:00 | 99.1 | | |
| | 06:00 | 98.2 | | |
| | 10:00 | 99.1 | | |
| | 14:00 | 98.6 | | |
| | 18:00 | 98.1 | | |
| | 22:00 | 100.3 | 0.81 | 98.89 |
| 02.01.10 | 02:00 | 99.2 | | |
| | 06:00 | 100.5 | | |
| | 10:00 | 100.5 | | |
| | 14:00 | 99.6 | | |
| | 18:00 | 99.2 | | |
| | 22:00 | 99.8 | 0.60 | 99.79 |
| 03.01.10 | : | : | 0.70 | 97.09 |
| 04.01.10 | : | : | 0.99 | 98.05 |
| 05.01.10 | : | : | 0.86 | 97.72 |
| : | : | : | : | : |
| 29.01.10 | : | : | 0.89 | 97.37 |
| 30.01.10 | : | : | 0.98 | 98.63 |
| 31.01.10 | : | : | 1.08 | 97.59 |

| | | |
|---|---|---|
| Avg | 1.18 | - |
| Stdev | - | 0.74 |

* Standard deviation of all daily samples

** Average of all daily samples

**Average of all daily stdev:**
**Compare with Short term uniformity target**

**Stdev of all daily averages:**
**Compare with Long term uniformity target**

# Uniformity Indicators – Targets for Excellence

| Material | Parameter | Targets for Excellence % | CoV [2] | stdev [3] | stdev [4] |
|---|---|---|---|---|---|
| **Cement** | Compliance to product specifications | ≥ 95 [1] | | | |
| | 2 day compressive strength | | ≤ 7 % | | |
| | 3 day compressive strength | | ≤ 5 % | | |
| | 28 day compressive strength | | ≤ 3 % | | |
| | Residue on 45 µm | | ≤ 10 % | | |
| | Blaine | | ≤ 3 % | | |
| **Clinker** | Compliance to clinker specifications | ≥ 90 [1] | | | |
| | Lime saturation (LS) | | | ≤ 1.2 | ≤ 1.0 |
| | Silica Ratio (SR) | | | ≤ 0.4 | ≤ 0.3 |
| | Alumina Ratio (AR) | | | ≤ 0.4 | ≤ 0.3 |
| | Free lime range (Max - Min) | 1.5 | | | |
| | $SO_3$ | | ≤ 10 % | | |
| | $K_2O$ | | ≤ 10 % | | |
| **Kiln feed** | Lime saturation (LS) | | | ≤ 1.2 | ≤ 1.0 |
| | Silica Ratio (SR) | | | ≤ 0.4 | ≤ 0.3 |
| | Alumina Ratio (AR) | | | ≤ 0.4 | ≤ 0.3 |
| **Raw meal** | Lime saturation (LS) | | | ≤ 3.6 | ≤ 1.0 |
| | Residue on 90 µm | | ≤ 5 % | | |

[1] % of total production volume

[2] Individual values over one month

[3] Short term (avg of daily stdev)

[4] Long term (stdev of daily avg)

# Mineralization

**"Guide for Clinker Mineralization" can be found on iShare**

Mineralization means the addition of fluoride in the raw mix to achieve a level of approx. 0.25% F in clinker. It enables to produce high $C_3S$ clinker (LS approx. 103) under normal burning condition.

**Benefits of mineralization:**

The main benefit of mineralization is the ability to produce higher performance clinker by increasing the LSF and hence the alite content for:

- Increasing the amount of MIC in composite cements (increase of cement volume and financial revenue)
- Production of higher performance cement
- In addition if may offer the possibility to increase the use of high sulfur fuels (petcoke) and raw materials.

**Cost of mineralization :**

- Increase of clinker cost by mineralization with fluorspar: Roughly +1 $/tcli (assuming fluorspar at 200€/t). If an alternative fluoride source is available the cost will be lower (example Ternate and Dotternhausen).
- If the MIC have a lower cost than clinker, the cost of cement with mineralized clinker can be lower compared to composite cement with OPC clinker and a higher clinker factor.
- CAPEX for the installation for storage and dosing is roughly 500'000 USD

# Alternative Raw Materials (AR)

## "Guidelines for Alternative Raw Material (AR) Utilization" can be found on iShare

**Definition:**

- Traditional raw materials are the materials gained from quarries or purchased from primary material supplying industries
- All fuels and raw materials, which are not traditional, are alternative
- Practical interpretation: Alternative raw materials are raw materials that have undergone any kind of previous industrial processing.

**Overview of impact of critical properties:**

| Properties | Environment | Health and Safety | Plant Operation | Product Quality |
|---|---|---|---|---|
| **Physical properties** (granulometry, moisture, heterogeneity) | | | X | |
| **Minor elements** (Cl, F, $SO_3$, alk, MgO etc) | | | X | X |
| **Trace and heavy metals** [1)] | X | X | | (X) |
| **Organics** (TOC, toxic components) | X | X | X | |
| **Mineralogy** (quartz, mullite etc) | | | X | X |

[1)] Chromium issue: soluble chromium in cement limited to 2 ppm in Europe; controlled with Fe(II)-sulfate; no regulations in USA. Significant intake of Cr with AR should be avoided.

**DO'S:**

- Perform expulsion testing before using AR, which have a risk of contamination with volatile organics (risk of critical VOC and dioxin/furan emission)
- Use specially designed equipment for storage, dosing and handling of AR:
  AR often can not be handled with the same equipment as the traditional raw materials
  → Other type of equipment is required
- Watch out for innovative solutions to improve co-processing (e.g. drill cuttings dryer in Macuspana)

**DONT'S:**

- Using of AR at the cold end of the kiln (raw mill, kiln feed), if containing volatile organics (emission)
- Using coarse (un-ground) AR in high amounts directly in the hot end of the kiln
- AR entering the plant without rigorous quality control

# Fuels: Conversion of CV and Basis

- **Converting from "Air-Dry Basis" to "As Received Basis"**

- **Moisture:**

$$M_{ar} = M_{ad} \times \left[\frac{100 - ADL}{100}\right] + ADL$$

$M_{ar}$ = Moisture content as received

$M_{ad}$ = Moisture content air dry basis

ADL = Air dry loss

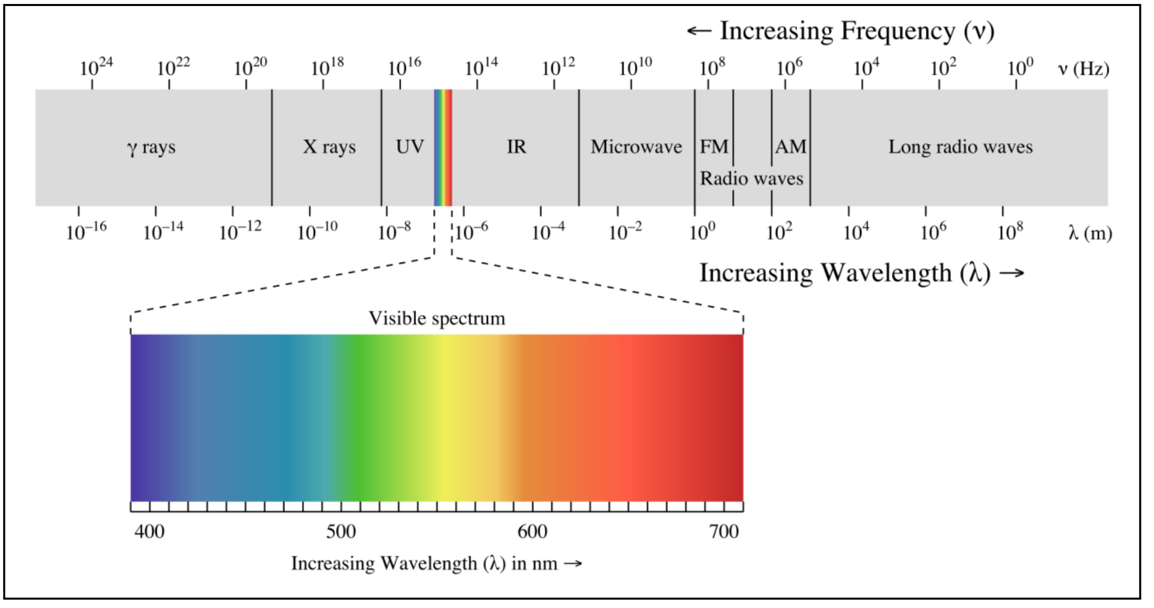
- **Converting Coal and Coke Analyses:**

Conversion Formula Chart

| Given | Wanted: As Determined (ad) | Wanted: As Received (ar) | Wanted: Dry (d) | Wanted: Dry Ash-free (daf) |
|---|---|---|---|---|
| As Determined (ad) | | $\frac{100 - M_{ar}}{100 - M_{ad}}$ | $\frac{100}{100 - M_{ad}}$ | $\frac{100}{100 - M_{ad} - A_{ad}}$ |
| As Received (ar) | $\frac{100 - M_{ad}}{100 - M_{ar}}$ | | $\frac{100}{100 - M_{ar}}$ | $\frac{100}{100 - M_{ar} - A_{ar}}$ |
| Dry (d) | $\frac{100 - M_{ad}}{100}$ | $\frac{100 - M_{ar}}{100}$ | | $\frac{100}{100 - A_{d}}$ |
| Dry Ash-free (daf) | $\frac{100 - M_{ad} - A_{ad}}{100}$ | $\frac{100 - M_{ar} - A_{ar}}{100}$ | $\frac{100 - A_{d}}{100}$ | |

# Physics

## Electromagnetic Spectrum




## Electromagnetic Radiation

**Basic formulas:** $E = h\nu$ **and** $\nu = \dfrac{c}{\lambda}$ **thus** $E = \dfrac{hc}{\lambda}$

**E: Energy of photon [J]**
**h: Planck's constant [Js]**
**c: speed of light [m/s]**
**ν: frequency [Hz = s$^{-1}$]**
**λ: wavelength [m]**
**e: Electron charge [C]**

**$\lambda_{min}$ of X-ray tube operating at voltage V:**

$$\lambda_{min} = \frac{hc}{eV} = \frac{1240}{V}$$

**$\lambda_{min}$: [nm]**

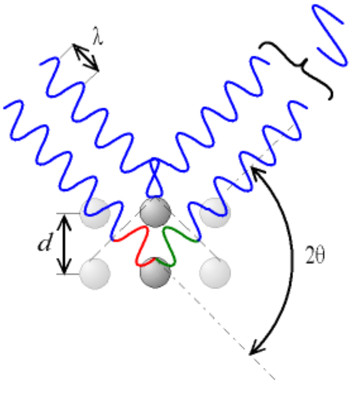
**Moseley's law: (XRF)**

$$\frac{1}{\lambda} = K(Z - \sigma)^2$$

**K, σ: Constants**
**Z: Atomic number**
**λ: wavelength of the characteristic X-ray photon**

**Principle of diffraction: Bragg's law:**

$$n\lambda = 2d\sin\theta$$



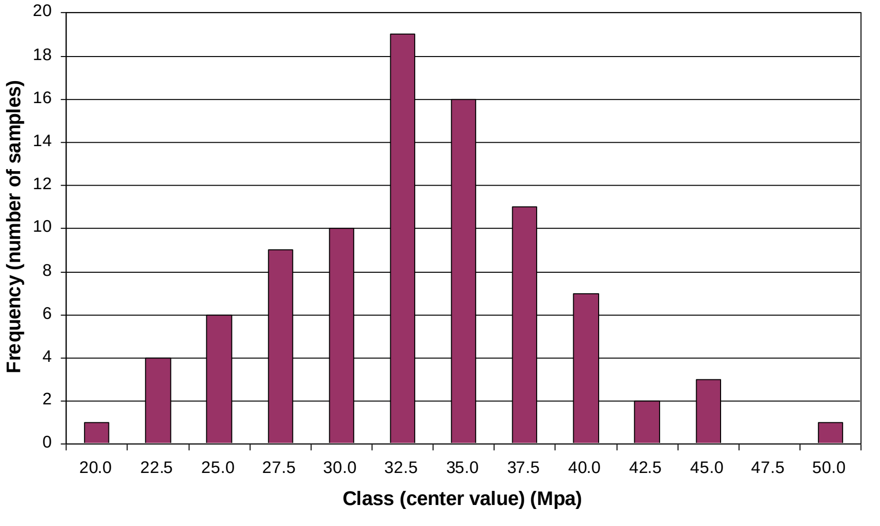

**λ: wavelength incoming photon**
**d: spacing of crystal planes**
**θ: Reflection angle**

# Statistics (1)

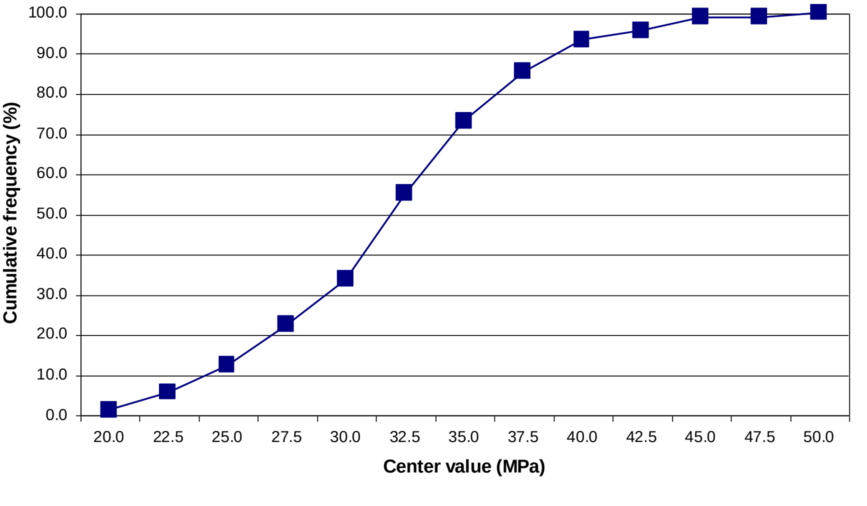
## Frequency table

| Class (MPa) | | Center value (MPa) | Number of samples | Relative frequency (%) | Cumulative frequency (%) |
|---|---|---|---|---|---|
| 18.75 | 21.25 | 20.0 | 1 | 1.1 | 1.1 |
| 21.25 | 23.75 | 22.5 | 4 | 4.5 | 5.6 |
| 23.75 | 26.25 | 25.0 | 6 | 6.7 | 12.4 |
| 26.25 | 28.75 | 27.5 | 9 | 10.1 | 22.5 |
| 28.75 | 31.25 | 30.0 | 10 | 11.2 | 33.7 |
| 31.25 | 33.75 | 32.5 | 19 | 21.3 | 55.1 |
| 33.75 | 36.25 | 35.0 | 16 | 18.0 | 73.0 |
| 36.25 | 38.75 | 37.5 | 11 | 12.4 | 85.4 |
| 38.75 | 41.25 | 40.0 | 7 | 7.9 | 93.3 |
| 41.25 | 43.75 | 42.5 | 2 | 2.2 | 95.5 |
| 43.75 | 46.25 | 45.0 | 3 | 3.4 | 98.9 |
| 46.25 | 48.75 | 47.5 | 0 | 0.0 | 98.9 |
| 48.75 | 51.25 | 50.0 | 1 | 1.1 | 100.0 |
| Total | | | 89 | 100.0 | |

## Histogram




## Cumulative frequency curve



# Statistics (2)

## Measure of location

**Mean**

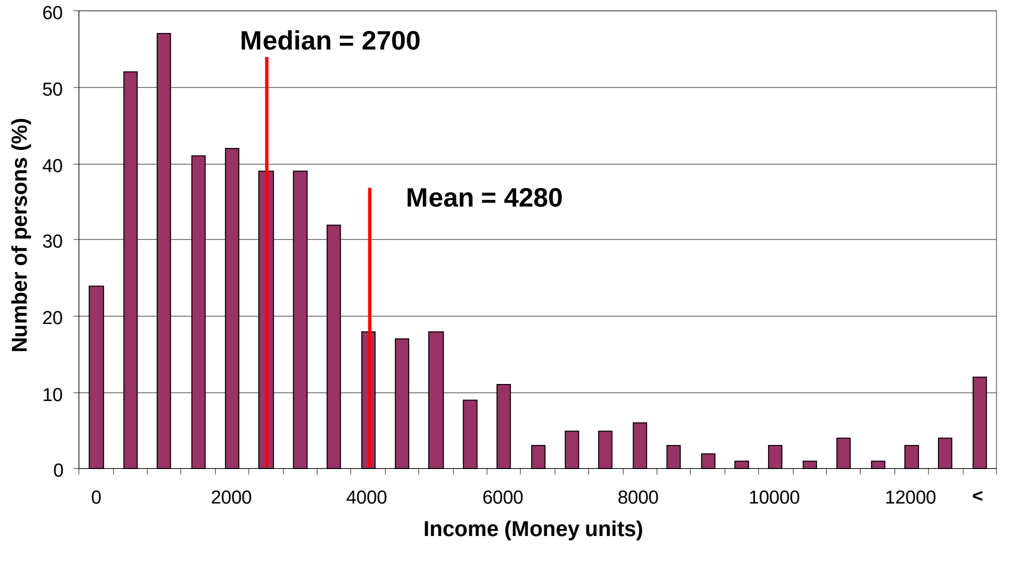
$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots x_n}{n} = 33.2$$

**Median, minimum and maximum**

| i | 1 | ... | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | ... | 89 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $x_i$ | 20.9 | ... | 32.5 | 32.8 | 32.8 | 33.0 | 33.3 | 33.3 | 33.4 | 33.5 | 33.6 | ... | 48.9 |

**minimum** **median** **maximum**

**Mean vs. median: Mean is sensitive to outliers**




## Measure of variability

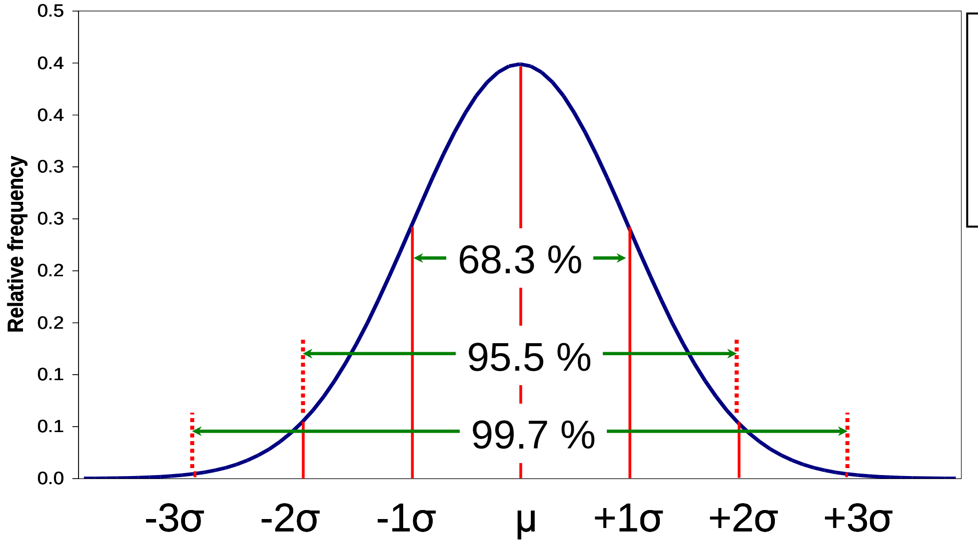
**Standard deviation = square root (Variance)**

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} = 5.6$$

**Range**

Range = maximum – minimum = 28.0

# Statistics (3)




Significance of standard deviation for data following a normal distribution

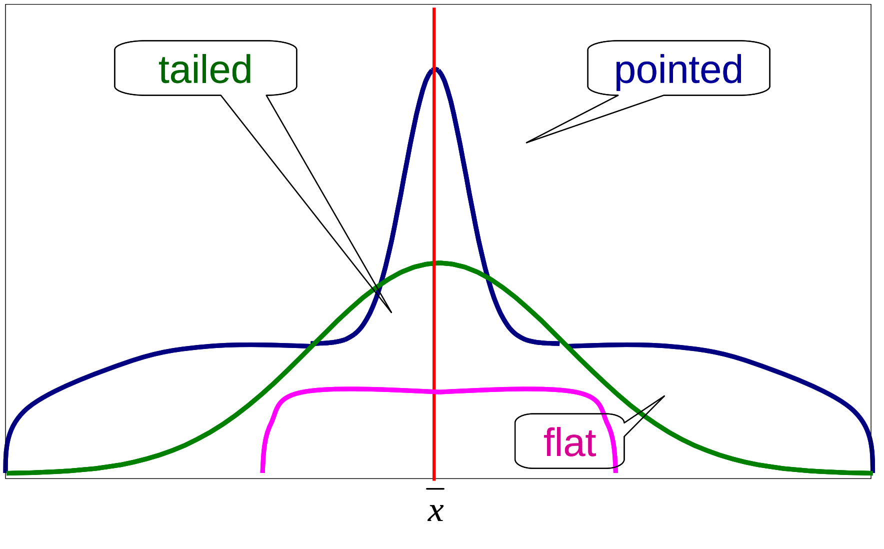
## Coefficient of variation

$$C.o.V. = \frac{s}{\bar{x}} \times 100\,\% = 16.7\%$$

## Criteria for normal distribution

| Criteria: | Example |
|---|---|
| 1 mean ≈ median | 33.2 ≈ 33.3 |
| 2 Coefficient of variation < 30 % | 16.7 % < 30 % |
| 3 Kurtosis: p = 3 ± 14.7/√n | p = 2.96 |
| 4 Skewness: p = 0 ± 7.35/ √n | p = 0.18 |

## Kurtosis




$$p = \frac{\sum (x_i - \bar{x})^4}{s_x^4 (n-1)}$$

$$normal: p = 3 \pm \frac{14.7}{\sqrt{n}}$$

$$pointed: p > 3 + \frac{14.7}{\sqrt{n}}$$

$$tailed\ /\ flat: p < 3 - \frac{14.7}{\sqrt{n}}$$

# Statistics (4)

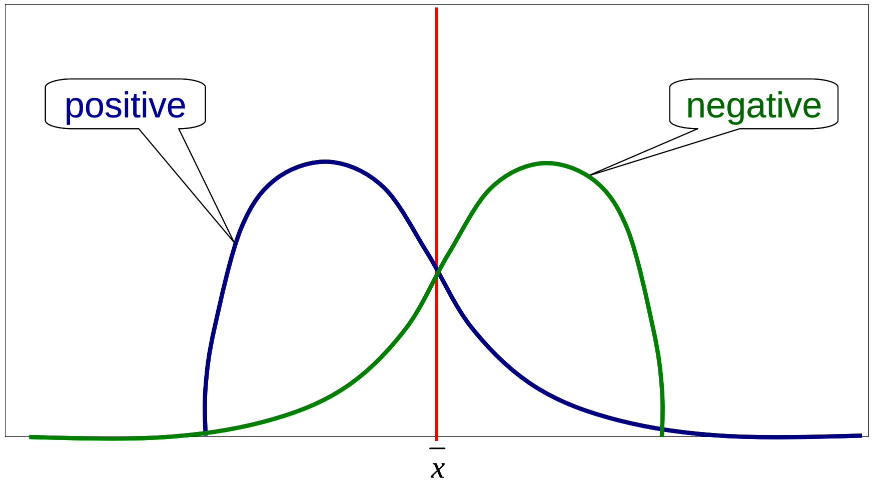
## Skewness

$$p = \frac{\sum (x_i - \bar{x})^3}{s_x^3 (n-1)}$$

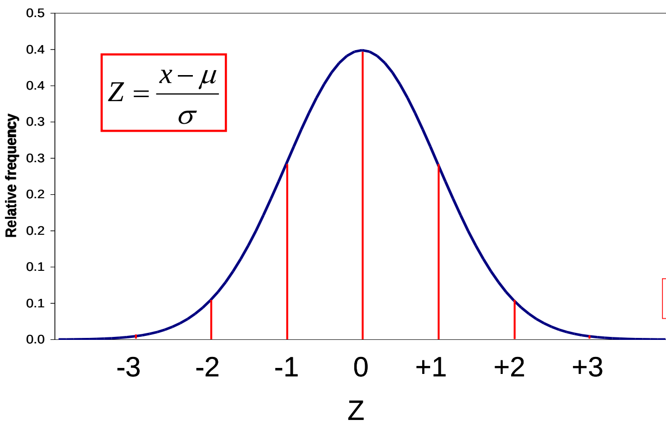
$$normal: p = 0 \pm \frac{7.35}{\sqrt{n}}$$

$$positive: p < \frac{7.35}{\sqrt{n}}$$

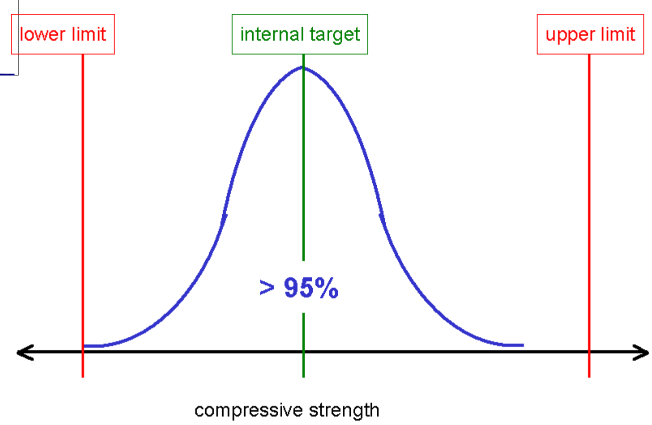
$$negative: p > \frac{7.35}{\sqrt{n}}$$




## Standardised normal distribution (Z)




**Significance of Z**




**Example:**
**Current level and variability of cement mortar strength: Mean: x = 33.2**
**Standard deviation: s = 5.6**
**Questions:**
**How many samples are below the target of 28 MPa?**
**Which is the target for the mean, that must be set that 95% of the samples are above target?**

**One-sided Z-test (Z ⇒ P)** **Z = (x - µ) / s = (28.0 – 33.2) / 5.6 = - 0.93**
**Z-Table (one sided, positive) ⇒ P (Z = 0.93)** **P (0.93) = 0.8238**

**Conclusion: 17.6% of the samples are < 28 MPa.**
**One-sided Z-test (P ⇒ Z)** **Z (P = 0.95) = 1.64**
**Z-Table (one sided, positive) ⇒ Z = -1.64** **µ = x - s × Z = 28.0 - 5.6 × (-1.64) = 37.2 MPa**
**Conclusion: The target for the mean should be 37.2 MPa.**

# Statistics (5)

## Standard normal (Z) table

### Find probabilities associated with the normal distribution


Values of $P$ corresponding to $z_p$ for the normal curve.

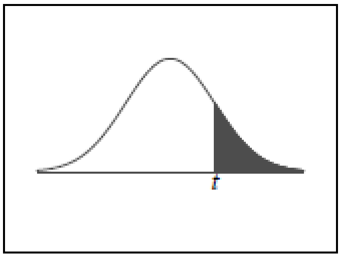
$z$ is the standard normal variable. The value of $P$ for $-z_p$ equals one minus the value of $P$ for $+z_p$, e.g., the $P$ for $-1.62$ equals $1 - .9474 = .0526$.

| $z_p$ | .00 | .01 | .02 | .03 | .04 | .05 | .06 | .07 | .08 | .09 |
|---|---|---|---|---|---|---|---|---|---|---|
| .0 | .5000 | .5040 | .5080 | .5120 | .5160 | .5199 | .5239 | .5279 | .5319 | .5359 |
| .1 | .5398 | .5438 | .5478 | .5517 | .5557 | .5596 | .5636 | .5675 | .5714 | .5753 |
| .2 | .5793 | .5832 | .5871 | .5910 | .5948 | .5987 | .6026 | .6064 | .6103 | .6141 |
| .3 | .6179 | .6217 | .6255 | .6293 | .6331 | .6368 | .6406 | .6443 | .6480 | .6517 |
| .4 | .6554 | .6591 | .6628 | .6664 | .6700 | .6736 | .6772 | .6808 | .6844 | .6879 |
| .5 | .6915 | .6950 | .6985 | .7019 | .7054 | .7088 | .7123 | .7157 | .7190 | .7224 |
| .6 | .7257 | .7291 | .7324 | .7357 | .7389 | .7422 | .7454 | .7486 | .7517 | .7549 |
| .7 | .7580 | .7611 | .7642 | .7673 | .7704 | .7734 | .7764 | .7794 | .7823 | .7852 |
| .8 | .7881 | .7910 | .7939 | .7967 | .7995 | .8023 | .8051 | .8078 | .8106 | .8133 |
| .9 | .8159 | .8186 | .8212 | .8238 | .8264 | .8289 | .8315 | .8340 | .8365 | .8389 |
| 1.0 | .8413 | .8438 | .8461 | .8485 | .8508 | .8531 | .8554 | .8577 | .8599 | .8621 |
| 1.1 | .8643 | .8665 | .8686 | .8708 | .8729 | .8749 | .8770 | .8790 | .8810 | .8830 |
| 1.2 | .8849 | .8869 | .8888 | .8907 | .8925 | .8944 | .8962 | .8980 | .8997 | .9015 |
| 1.3 | .9032 | .9049 | .9066 | .9082 | .9099 | .9115 | .9131 | .9147 | .9162 | .9177 |
| 1.4 | .9192 | .9207 | .9222 | .9236 | .9251 | .9265 | .9279 | .9292 | .9306 | .9319 |
| 1.5 | .9332 | .9345 | .9357 | .9370 | .9382 | .9394 | .9406 | .9418 | .9429 | .9441 |
| 1.6 | .9452 | .9463 | .9474 | .9484 | .9495 | .9505 | .9515 | .9525 | .9535 | .9545 |
| 1.7 | .9554 | .9564 | .9573 | .9582 | .9591 | .9599 | .9608 | .9616 | .9625 | .9633 |
| 1.8 | .9641 | .9649 | .9656 | .9664 | .9671 | .9678 | .9686 | .9693 | .9699 | .9706 |
| 1.9 | .9713 | .9719 | .9726 | .9732 | .9738 | .9744 | .9750 | .9756 | .9761 | .9767 |
| 2.0 | .9772 | .9778 | .9783 | .9788 | .9793 | .9798 | .9803 | .9808 | .9812 | .9817 |
| 2.1 | .9821 | .9826 | .9830 | .9834 | .9838 | .9842 | .9846 | .9850 | .9854 | .9857 |
| 2.2 | .9861 | .9864 | .9868 | .9871 | .9875 | .9878 | .9881 | .9884 | .9887 | .9890 |
| 2.3 | .9893 | .9896 | .9898 | .9901 | .9904 | .9906 | .9909 | .9911 | .9913 | .9916 |
| 2.4 | .9918 | .9920 | .9922 | .9925 | .9927 | .9929 | .9931 | .9932 | .9934 | .9936 |
| 2.5 | .9938 | .9940 | .9941 | .9943 | .9945 | .9946 | .9948 | .9949 | .9951 | .9952 |
| 2.6 | .9953 | .9955 | .9956 | .9957 | .9959 | .9960 | .9961 | .9962 | .9963 | .9964 |
| 2.7 | .9965 | .9966 | .9967 | .9968 | .9969 | .9970 | .9971 | .9972 | .9973 | .9974 |
| 2.8 | .9974 | .9975 | .9976 | .9977 | .9977 | .9978 | .9979 | .9979 | .9980 | .9981 |
| 2.9 | .9981 | .9982 | .9982 | .9983 | .9984 | .9984 | .9985 | .9985 | .9986 | .9986 |
| 3.0 | .9987 | .9987 | .9987 | .9988 | .9988 | .9989 | .9989 | .9989 | .9990 | .9990 |
| 3.1 | .9990 | .9991 | .9991 | .9991 | .9992 | .9992 | .9992 | .9992 | .9993 | .9993 |
| 3.2 | .9993 | .9993 | .9994 | .9994 | .9994 | .9994 | .9994 | .9995 | .9995 | .9995 |
| 3.3 | .9995 | .9995 | .9995 | .9996 | .9996 | .9996 | .9996 | .9996 | .9996 | .9997 |
| 3.4 | .9997 | .9997 | .9997 | .9997 | .9997 | .9997 | .9997 | .9997 | .9997 | .9998 |

# Statistics (6)

## T-Distribution table

**Find probabilities associated with the student's t-distribution (one-sided, df = degrees of freedom)**



The shaded area is equal to $\alpha$ for $t = t_{\alpha}$.

| $df$ | $t_{.100}$ | $t_{.050}$ | $t_{.025}$ | $t_{.010}$ | $t_{.005}$ |
|---|---|---|---|---|---|
| 1 | 3.078 | 6.314 | 12.706 | 31.821 | 63.657 |
| 2 | 1.886 | 2.920 | 4.303 | 6.965 | 9.925 |
| 3 | 1.638 | 2.353 | 3.182 | 4.541 | 5.841 |
| 4 | 1.533 | 2.132 | 2.776 | 3.747 | 4.604 |
| 5 | 1.476 | 2.015 | 2.571 | 3.365 | 4.032 |
| 6 | 1.440 | 1.943 | 2.447 | 3.143 | 3.707 |
| 7 | 1.415 | 1.895 | 2.365 | 2.998 | 3.499 |
| 8 | 1.397 | 1.860 | 2.306 | 2.896 | 3.355 |
| 9 | 1.383 | 1.833 | 2.262 | 2.821 | 3.250 |
| 10 | 1.372 | 1.812 | 2.228 | 2.764 | 3.169 |
| 11 | 1.363 | 1.796 | 2.201 | 2.718 | 3.106 |
| 12 | 1.356 | 1.782 | 2.179 | 2.681 | 3.055 |
| 13 | 1.350 | 1.771 | 2.160 | 2.650 | 3.012 |
| 14 | 1.345 | 1.761 | 2.145 | 2.624 | 2.977 |
| 15 | 1.341 | 1.753 | 2.131 | 2.602 | 2.947 |
| 16 | 1.337 | 1.746 | 2.120 | 2.583 | 2.921 |
| 17 | 1.333 | 1.740 | 2.110 | 2.567 | 2.898 |
| 18 | 1.330 | 1.734 | 2.101 | 2.552 | 2.878 |
| 19 | 1.328 | 1.729 | 2.093 | 2.539 | 2.861 |
| 20 | 1.325 | 1.725 | 2.086 | 2.528 | 2.845 |
| 21 | 1.323 | 1.721 | 2.080 | 2.518 | 2.831 |
| 22 | 1.321 | 1.717 | 2.074 | 2.508 | 2.819 |
| 23 | 1.319 | 1.714 | 2.069 | 2.500 | 2.807 |
| 24 | 1.318 | 1.711 | 2.064 | 2.492 | 2.797 |
| 25 | 1.316 | 1.708 | 2.060 | 2.485 | 2.787 |
| 26 | 1.315 | 1.706 | 2.056 | 2.479 | 2.779 |
| 27 | 1.314 | 1.703 | 2.052 | 2.473 | 2.771 |
| 28 | 1.313 | 1.701 | 2.048 | 2.467 | 2.763 |
| 29 | 1.311 | 1.699 | 2.045 | 2.462 | 2.756 |
| 30 | 1.310 | 1.697 | 2.042 | 2.457 | 2.750 |
| 32 | 1.309 | 1.694 | 2.037 | 2.449 | 2.738 |
| 34 | 1.307 | 1.691 | 2.032 | 2.441 | 2.728 |
| 36 | 1.306 | 1.688 | 2.028 | 2.434 | 2.719 |
| 38 | 1.304 | 1.686 | 2.024 | 2.429 | 2.712 |
| $\infty$ | 1.282 | 1.645 | 1.960 | 2.326 | 2.576 |

# Own Formulas and Notes

# Own Formulas and Notes

# Reference Guide for

## Mechanical Process

# Contents "Mechanical Process"

## Raw Material Preparation



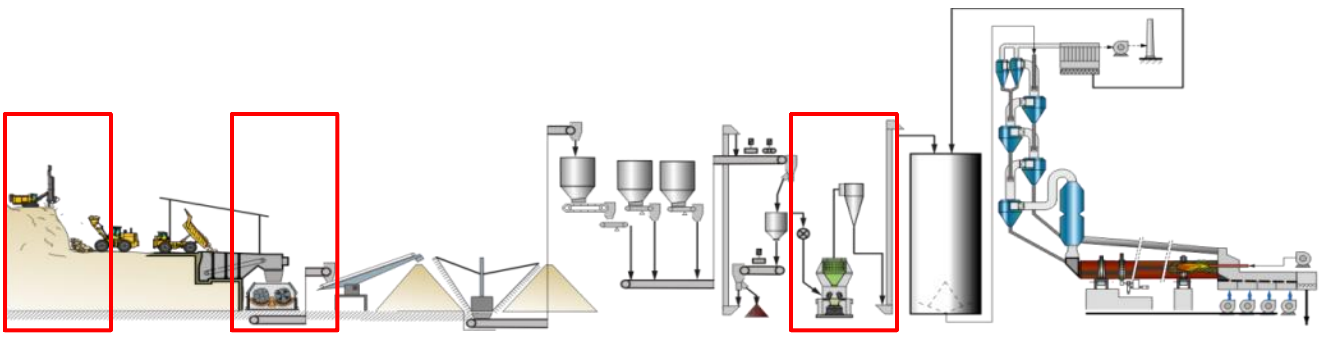
## Grinding

# Contents "Mechanical Process"

# Raw Material Preparation – Overview

## Size Reduction Process

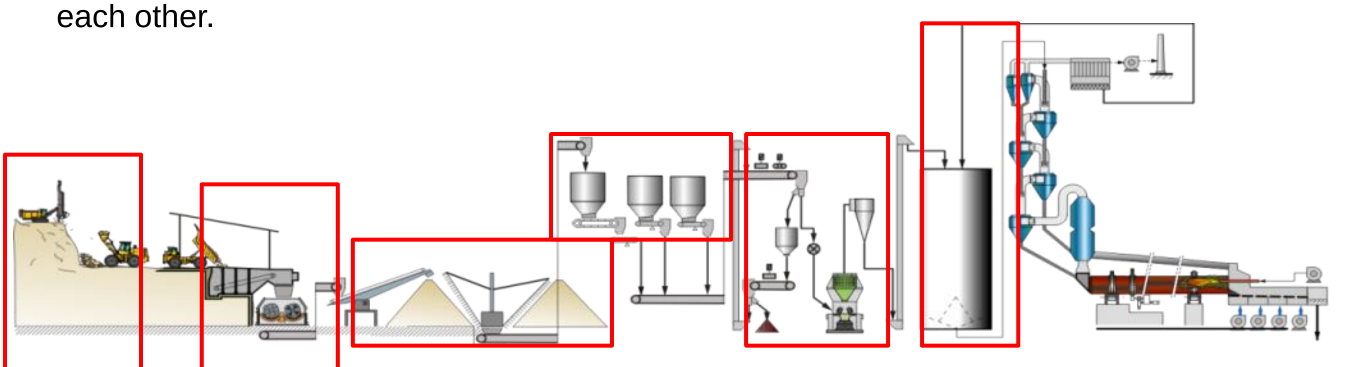
Material size reduction from solid rock in the quarry to raw meal takes place in 3 main steps: Mining (such as drilling & blasting), crushing and grinding. This process chain has to be optimised with a holistic approach.



Mining Crushing Grinding

## Homogenizing Process

Homogenizing of the chemical composition of raw material in order to reach the uniformity targets of kiln feed consists of several steps, each with their time-frame and influencing each other.



Quarry: Extraction planning

Crushing: Combination of different qualities

Preblending

Dosing: Raw mix proportioning

Grinding: Mixing effect

Homogenizing & Kiln dust management

Control of long term fluctuations (days)

Control of short term fluctuations (hours)

# Raw Material Preparation – Material Properties

## **Default material properties** (to be confirmed by material tests)

| Designation | | Granulo-metry | Bulk density (dry basis) | | | | Angle of repose | | Wall angle of feed bins |
|---|---|---|---|---|---|---|---|---|---|
| | | Grain size range [mm] | For mechanical conveyors [kg/$m^3$] | Aerated materials[*1] [kg/$m^3$] | Silos / stockyards [volume] [kg/$m^3$] | Civil structures[*2] [load] [kg/$m^3$] | For silos / stockyards and bins [volume] [°] | Surcharge angle for conveyors [°] | Min. wall angle; valley angle of rectangular bins [°] |
| **Main Raw Materials, Correctives and Alternative Raw Materials** | | | | | | | | | |
| Limestone: | | 0 - 100 | 1'250 | | 1'400 | 1'680 | 38 | 20 | 70 |
| Marl | | | 1'350 | | 1'500 | 1'750 | 40 | 25 | 70 |
| Shale | | | 1'350 | | 1'500 | 1'750 | 40 | 25 | 75 |
| Clay: | | 0 -50 | 1'350 | | 1'500 | 1'750 | 40 | 25 | 90 |
| Pre-mix of main components | | | 1'300 | | 1'450 | 1'700 | 38 | 20 | 70 |
| Iron Ore | | | 2'000 | | 2'400 | 2'800 | 35 | 20 | 75 |
| Pyrite | | | 2'000 | | 2'400 | 2'800 | 35 | 20 | 75 |
| Sand | | | 1'450 | | 1'600 | 1'800 | 35 | 20 | 70 |
| Bauxite (Alumina Corrective) | | | 1'200 | | 1'350 | 1'600 | 35 | 20 | 75 |
| Fluorite | | | 1'450 | | 1'600 | 1'850 | 38 | 20 | 70 |
| Basalt | | | 1'400 | | 1'550 | 1'800 | 38 | 20 | 70 |
| Bottom ash | wet | | 950 | | 1'100 | 1'350 | 40 | 25 | 75 |
| **Clinker, Gypsum, Cement Additives and Mineral Components** | | | | | | | | | |
| Natural Gypsum | | | 1'250 | | 1'400 | 1'650 | 38 | 20 | 70 |
| Synthetic Gypsum | | | 1'250 | | 1'400 | 1'650 | 40 | 25 | 90 |
| Pozzolana | coarse, wet | | 1'200 | | 1'350 | 1'600 | 38 | 20 | 70 |
| Pozzolana | pulverized | | 950 | 850 | 1'100 | 1'350 | 10 | 5 | 70 |
| Fly ash | pulverized | | 900 | 800 | 1'050 | 1'500[*3] | 10 | 5 | 70 |
| Slag | granular, wet | | 1'150 | | 1'300 | 1'550 | 35 | 20 | 70 |
| Slag | pulverized | | 800 | 700 | 950 | 1'200 | 15 | 5 | 70 |
| **Fuels** | | | | | | | | | |
| Coal: | anthracite | | 800 | | 950 | 1'000[*3] | 38 | 20 | 70 |
| | bituminous | | 750 | | 850 | 1'000[*3] | 38 | 20 | 70 |
| | pulverized | | 500 | 400 | 650 | 800[*3] | 10 | 5 | 72 |
| Petcoke: | raw | | 550 | | 650 | 800[*3] | 35 | 20 | 70 |
| | pulverized | | 400 | 350 | 550 | 600 | 10 | 5 | 70 |
| Oil: | diesel | | | | 850 | | | | |
| | heavy | | | | 900 | 950 | | | |
| Alternative Fuels | | | | | | | | | |
| Tires (whole) | car: 8-10 kg<br>truck: 40-60 kg | | | | 100 | | | | 90 |
| Tires shredded | | 0 - 100 | 300 | | 500 | | | 10 | 90 |
| Animal meal | bone meal | | 800 | | 900 | | | 10 | 90 |
| Animal meal | meat meal | | 600 | | 700 | | | 10 | 90 |
| Saw dust | clean | | 300 | | 350 | | | 10 | 90 |
| Saw dust | impregnated | | 400 | | 500 | | | 10 | 90 |
| Dried sewage sludge | | 0 - 6 | 800 | | 900 | | | 10 | 90 |
| Fluff (light fraction from air separator) | | 0 -30 | 60 | | 90 | | | 10 | 90 |
| Fluff (w/o air separation) | | 0 -30 | 100 | | 200 | | | 10 | 90 |
| Rice husks | | 0 - 3 | 100 | | 150 | | | 10 | 90 |
| Palm kernel shells | | 0 - 20 | 600 | | 800 | | | 10 | 90 |
| **Intermediate / Final Products** | | | | | | | | | |
| Raw meal | | | 900 | 800 | 1'200 | 1'600 | 10 | 5 | 70 |
| Kiln dust | | | 650 | 500 | 950 | 1'400 | 10 | 5 | 72 |
| By-pass dust | | | 600 | 500 | 800 | 1'400 | 15 | 5 | 72 |
| Clinker | | | 1'200 | | 1'400 | 1800[*3] | 34 | 20 | 55 |
| Clinker mineralized | | | 1'000 | | 1'200 | 1'800 | 34 | 20 | 55 |
| Clinker dust | | | 850 | 750 | 1'000 | 1'200 | 10 | 5 | 70 |
| Cement (OPC) | | | 950 | 850 | 1'300 | 1600[*3] | 10 | 5 | 65 |

[*1] at airslide discharge, aerated silo extaction
[*2] for information only, valid codes have to be applied
[*3] from DIN 1055-6, 2005
[*4] After primary crushing stage
[*5] After secondary crushing stage
[*6] After tertiary crushing stage

# Raw Material Preparation – Material Properties

## Bulk Density

The bulk density is defined to be the mass of a bulk material divided by the total bulk volume (including void volume and porosity).

$$\rho_b = \frac{m_{solid} + m_{voids}}{V_{solid} + V_{voids}} = \frac{m_{total}}{V_{total}} \left[ kg/m^3 \right]$$

$\rho_b$ = bulk density

## Moisture

Moisture content is defined as the percentage of water in a product (wet base):

$$\text{Moisture content} = \frac{m_{wet} - m_{dry}}{m_{wet}} \times 100 \ \left[ \%H_2O \right] = \frac{m_{H_2O}}{m_{wet}} \times 100 \ \left[ \%H_2O \right]$$

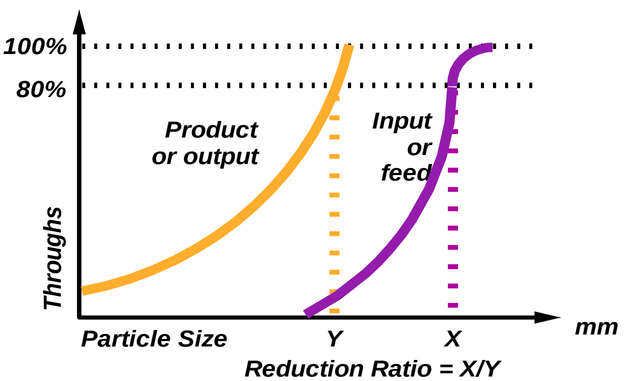
$m_{wet}$ = mass wet [kg]    $m_{dry}$ = mass dry [kg]    $m_{H2O}$ = mass water [kg]

## Bulk solid granulometry

| Descriptive term | Particle Size Range | Example |
|---|---|---|
| ROM (Run of Mine) | 0 - 800 mm | limestone |
| coarse (crushed) solid | 0 - 300 mm | limestone |
| granular solid | 0.3 - 5 mm | sand |
| coarse powder | 100 - 300 µm | separator grits |
| fine powder | 10 - 100 µm | cement |
| superfine powder | 1 - 10 µm | dust collector product |
| ultrafine powder | < 1 µm | paint pigments |

# Raw Material Preparation – Crushing

## Reduction ratio

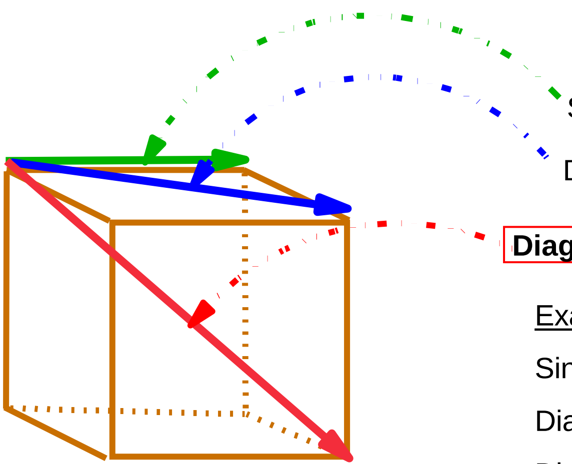



*Reduction Ratio*

$$\text{The reduction ratio} = \frac{\text{80\% passing Feed size}}{\text{80\% passing Product size}}$$

## Rock sizing

Edge length of rocks: Always use diagonal in 3 planes for crusher feed sizing.




Example:

| | |
|---|---|
| Single side | 0.8m |
| Diagonal in 2 planes | 1.1m |
| Diagonal in 3 planes | 1.4m |

## Classification of Abrasiveness of Limestone according Pennsylvania Abrasion Test

| Very low | Low | Low to medium | Medium to high | High | Very high |
|---|---|---|---|---|---|
| < 40 | 40 - 80 | 80 - 120 | 120 - 160 | 160 - 200 | > 200 |

# Raw Material Preparation – Crushing

## Crusher types

| Crusher type | Reduction Ratio | Application | Mechanical Method |
|---|---|---|---|
| ***Impact or Hammer fast running*** | | | |
| Impactor | ▪ Prim. 15:1<br>▪ Secondary 10:1 | ▪ For soft to medium hard materials<br>▪ Not for abrasive materials<br>▪ For non-sticky materials (< 8 % $H_2O$) | **Impact** |
| Reversible Impactor | ▪ Secondary 5:1 | | **Impact** |
| Double rotor Hammer with grate | ▪ Primary 50:1 | ▪ For soft to medium hard materials<br>▪ Not for abrasive or sticky materials<br>▪ For slightly sticky materials (8–12 % $H_2O$)<br>▪ 1 stage crushing | **Impact**, Shear, Compression |
| Single rotor Hammer with grate | ▪ Primary 50:1 | | **Impact**, Shear, Compression |
| ***Roller or Mineral Sizer low running*** | | | |
| Single Roller | ▪ Primary 4:1<br>▪ Secondary 6:1 | ▪ For soft to medium hard materials<br>▪ UCS < 150 MPa<br>▪ For sticky materials (> 8 % $H_2O$) | **Shear**, Compression |
| Double Roller | ▪ Primary 4:1<br>▪ Secondary 6:1 | | **Shear**, Compression |
| Mineral sizer | ▪ Primary 3.5:1<br>▪ Secondary 3:1 | ▪ For soft to medium hard materials<br>▪ UCS < 200 MPa<br>▪ For sticky materials (> 12 % $H_2O$) | **Shear**, Compression |
| ***Gyratory low running*** | | | |
| Gate System | ▪ Primary 5:1 | ▪ For hard, abrasive materials<br>▪ For non-sticky materials (< 8 % $H_2O$)<br>▪ Choke feed | **Compression**, Attrition |
| Symons System Cone | ▪ Secondary 5:1 | | **Compression**, Attrition |
| Hydrocone | ▪ Secondary 5:1 | | **Compression**, Attrition |
| ***Jaw*** | | | |
| Single Toggle | ▪ Primary 4:1 | ▪ For hard, abrasive materials<br>▪ For non-sticky materials (< 8 % $H_2O$)<br>▪ Choke feed | **Compression**, Attrition |
| Double Toggle | ▪ Primary 4:1<br>▪ Small Capacity | | **Compression**, Attrition |

1

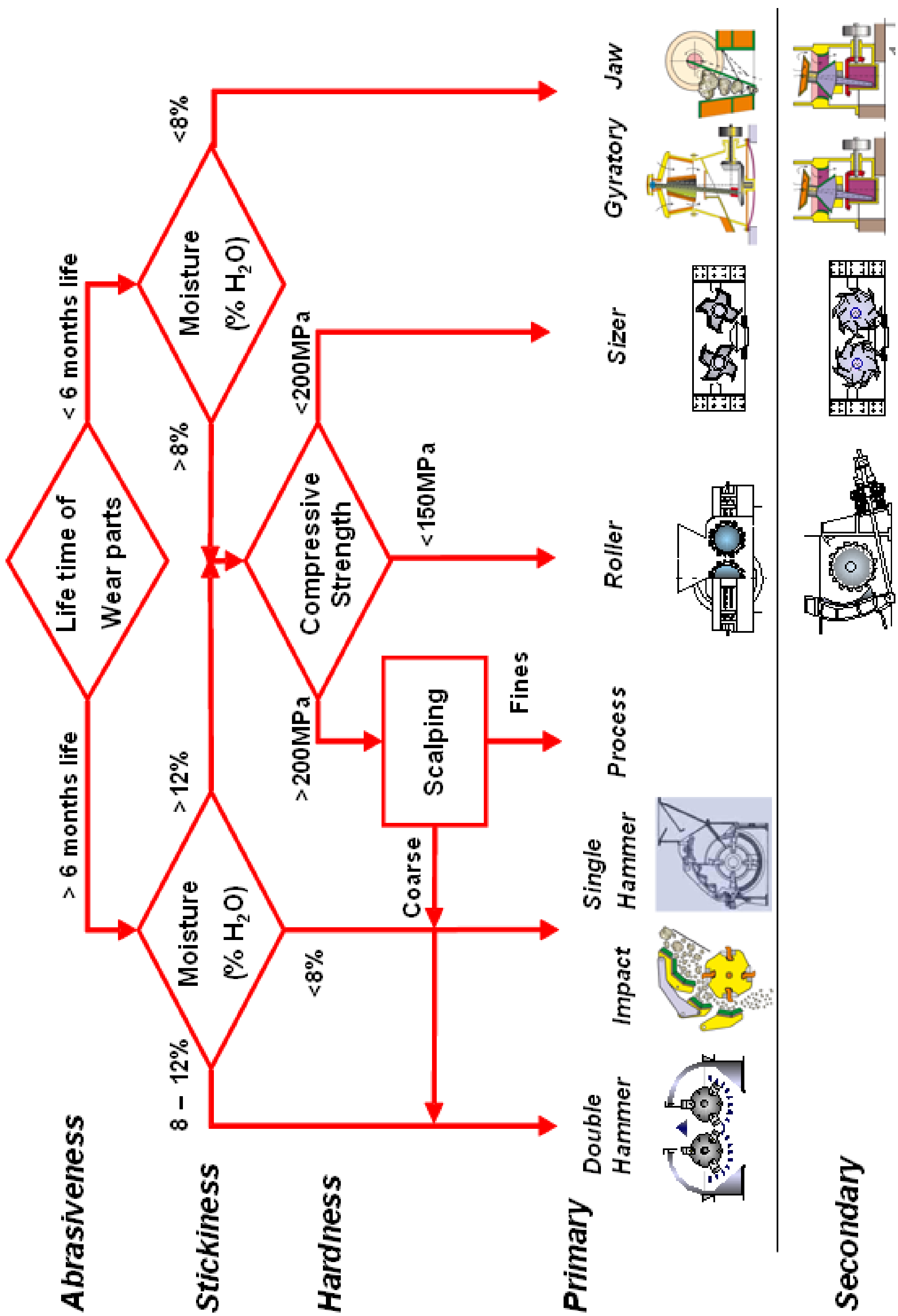
# Raw Material Preparation – Crushing

## Crusher Settings & Wear Parts

| Crusher Type | Settings | Wear Parts |
|---|---|---|
| **Impact Crusher** | • Breaker plate position<br>• Grinding path (if any) | • Blow bars<br>• Breaker plates |
| **Hammer Crusher** | • Grate opening<br>• Grate basket position<br>• Breaker plate position (single rotor type only) | • Hammers<br>• Grate(s)<br>• Breaker plates (single rotor type only) |
| **Jaw Crusher** | • Mobile jaw (close side setting) | • Jaw plates<br>• Cheek plates |
| **Gyratory / Hydrocone Crusher** | • Crushing shaft position (open side setting) | • Mantle(s)<br>• Concaves or wear bowl |
| **Symons Type Cone Crusher** | • Bowl position (closed side setting) | • Mantle<br>• Wear bowl |
| **Double Roller Crusher** | • Roller position / gap | • Teeth / roller shell<br>• Side walls<br>• Scrapers |
| **Single Roller Crusher** | • Breaker wall position | • Teeth<br>• Breaker wall |
| **Mineral Sizer** | • Anvil position<br>• Scrapers position | • Teeth<br>• Scrapers |

# Raw Material Preparation – Crushing

## Decision Tree for Crusher Selection



# Material Preparation – Preblending

## Number of layers

Target: Not less than 250

**Longitudinal**

$$n = A \cdot \frac{v_{st}}{q_{st}} = \frac{w * h}{2} * \frac{v_{st}}{q_{st}}$$

n = number of layers [- ]
w = width of pile [m]
h = high of pile [m]
$v_{st}$ = stacker speed [m/min]
$q_{st}$ = stacker capacity [m3/min]

**Circular**

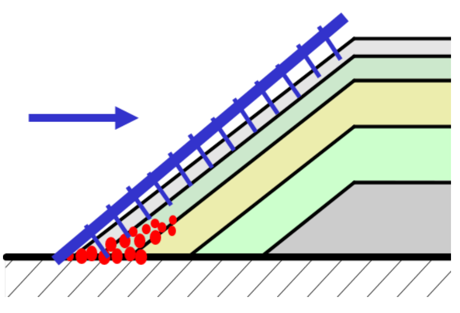
$$n = A \cdot \frac{v_{st}}{q_{st}} = \frac{(D_o - D_i)^2 * \tan\alpha}{16} \cdot \frac{v_{st}}{q_{st}}$$

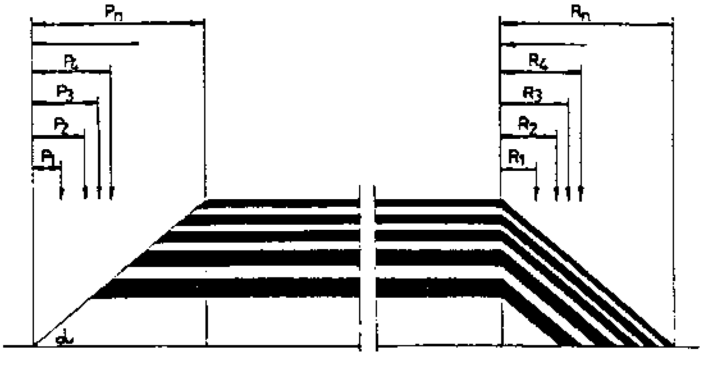
$D_o$ = outer diameter [m]
$D_i$ = inner diameter [m]
$\alpha$ = reclaimer inclination (typically 38°)

## End cone effect

Problem: Only few layers and mostly coarse material is reclaimed when cutting a new pile.

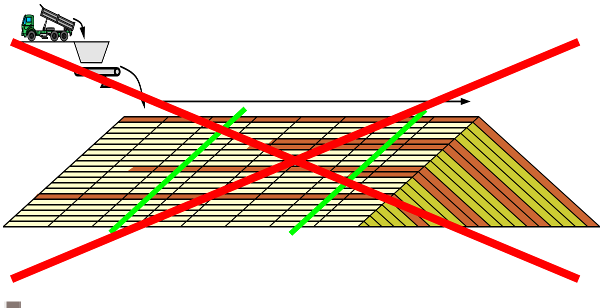
Solution: Apply variable instead of fixed stacker reversing points (contact HTEC for calculation).

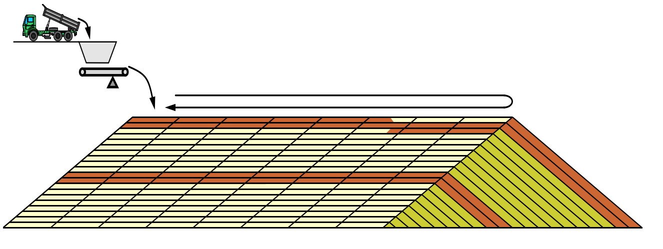





## Corrective layers

When applying corrective layers onto a longitudinal preblending pile, always add a batch that is equivalent to one double layer (forth and back movement of stacker) to ensure equal distribution.





# Material Preparation – Feed Bins

## Design of Feed Bins

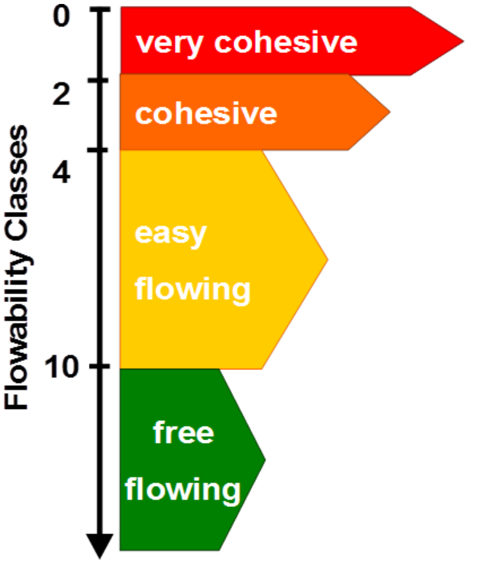
There are some general principles to be observed when designing bulk solid handling systems:

Rule 1: Storage and process feed functions should be separated whenever possible.

Rule 2: Feed bins should be designed for the lowest possible volume and not be abused for additional storage capacity.

Rule 3: Feed bins should be designed for mass-flow on principle.

All feed bins are designed according to material characteristics, the main influence having flowability and abrasiveness.
**Flowability** differs between materials and is quantified with a set of shear tests.
**Shear tests** are determining the internal friction of a material as well as the wall friction against different wall materials. These test should always reflect the worst case situation, meaning the moisture content that results in highest internal and external friction.




The internal friction values describe the tendency of a material to form bridges and thus define the minimum required **outlet opening** of a feed bin.

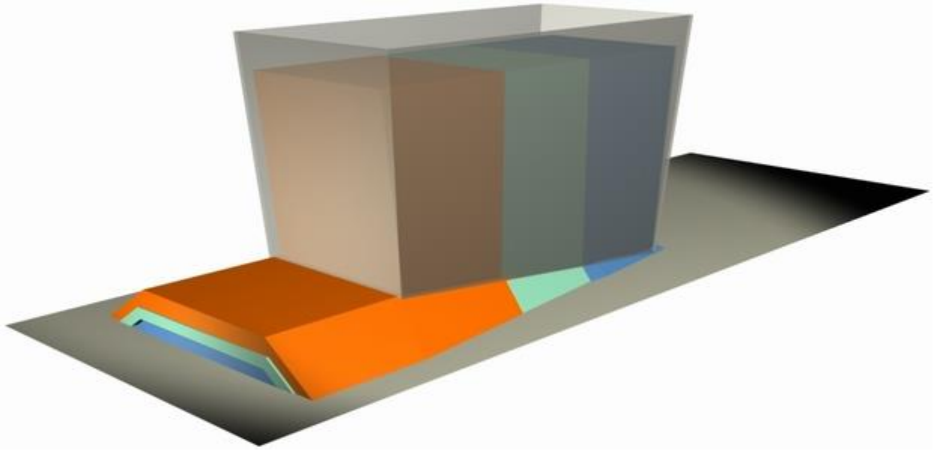
The external friction values define the minimum required **wall angles** and the suitable **wall / lining material**.
Typical wall / lining materials include mild steel, polished stainless steel and different UHMW-PE materials.

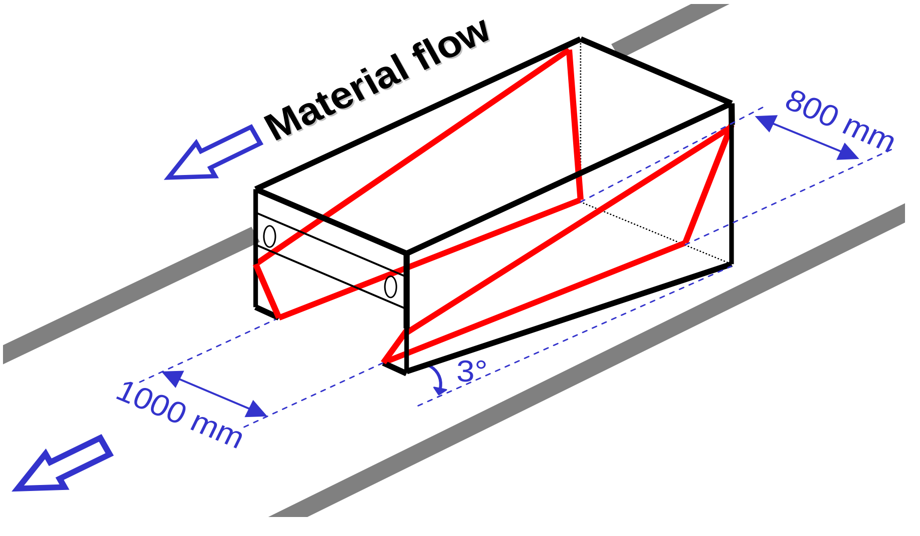
# Material Preparation – Feed Bins

## Feed Bin Extraction Design

Design of opening, wall angles and wall material (lining) are determined by shear tests.

The feed bin outlet has to allow for full activation of the material and thus has to widen in direction of conveying. This can be achieved by an expanding outlet or a "tapered box" design. The figures below are examples of such designs.





# Grinding – Holcim Performance Indicators

## Mill Net availability index:

$$\text{Net Availability Index}\,[\%] = \frac{(\text{Actual Operating Time}\,[h] + \text{Idle Time}\,[h]) \cdot 100}{\text{Calendar Time}\,[h]}$$

$$\text{Net Availability Index}\,[\%] \geq 90\%\ (\text{guide value})$$

**Idle Time** = equipment is not operating but is in a condition for immediate start up
**Calendar Time** = actual operating time + idle time + other downtime

## Mill Production rate index:

$$\text{Production Rate Index}\,[\%] = \frac{\text{Actual Production Rate}\,[t/d] \cdot 100}{\text{BDP}\,[t/d]}$$

$$\text{Production Rate Index}\,[\%] \geq 95\%\ (\text{guide value})$$

**Best Demonstrated Practice (BDP) Mill:** The BDP per type of product is the arithmetic average of the five highest production rates (tons/hour) of at least 8 hours runs, achieved during the last 24 months before the budget phase.
If there is a regular production of two or more cement types, the mill system BDP will be an average BDP. It is determined by weighing the BDPs of each cement type with the operating times of each cement type

## Net OEE (Overall Equipment Efficiency):

$$OEE_{net}\,[\%] = (\text{Net Availability Index} \cdot \text{Production Rate Index})/100$$

$$OEE_{net}\,[\%] \geq 85\%\ (\text{guide value})$$

## MTBF (Mean Time Between Failure):

$$MTBF\,[h] = \frac{\text{Actual Operating Time}\,[h]}{\text{Failures}\,[\#]}$$

Guide value for MTBF [h]:

- Vertical Roller Mill, Roller Press, Horomill: 50 h
- Ball Mill: 125 h

Notes for MTBF calculation:

- Mill shutdowns to change material and/or product type are not to be considered as failures
- Raw Mill shutdowns due to kiln failures are not to be considered as failures
- A maximum of 2 planned maintenance stops per month are excluded from the MTBF calculation for raw and cement mill system

Above definitions are based on the HARP (**H**olcim **A**ccounting and **R**eporting **P**rinciples) Manual
For the most current definition check the HARP Manual on the Holcim Portal.

# Grinding – Mill Sizing

## Raw Mill

$$\text{Design Production Rate [t/h]} = \frac{\text{KilnBDP [t/d Clinker]} \cdot \text{Raw Meal / Clinker Factor [-]} \cdot \text{Wear Factor [-]}}{24\,[\text{h}] \cdot \text{OEE}_{net}\ \text{mill}[\%]/100}$$

$OEE_{net}$ mill = Net Overall Equipment Efficiency mill ≥ 85%

Wear factors: Vertical Roller Mill = 1.0-1.10 Ball Mill = 1.0-1.03 Roller Press = 1.0-1.05

Raw Meal / Clinker Factor: ~1.55 for normal applications (up to 1.8 if kiln bypass installed)

## Coal Mill

$$\text{Design Production Rate [t/h]} = \frac{\text{KilnBDP [t/d Clinker]} \cdot \text{Heat Consumption [MJ/t Clinker]} \cdot \text{Wear Factor [-]}}{24\,[\text{h}] \cdot \text{OEE}_{net}\ \text{mill}[\%]/100 \cdot \text{NCV [MJ/t coal]}}$$

$OEE_{net}$ mill = Net Overall Equipment Efficiency mill ≥ 85%

Wear factors: Vertical Roller Mill = 1.0-1.10 Ball Mill = 1.0-1.03

NCV = Net Calorific Value (coal/petcoke) [MJ/$t_{Coal}$]

Heat Consumption = specific thermal heat consumption of kiln system

## Cement Mill

$$\text{Design Production Rate [t/h]} = \frac{\text{Average Cement Production [t/h]} \cdot \text{Seasonality factor [-]} \cdot \text{Wear Factor [-]}}{\text{OEE}_{net}\ \text{mill}[\%]/100}$$

$$\text{Seasonality factor} = \frac{\text{Max monthly sales}}{\text{Monthly average sales}}\ [-]$$

Average Cement Production = weighted average of all cements produced (weighted with the operating times of each cement type)

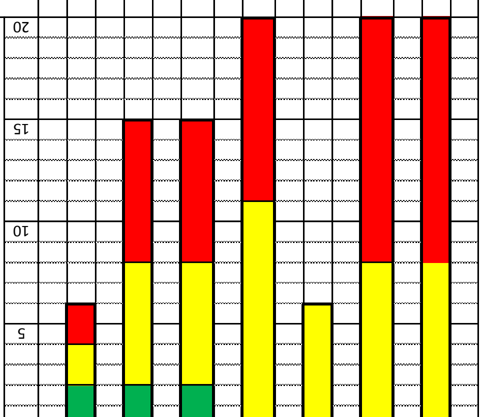
$OEE_{net}$ mill = Net Overall Equipment Efficiency mill ≥ 85%

Wear factors: Vertical Roller Mill = 1.0-1.10 Ball Mill = 1.0-1.03 Roller Press = 1.0-1.05

# Grinding – Mill Sizing

## Limitations of Mills in Raw Grinding Systems

| Type of mill | Drying capacity (%) $H_2O$ | Max. mill feed size (mm) | Max. mill gas speed (m/s) | Max. mill capacity (t/h) | Max. hot gas temperature (°C) | Specific load ($kg\ H_2O/m^3h$)* | | | El. energy consumption | Suitability for sticky materials | Maintenance requirement |
|---|---|---|---|---|---|---|---|---|---|---|---|
| End- discharge ball mill | | 25-50 | 2 | 700 | 450 | < 150 | < 200 | | medium | no | low |
| Center-discharge ball mill | | 25-50 | 2 | 700 | 450 | < 150 | < 200 | | high | suited | low |
| Air-swept ball mill | | 25-50 | 6 | 350 | 450/800[1] | | < 220 | < 350 | medium | suited | low |
| Vertical roller mill | | 40-100 | 6.5 | 1000 | 450/800[1] | | | | low | suited | high |
| Roller press with separator | | 50 - 70 | | 700 | 350 | | | | low | no | high |
| Hammer mill | | 200 | | 100 | 450/800[1] | | | | medium | very suited | medium |
| Autogenous mill | | 300 | | 400 | 450 | | | | high | very suited | low |




[1] hot gas section made of heat resistant steel and/or equipped with refractory

Legend:
- without drying comportment
- with hot gases of max. 350°C hot gas (clinker cooler or preheater exhaust gas 4/5/6 stages)
- with hot gases of more than 350°C (hot gas generator or preheater exhaust gas 2/3 stages)

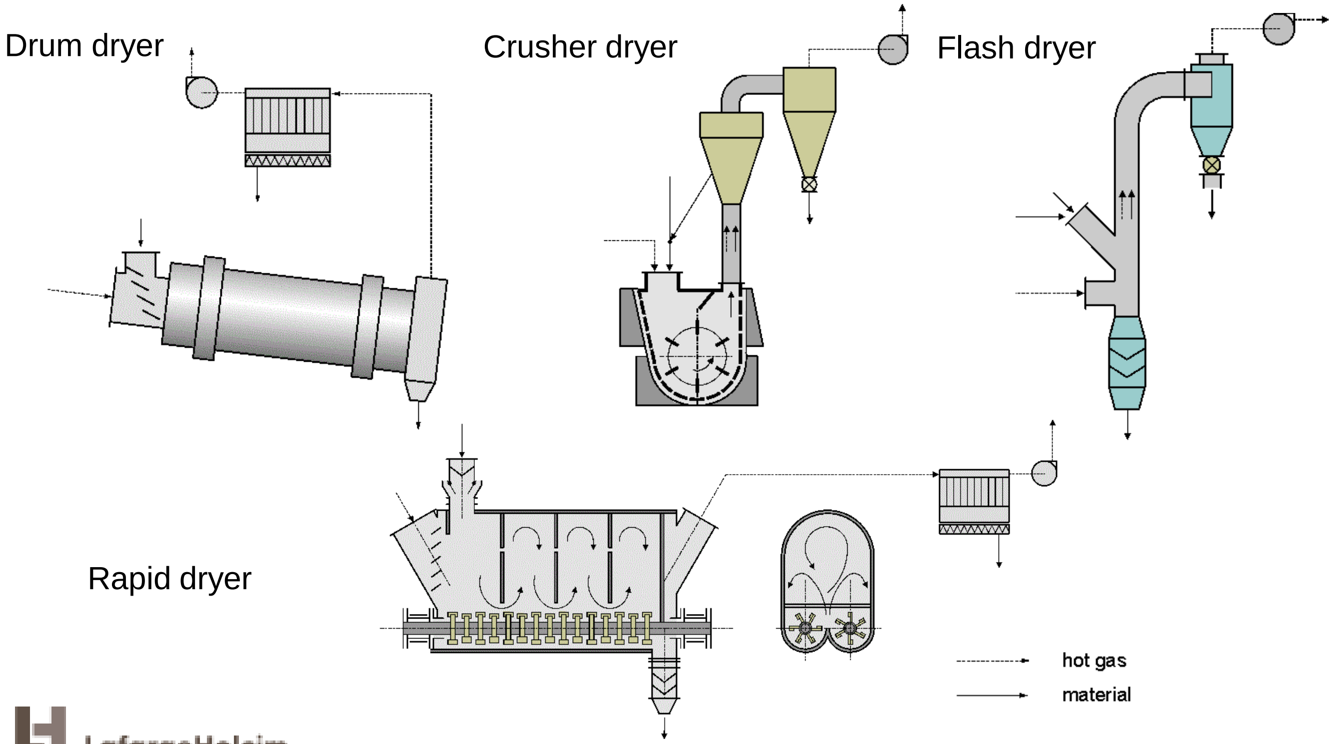
Higher drying capacities can be achieved with pre-drying facilities (e.g. flash dryer)

# Grinding – Dryers in Grinding Systems

## Limitations of Dryers

| Type of dryer | Max. feed size [mm] | Drying capacity [% $H_2O$] | Specific load [kg $H_2O$ / $m^3h$]* | Max. hot gas temp. [°C] |
|---|---|---|---|---|
| Drum dryer (rotary) | 200 - 300 | < 25 | < 150 | < 1200 |
| Rapid dryer | < 500 (soft material) | < 20 | < 200 | < 800 |
| Crusher dryer | < 150 (depends on crusher size) | < 25 (air swept with flash dryer) | < 500 (air swept with flash dryer) | < 800 |
| Flash dryer | < 20 | < 35 | < 500 | < 900 |

* $m^3$ of free volume inside the dryer



# Grinding – Mill Feed Properties

## VRM feed size (guide values)

### Material feed size relating to roller diameter

- **Raw materials, pozzolana, coal:**

| | Feed size | Material grindability |
|---|---|---|
| Max feed granulometry | $d_{95} \leq 3$ [%] $D_{Roller}$ | for > 5.5 [kWh/t] motor shaft |
| | $d_{95} \leq 5$ [%] $D_{Roller}$ | for ≤ 5.5 [kWh/t] motor shaft |
| | $d_{30} \geq 1$ [mm] objective ( ≥ 70 [%] R 1 [mm] - more fines require lower table speeds) | |
| | 100 [%] ≤ 100 [mm] | |

- **Clinker, slag:**

| | Feed size |
|---|---|
| Max feed granulometry | $d_{95} \leq 2.5$ [%] $D_{Roller}$<br>$d_{30} \geq 1$ [mm] objective, ( ≥ 70 [%] R 1 [mm])<br>100 [%] ≤ 100 [mm] |

## Ball Mill feed size (guide values)

Max feed granulometry $d_{95} \leq 30$ [mm]
100 [%] ≤ 50 [mm]

## Roller Press feed size (guide values)

Max feed granulometry $d_{95}{}^{*} \leq 3$ [%] $D_{Roller}$

*of at least 1 plane

$d_{95}$ = sieve opening [mm] passing 95 [%] of particles ( 5 [%] ≥ x [mm])

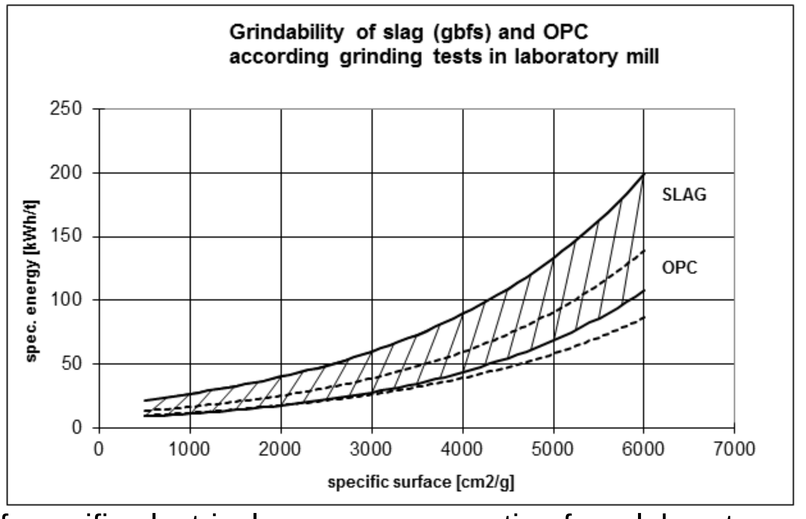
$d_{30}$ = sieve opening [mm] passing 30 [%] of particles ( 70 [%] ≥ x [mm])

$D_{Roller}$ = Diameter of roller [mm]

# Grinding – Mill Feed Properties

## Grindability based on HTEC Laboratory Ball Mill

### Grindability of slag (gbfs) and OPC → Grindability tests at mill shaft



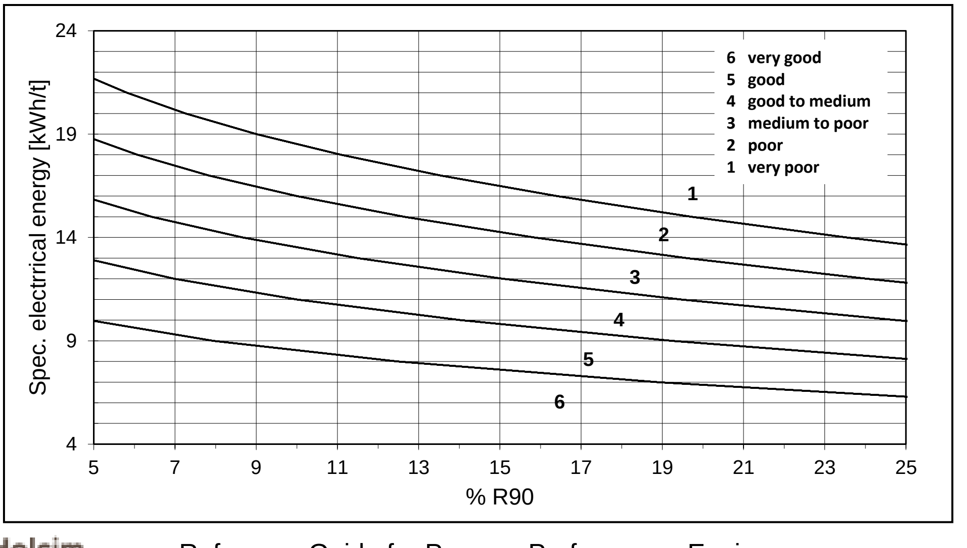

Conversion of specific electrical energy consumption from laboratory mill (at mill shaft) to industrial mill (at mill shaft):

- Open Ball Mill Circuit: IM = LM
- Closed Ball Mill Circuit:
  - 1st Generation Separator IM = 0.95 x LM
  - 2nd Generation Separator IM = 0.90 x LM
  - 3rd Generation Separator IM = 0.85 x LM
- Vertical Mill: IM = 0.5 x LM (cement and raw meal)
  IM = 0.3 x LM (slag)

IM: Industrial Mill

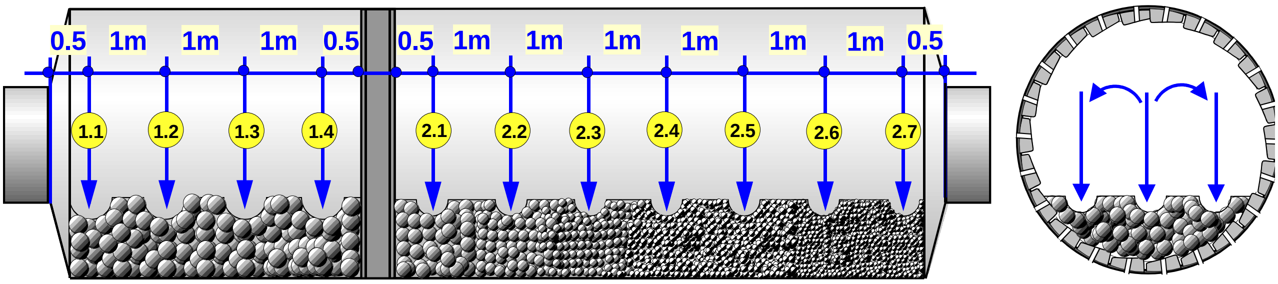
LM: Laboratory Mill

### Grindability of raw material → Grindability tests at mill shaft

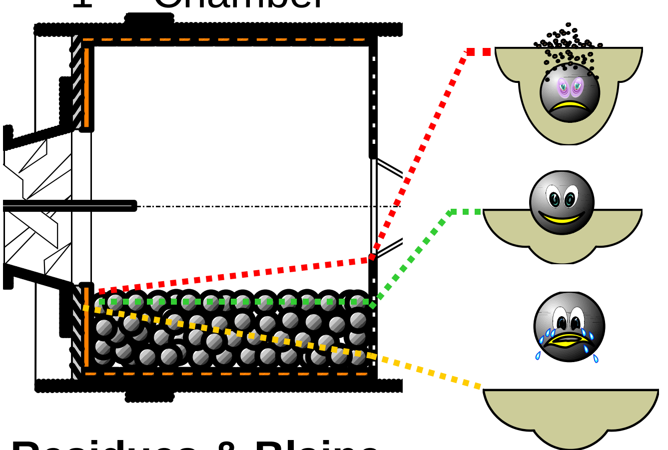


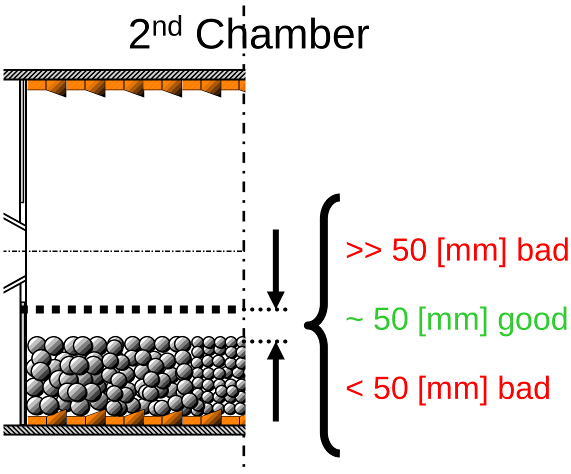
# Grinding – Ball Mill Assessment

## Longitudinal sieving




## Material level




## Residues & Blaine

| | | Chamber 1 | | | | Chamber 2 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sample point | 1.1 | 1.2 | 1.3 | 1.4 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 |
| Sieve [mm] | 16 | | | | | | | | | | | |
| | 8 | | | | | | | | | | | |
| | 4 | | | | | | | | | | | |
| | 2 | | | | Guide value: < 5 % | | | | | | | |
| | 1 | | | | | | | | | | | |
| | 0.5 | | | | Guide value: 15 – 25 % | | | | | | | |
| | 0.2 | | | | | | | | | | | Guide value: < 5 % |
| | 0.12 | | | | | | | | | | | |
| | 0.09 | | | | | | | | | | | Guide value: 15 – 25 % |
| | 0.063 | | | | | | | | | | | |
| | 0.045 | | | | | | | | | | | |
| Blaine [$cm^2/g$] | | | | | | | | | | | | Guide value: ~50 % of product |

*Guide values valid for 3000 Blaine of cement product, closed circuit, without pre-grinder*

# Grinding – Ball Mill Assessment

## Ball charges – 1st Chamber

**Standard**

| 1.Compartment | | |
|---|---|---|
| Ø Ball [mm] | Weight [ t ] | Percent [%] |
| 90 | 25.0 | 25.0 |
| 80 | 35.0 | 35.0 |
| 70 | 25.0 | 25.0 |
| 60 | 15.0 | 15.0 |
| Total | 100.0 | 100 |
| Average ball weight | [ g ] | 1667 |
| Spec. media surface | [m2 / t ] | 10.2 |

**Coarse**

| 1.Compartment | | |
|---|---|---|
| Ø Ball [mm] | Weight [ t ] | Percent [%] |
| 90 | 40.0 | 40.0 |
| 80 | 30.0 | 30.0 |
| 70 | 20.0 | 20.0 |
| 60 | 10.0 | 10.0 |
| Total | 100.0 | 100 |
| Average ball weight | [ g ] | 1873 |
| Spec. media surface | [m2 / t ] | 9.8 |

**Very coarse***

| 1.Compartment | | |
|---|---|---|
| Ø Ball [mm] | Weight [ t ] | Percent [%] |
| 90 | 45.0 | 45.0 |
| 80 | 30.0 | 30.0 |
| 70 | 25.0 | 25.0 |
| 60 | | |
| Total | 100.0 | 100 |
| Average ball weight | [ g ] | 2114 |
| Spec. media surface | [m2 / t ] | 9.5 |

* needs 60 mm balls in 2nd chamber

# Grinding – Ball Mill Assessment

## Ball charges – 2nd Chamber

### Coarse

e.g. OPC < 3200 $cm^2/g$

| 2.Compartment | | | |
|---|---|---|---|
| | Ø Ball [mm] | Weight [ t ] | Percent [%] |
| | 50 | 8.0 | 8.0 |
| | 40 | 10.0 | 10.0 |
| | 30 | 24.0 | 24.0 |
| | 25 | 29.0 | 29.0 |
| | 20 | 29.0 | 29.0 |
| | 17 | | |
| | Total | 100.0 | 100 |
| Average ball weight | | [ g ] | 62 |
| Spec. media surface | | [m2 / t] | 29.4 |

### Fine

e.g. OPC > 3200 $cm^2/g$

| 2.Compartment | | | |
|---|---|---|---|
| | Ø Ball [mm] | Weight [ t ] | Percent [%] |
| | 50 | 10.0 | 10.0 |
| | 40 | 10.0 | 10.0 |
| | 30 | 16.0 | 16.0 |
| | 25 | 16.0 | 16.0 |
| | 20 | 21.0 | 21.0 |
| | 17 | 27.0 | 27.0 |
| | Total | 100.0 | 100 |
| Average ball weight | | [ g ] | 41 |
| Spec. media surface | | [m2 / t] | 32.8 |

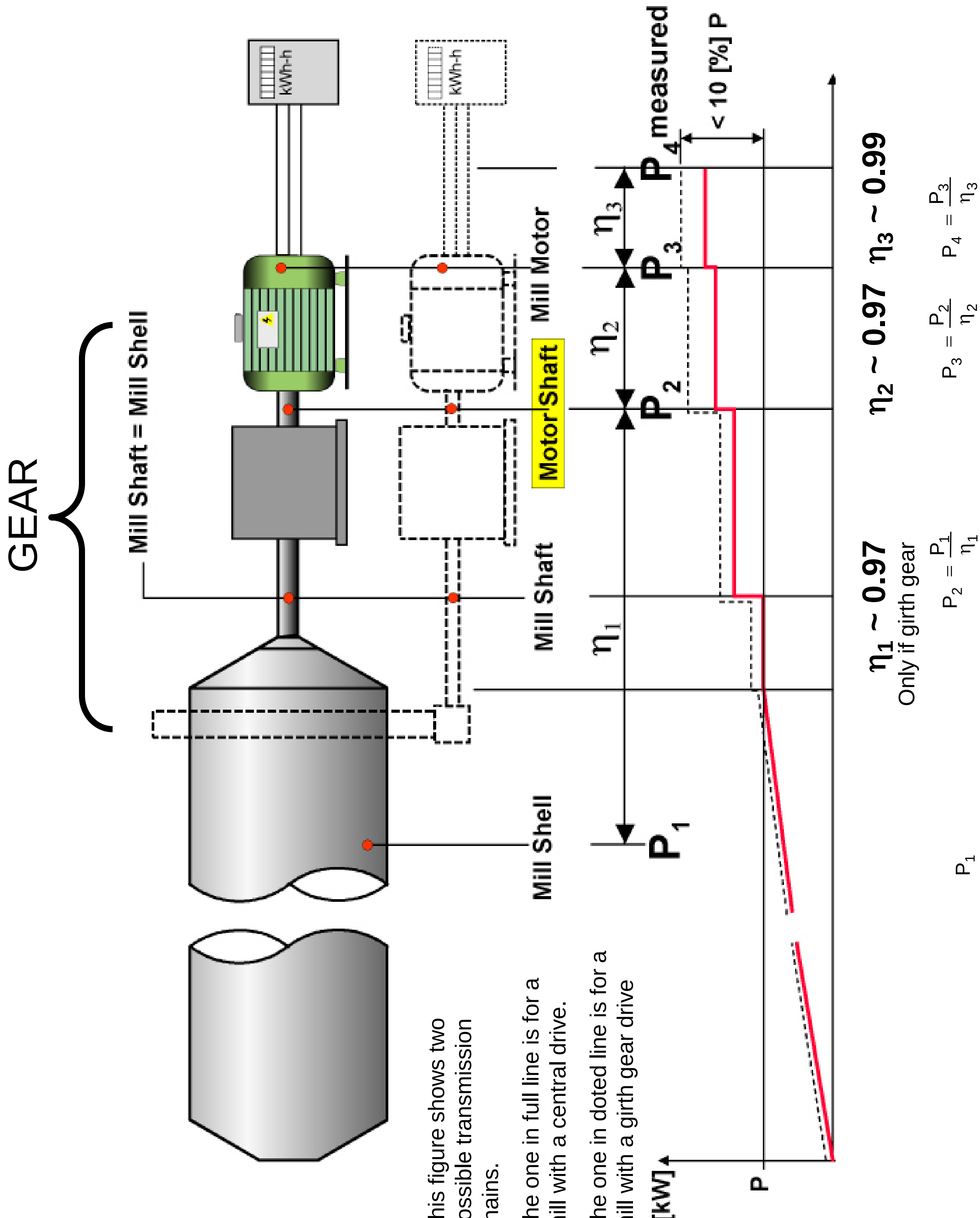
### Very fine

e.g. mono-chamber mill after pregrinder

| 2.Compartment | | | |
|---|---|---|---|
| | Ø Ball [mm] | Weight [ t ] | Percent [%] |
| | 40 | | |
| | 30 | | |
| | 25 | 20.0 | 20.0 |
| | 20 | 27.0 | 27.0 |
| | 17 | 27.0 | 27.0 |
| | 15 | 26.0 | 26.0 |
| | Total | 100.0 | 100 |
| Average ball weight | | [ g ] | 23 |
| Spec. media surface | | [m2 / t] | 42.1 |

# Grinding – Ball Mill Power

## Power transmission chain




This figure shows two possible transmission chains.

The one in full line is for a mill with a central drive.

The one in doted line is for a mill with a girth gear drive

# Grinding – Ball Mill Power

## Critical mill speed

$$n_{crit} = \frac{\sqrt{2g}}{2\pi} \cdot 60 \frac{s}{min} \cdot \frac{1}{\sqrt{D_i}} = \frac{42.3}{\sqrt{D_i}}$$

## Actual mill speed as percentage k of critical mill speed

$$n = \frac{k}{100} \cdot n_{crit} = \frac{k}{100} \cdot \frac{42.3}{\sqrt{D_i}}$$

n = actual mill speed [1/min]

- (typically 72 – 78 %)

k = percentage of critical speed [%]

$n_{crit}$ = critical mill speed [1/min]

## Absorbed power at mill shell

$$P = c_{ch} \cdot \mu \cdot Q_{ch} \cdot D_i \cdot n$$

$$= c_{ch} \cdot \mu \cdot \frac{\pi}{4} \cdot D_i^2 \cdot L_i \cdot \gamma \cdot f \cdot D_i \cdot n$$

P = mill net driving power at shell [kW]

$c_{ch}$ = power consumption factor of chamber [-]

$\mu$ = friction factor [-]

- (typically 0.9 – 1.0)

$Q_{ch}$ = weight of grinding media in chamber

$D_i$ = internal mill diameter [m]

$\gamma$ = bulk density of grinding media [t/m³]:

- 1st chamber: 4.4 – 4.5 [t/m³] - 2nd chamber: 4.6 – 4.7 [t/m³]

f = filling degree [%]

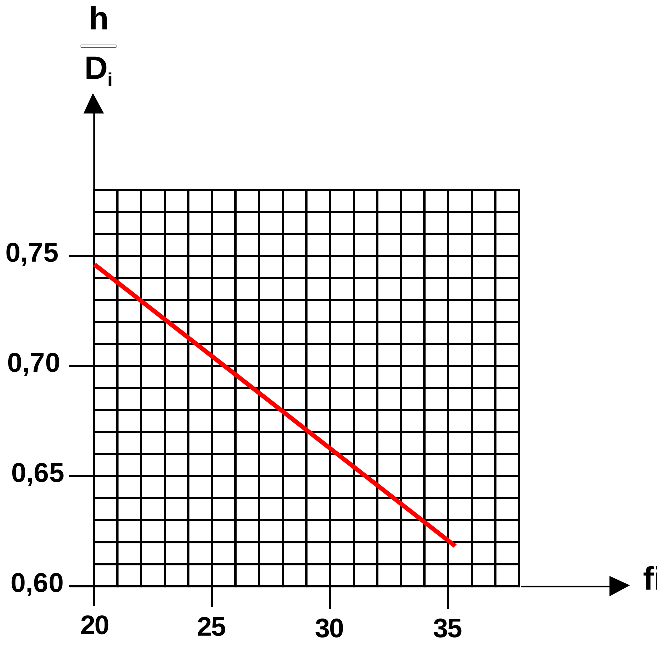
$L_i$ = useful mill length [m]

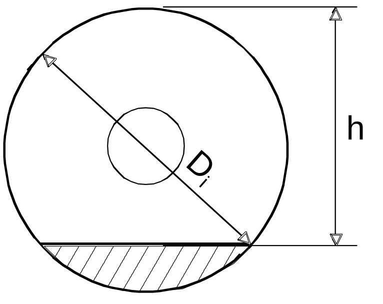
$D_i$= internal mill diameter [m]

n = mill speed [1/min]

# Grinding – Ball Mill Power

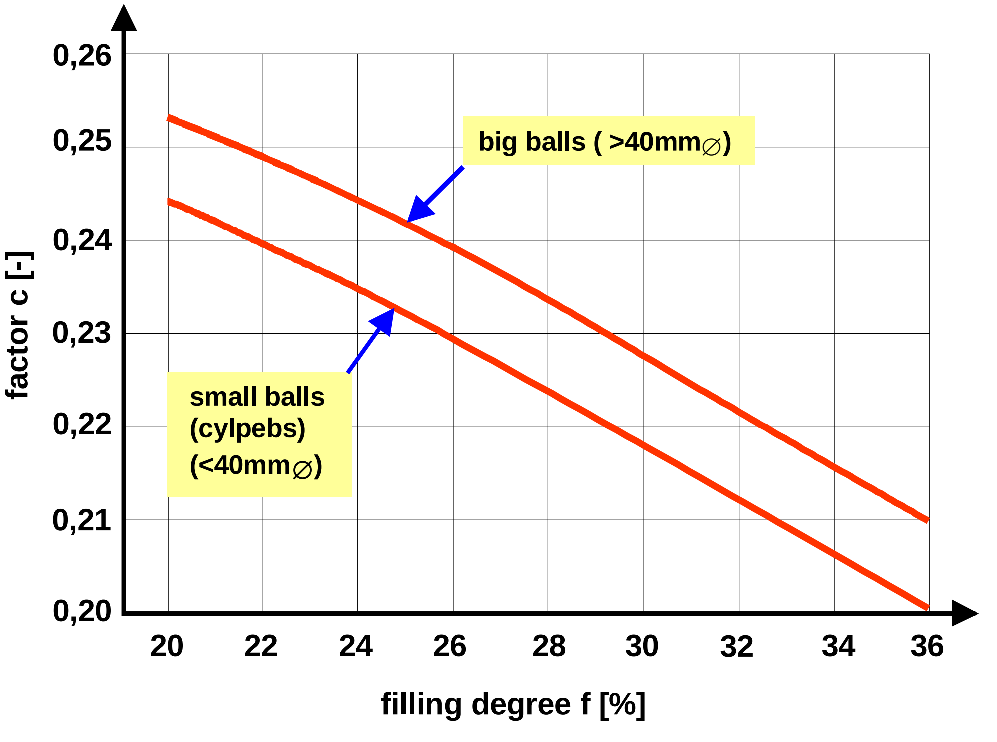
## Filling degree f from free height above grinding media charge




Di = Mill diameter inside mill liners

## Factor c - depending on filling degree and ball size



# Grinding – Ball Mill Power

## $R_{Es1}$ Calculation

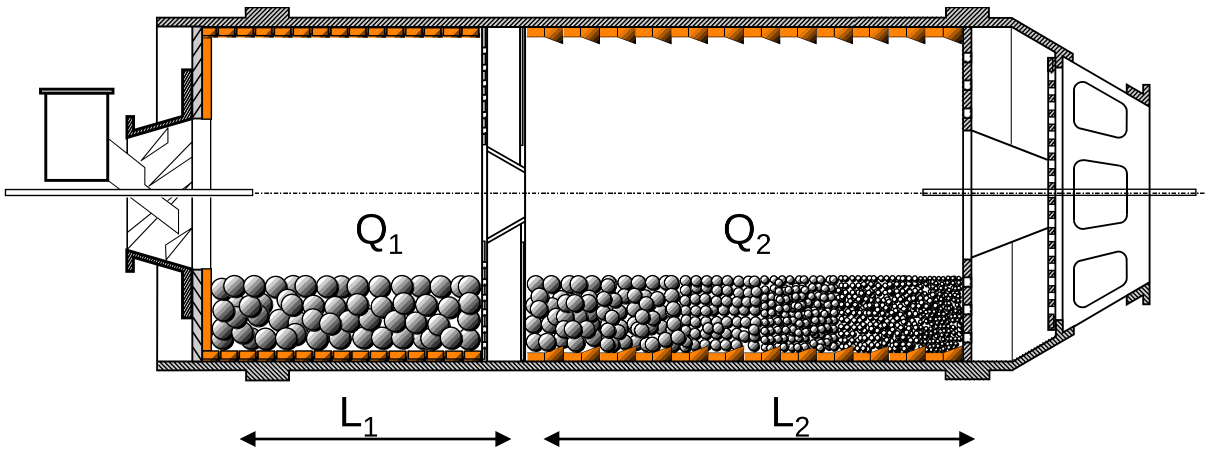
**Definition**

$$R_{Es1} = \frac{1^{st}\ \text{Chamber Actual Spec. El. Energy Cons.}}{1^{st}\ \text{Chamber Theoretical Spec. El. Energy Cons.}} = \frac{E_{S1}}{E_{ST}}$$

$E_{S1}$ = Actual specific energy in the 1st mill chamber [kWh/t]

$E_{ST}$ = Theoretical specific energy in the 1st mill chamber [kWh/t]

**Calculation**




$$E_{S1} = q \cdot \frac{P_{abs}}{\dot{m}}$$

$$q = \frac{Q_1}{Q_1 + Q_2}$$

$P_{abs}$ = mill shell absorbed power [kW]

$Q_1$ = weight of grinding media 1st chamber [t]

$Q_2$ = weight of grinding media 2nd chamber [t]

m = production rate mill [t/h]

q = weight ratio of grinding media 1st and 2nd chamber [-]

### $E_{ST}$ – Calculation example (using grindability guide values)

| | | Guide Value | | Example | | |
|---|---|---|---|---|---|---|
| $E_{ST}$ | Material | required [kWh/t] @ counter | | required [kWh/t] @ counter | Ratio of compo-nent in the mix [%] | kWh/t per compo-nent |
| | Clinker + Gypum | 9-11 | | 10 | 90 | 9.0 |
| | Limestone | 4-7 | | 5 | 5 | 0.3 |
| | Slag | 2-5 | | 5 | 5 | 0.3 |
| | Pozzolan | 4-6 | | | | |
| | Fly ash, dust | 0-2 | | | | |
| | | | | | Total $E_{ST}$ | 9.5 |

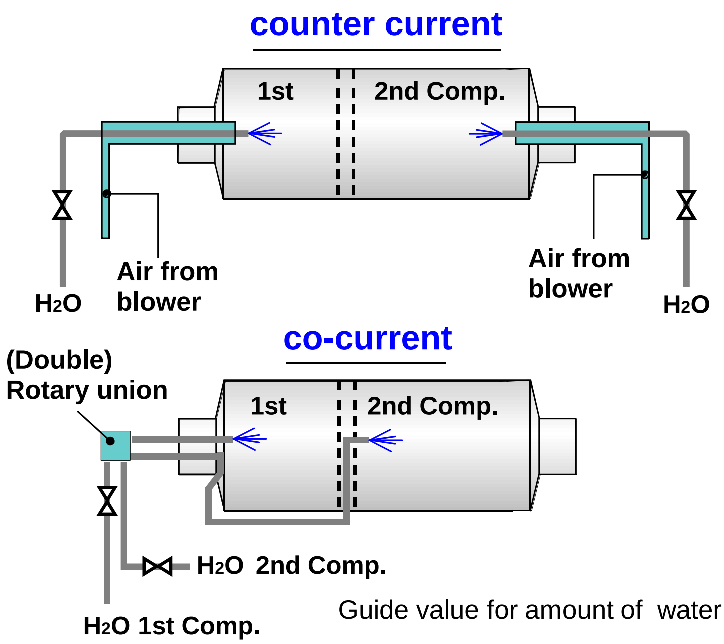
$$R_{Es1} = \frac{E_{S1}}{E_{ST}}$$

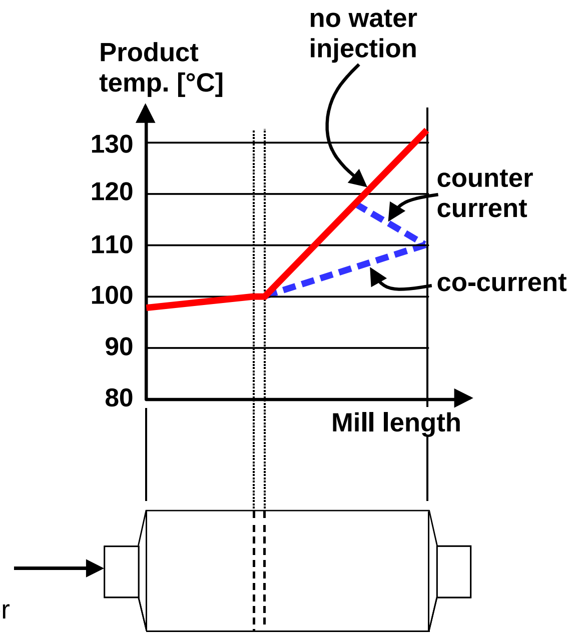
**> 1.2 → excess of grinding in the first chamber**

**< 1 → lack of grinding in the first chamber**

# Grinding – Ball Mill Ventilation & Cooling

## Water injection - systems



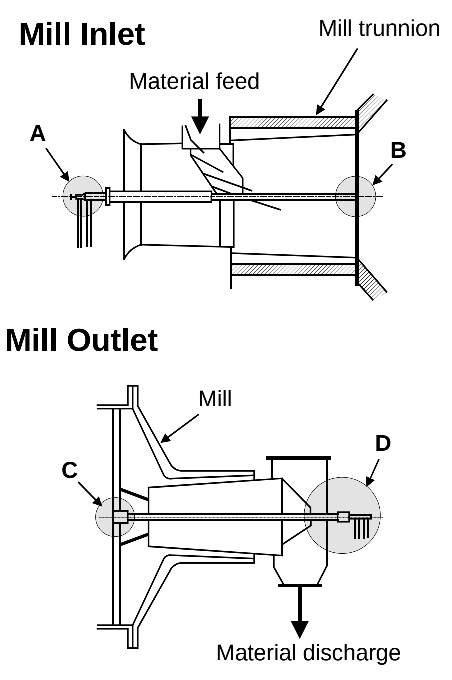



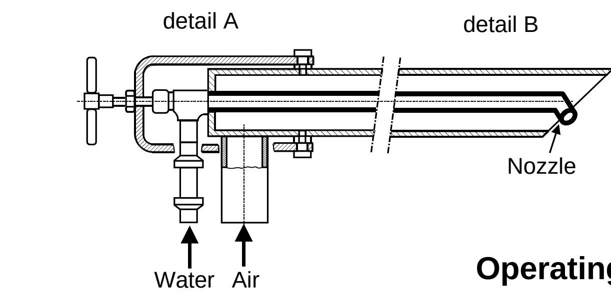

Guide value for amount of water

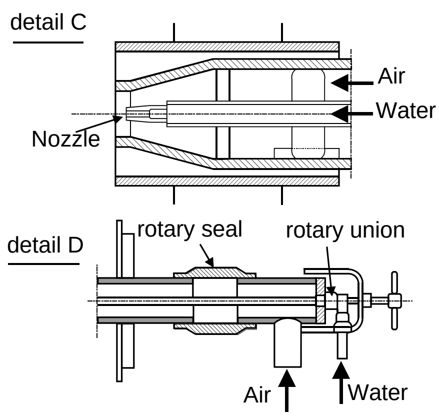
1st chamber: < 1 %

2nd chamber: < 2 %

## Water injection - devices



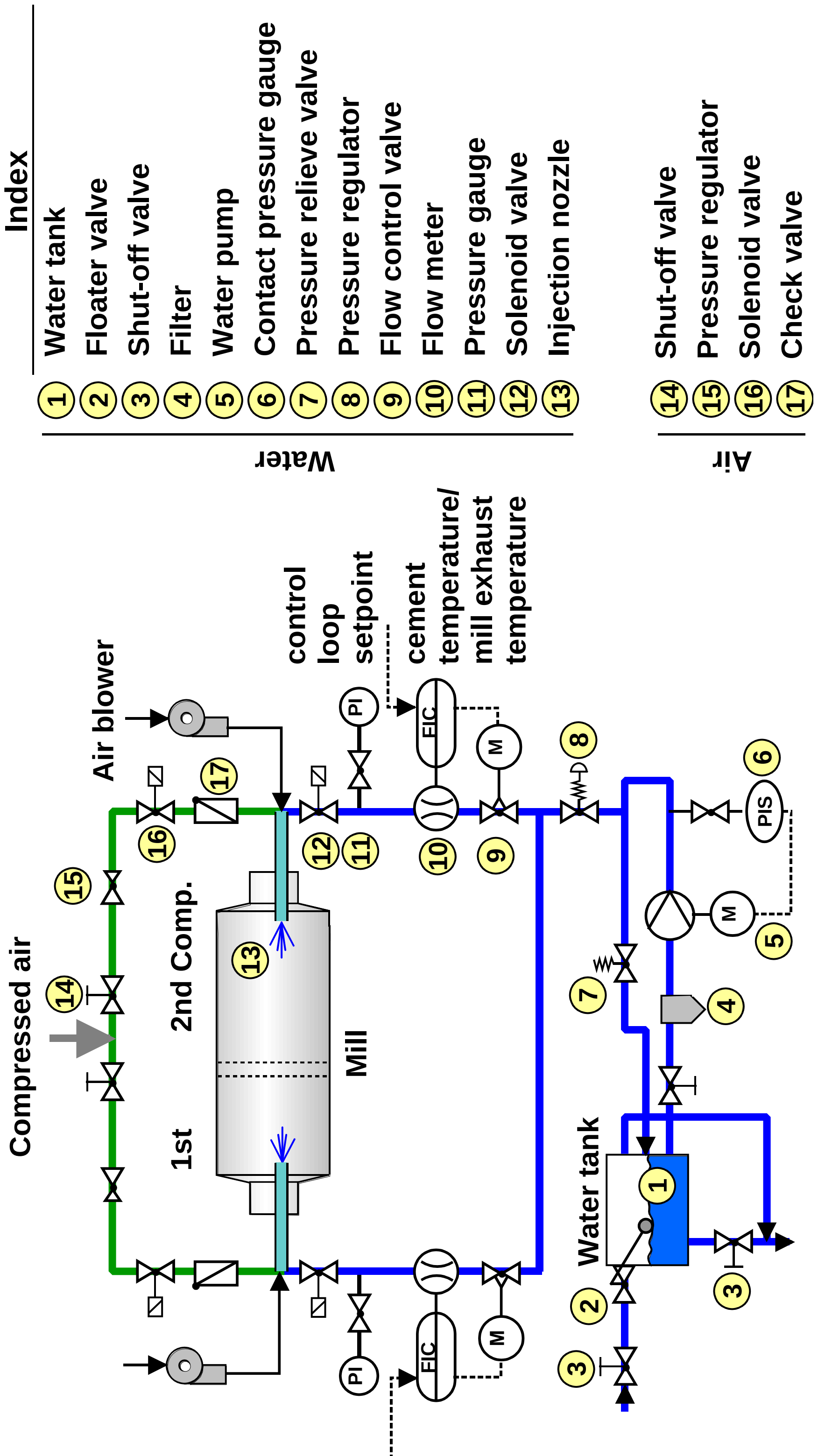




### Operating Pressures

| | | |
|---|---|---|
| Water [bar] | min<br>normal<br>max | 3<br>4-6<br>9 |
| Air blower [mbar] | | ≥ 50 |
| Compressed air [bar] | | ~ 5 |

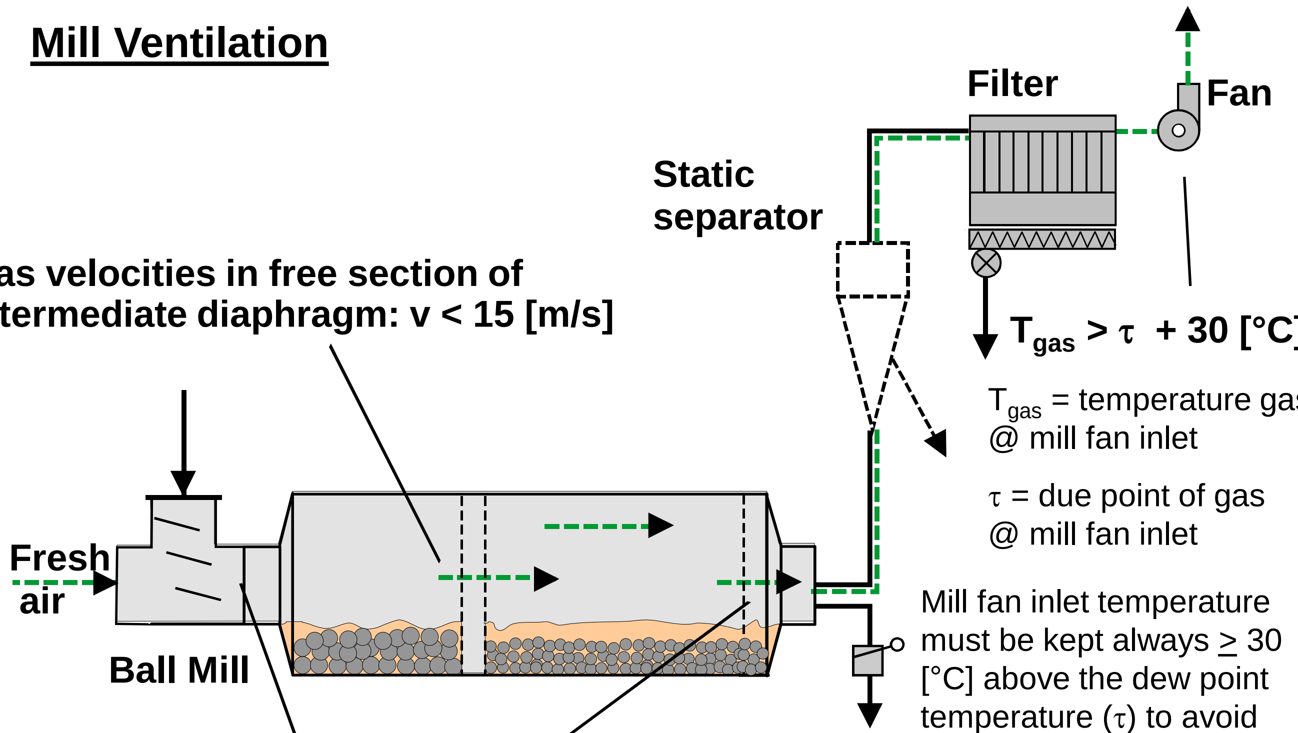
# Grinding – Ball Mill Ventilation & Cooling

## Water injection - control



# Grinding – Ball Mill Ventilation & Cooling

## Mill Ventilation




**Gas velocities in free section of inlet and outlet trunnion: v < 25 [m/s]**

Mill fan inlet temperature must be kept always ≥ 30 [°C] above the dew point temperature ($\tau$) to avoid condensation problems in the filter.

Excessive false air can favor condensation.

Dedusting system is typically design for a false air rate of ~15 % between mill outlet and fan.

With low false air intake @ mill outlet, temperature of gas at mill discharge is ~5 [°C] below cement temperature

**Gas velocities over ball charge (guide values)***

| Mill type | [m/s] |
|---|---|
| Open circuit mill | ~ 1 |
| Air swept mill | 5 – 6 |
| Closed circuit raw mill | 1 – 2 |
| Closed circuit cement mill | 1 – 1.5 |

* gas velocities based on mill outlet conditions

# Grinding – VRM Assessment

**Roller force F** consists of the roller and corresponding suspension weight $\mathbf{G_R}$ and the force $\mathbf{F_2}$ at roller exerted by the hydraulic cylinder. The force $\mathbf{F_2}$ at roller, which is perpendicular to the table, must be calculated from the hydraulic force $\mathbf{F_1}$ at cylinder with the lever arm ratio $l_1/l_2$.

$$F = G_R + F_2$$

$$F_2 = \frac{l_1}{l_2} \cdot F_1$$

F = Roller force [kN]

$G_R$ = Roller and suspension weight [kN]

$F_1$ = Force from hydraulic cylinder [kN]

$F_2$ = Force of hydraulic cylinder at roller [kN]

| | Guide value for lever arm ratio $l_1/l_2$ |
|---|---|
| Polysius Dorol | 0.9 – 1.0 |
| Polysius Quadropol | ~0.46 |
| Loesche LM and Fuller FRM | ~ 0.85 |
| FLS OK | 0.92 – 0.95 |
| FLS Atox | 0.9 – 1.0 |
| Gebr. Pfeiffer MPS | 1.0 |

**Grinding pressure k** is defined as the total roller force **F** divided by the projected roller section $\mathbf{D_R}$ **x** $\mathbf{W_R}$. Each mill type has its operating range. The necessary or achievable grinding pressure is related to the operating conditions.

$$k = \frac{F}{D_R \cdot W_R}$$

k = Grinding pressure [kN/m²]

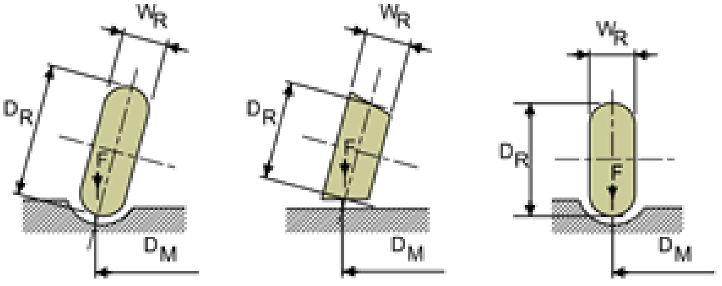
F = Roller force [kN]

$D_R$ = Medium diameter of roller [m]

$W_R$ = Width of roller [m]

**Table speed n** is a function of $\mathbf{D_M}$ for a constant centrifugal force of the material on the grinding table. Typical speed constant **c** are given for each supplier. In certain cases, lower speeds are used for fine and dry feed materials.

$$n = \frac{c}{\sqrt{D_M}}$$




n = Table speed [min$^{-1}$]

c = Speed constant [m$^{1/2}$ min$^{-1}$]

$D_m$ = Medium diameter of the grinding track [m]

# Grinding – VRM Power

**Friction factor μ** is a coefficient which describes the ratio of the rolling resistance force to the roller force applied. Typically the friction factor decreases with increasing roller force.

**Typical friction factors depending on mill type and material ground**

| Mill | Raw meal | Cement | Slag |
|---|---|---|---|
| Polysius | 0.09 - 0.12 | - | 0.14 - 0.16[1] |
| FLS | | 0.08 - 0.11 | 0.10 - 0.13 |
| Pfeiffer | | 0.07 - 0.10 | 0.09 - 0.12 |
| Loesche | 0.10 - 0.15 | 0.10 - 0.15 | 0.16 - 0.18 |

[1] only one case; Camden Slag Grinding Plant

$$P_{abs} = M \cdot \omega = i \cdot F \cdot \mu \cdot \frac{D_M}{2} \cdot \frac{2 \cdot \pi \cdot n}{60} = i \cdot \mu \cdot k \cdot D_R \cdot W_R \cdot D_M \cdot \pi \cdot \frac{n}{60}$$

$P_{abs}$ = Power absorbed at table [kW]

M = Torque required to turn table [kNm]

$\omega$ = Angular velocity [$s^{-1}$]

i = Number of rollers [-]

F = Roller force [kN]

μ = friction factor [-]

$D_m$ = Medium diameter of the grinding track [m]

n = Table speed [$min^{-1}$]

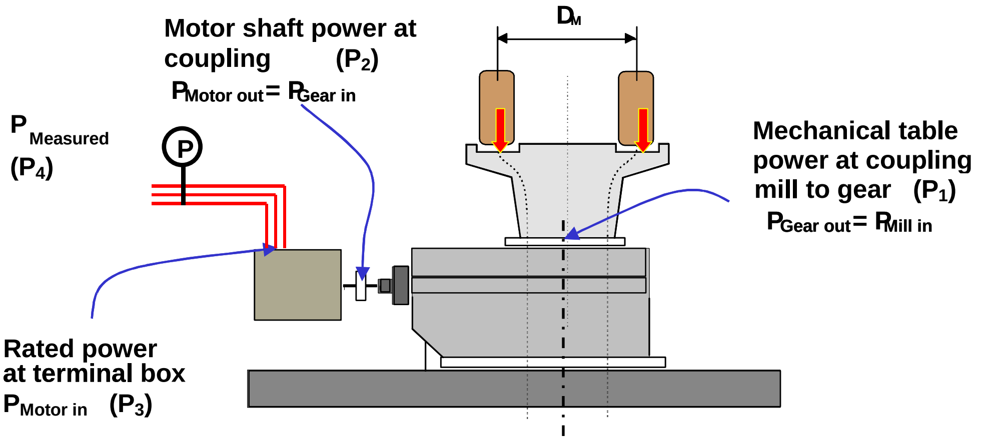
k = Grinding pressure [$kN/m^2$]

$D_R$ = Medium diameter of roller [m]

$W_R$ = Width of roller [m]

# Grinding – VRM Power

## Power transmission chain




$\eta_3$ $\eta_2$ $\eta_1$

$P_4$ $P_3$ $P_2$ $P_1 = P_{abs}$

$$P_4 = \frac{P_3}{\eta_3} \quad P_3 = \frac{P_2}{\eta_2} \quad P_2 = \frac{P_1}{\eta_1}$$

$\eta_1 = 0.98$ (gearbox)

$\eta_2 = 0.97$ (motor)

$\eta_3 = 0.99$ (without VFD)

$\eta_3 = 0.97$ (with VFD)

$$\boxed{E_s = \frac{P_4}{\dot{m}} \cdot \eta_1 \cdot \eta_2 \cdot \eta_3}$$

$E_s$ = specific electrical energy consumption (SEEC) @ table (e.g. from grindability test) [kWh/t]

$P_1 = P_{abs}$ = absorbed mechanical power at table [kW]

$P_2$ = mechanical power at motor shaft [kW]

$P_3$ = electrical power at terminal box of motor [kW]

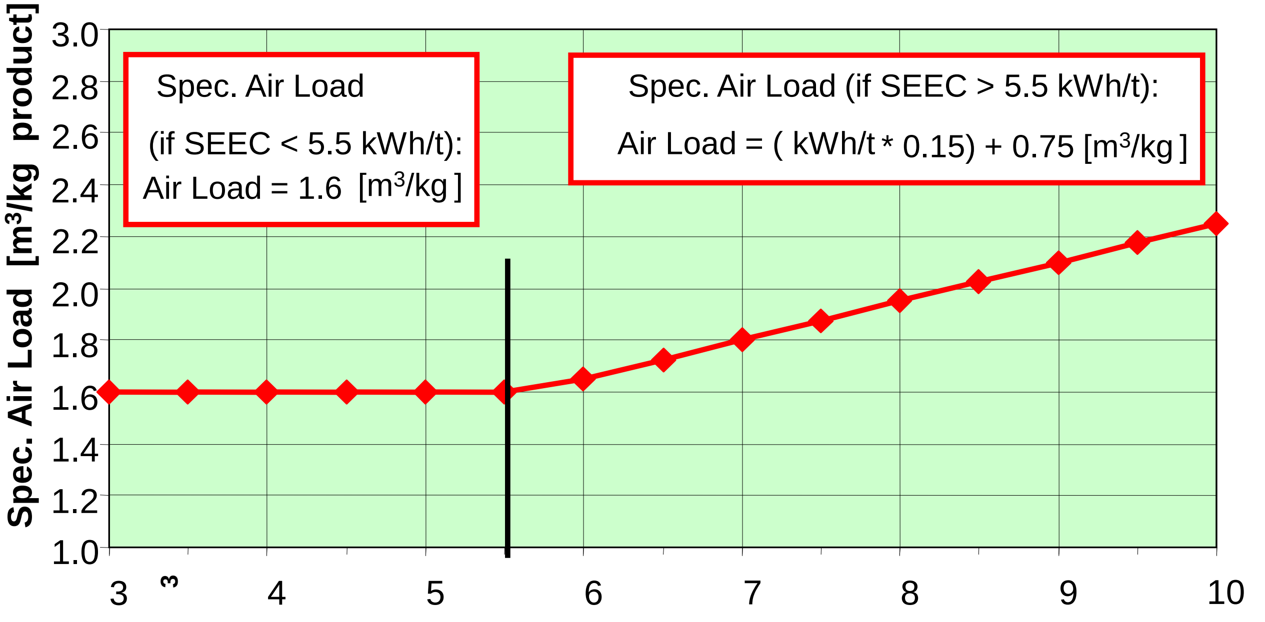
$P_4$ = electrical power at counter [kW]

m = production rate mill [t/h]

# Grinding – VRM Ventilation & Cooling

## Ventilation of VRMs (Holcim Standard)

### Specific Air Load (@mill exit) for Raw Material, Coal and Pozzolana




### Specific Air Load (@mill exit) for Cement Applications:

Specific Air Load ~ 3.2 [m³/kg] @ mill outlet (for 3500 Blaine)

### Gas speed

The mill has to be sized to meet the following required gas speed ranges (all gas flows and thus velocity calculations, including nozzle ring are based on the gas temperature at mill outlet, but on prevailing pressure):

- **Nozzle ring: ≥ 30 [m/s]** only vertical velocity component used
(gas velocity = actual gas flow (@ T mill outlet and p mill inlet) / horizontal open area of nozzle ring)

- **Mill casing: < 6.0 [m/s]** for vertical transport

- **Separator: 4.5 – 6.0 [m/s]** through the cage rotor (gross area)

False air calculation according page 150

# Grinding – Roller Press Assessment

## Press throughput

$$\dot{m} = \frac{w \cdot s \cdot v_u \cdot \rho_G \cdot 3.6}{1000}$$

m = Press throughput [t/h]

w = Roller width [mm]

s = Slab thickness [mm]

$v_u$ = Circumferential speed [m/s]

$\rho_G$ = Slab density [t/m³]

| | |
|---|---|
| $\rho_G$ Clinker | 2.4 – 2.5 [t/m³] |
| $\rho_G$ Limestone | ~2.3 [t/m³] |
| $\rho_G$ Slag | ~2.3 [t/m³] |

## Grinding force

$$F = \left(\frac{d}{1000}\right)^2 \cdot \frac{\pi}{4} \cdot z \cdot p \cdot 100$$

F = Grinding force [kN]

d = Diameter of hydraulic cylinder [mm]

z = Number of hydraulic cylinders[-]

p = Hydraulic pressure [bar]

## Grinding pressure

$$K = \frac{F \cdot 10^6}{D \cdot w}$$

$K \leq$ 6000 [kN/m²]

K = Grinding pressure [kN/m²]

F = Grinding force [kN]

D = Diameter of roller [mm]

w = Roller width [mm]

## Absorbed motor power at counter

$$P = \frac{2 \cdot F \cdot \beta \cdot \pi \cdot v_u}{\eta \cdot 180}$$

P = Absorbed motor power [kW]

F = Grinding force [kN]

$\beta$ = Attack angle [-]

$v_u$ = Circumferential speed [m/s]

$\eta$ = Efficiency of gear, motor and cable (~0.93 – 0.94) [-]

| | |
|---|---|
| $\beta$ Clinker | 2.3 – 2.85 [°] |
| $\beta$ Raw Material | 2.85– 4.0 [°] |
| $\beta$ Slag | 1.7 – 2.3 [°] |

# Grinding – Roller Press Assessment

## Specific surface load

$$L = \frac{F \cdot 10^3 \cdot 180}{w \cdot \frac{D}{2} \cdot \alpha \cdot \pi}$$

L = Specific surface load [N/mm²]

F = Press force [kN]

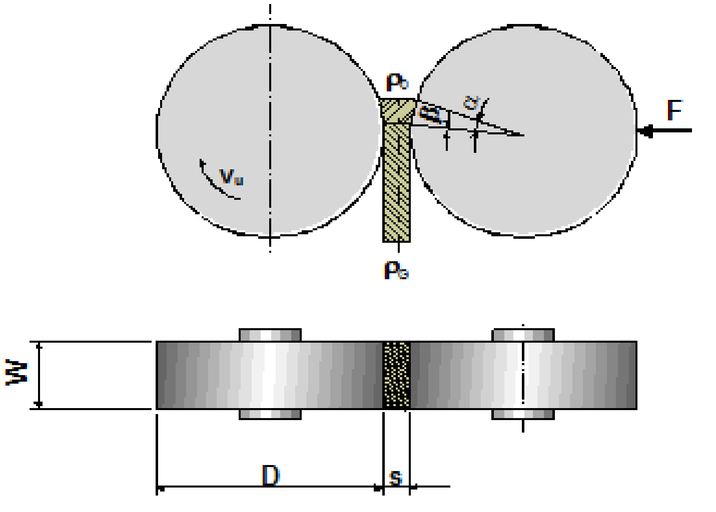
w = Roller width [mm]

D = Diameter of roller [mm]

$\alpha$ = Nip angle

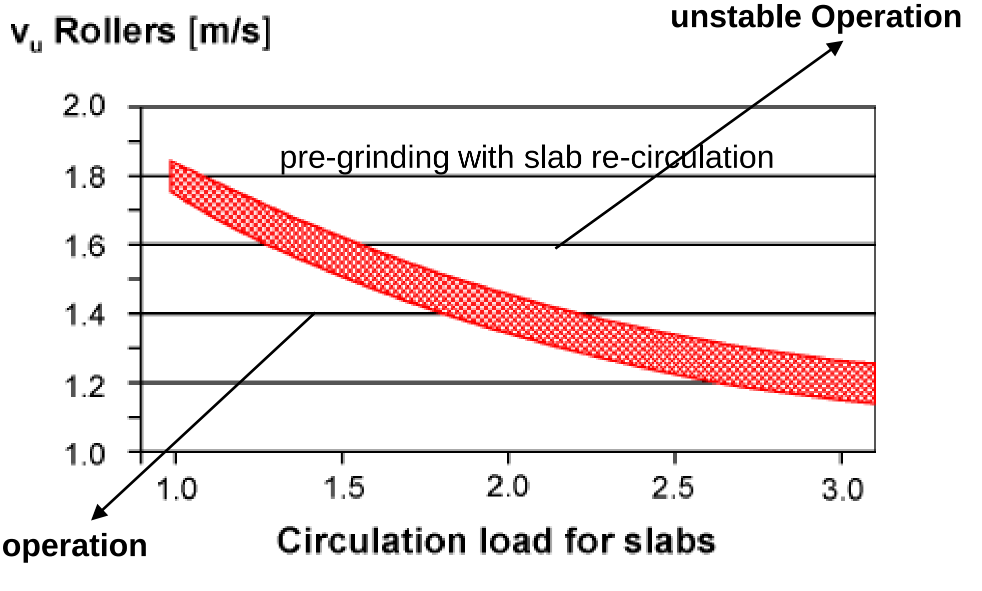
| | | |
|---|---|---|
| $\alpha$ Clinker | 6.9 – 9.2 | [°] |
| $\alpha$ Raw Material | 9.2– 12.6 | [°] |
| $\alpha$ Slag | 5.7 – 7.5 | [°] |

$L \leq 100$ [N/mm²]




## Roller Presses – Guide Values for Circumferential speed $v_u$

**Note: only for Pre-grinding units**



# Grinding – Separator Assessment

## Static Separators (or static classifiers)

### Cyclone

Nominal design gas flow through cyclones (rule of thumb)

$$V = \frac{d^2 \cdot n \cdot \pi \cdot 2.6 \cdot 3600}{4}$$

V = Total airflow [$m^3$/h]

d = Nominal diameter cyclone [m]

n = Number of cyclones [ - ]

Operation: - pressure drop 10 - 15 [mbar], dedusting efficiency 80 - 95 [%]

### Grit Separator

Nominal design gas flow through grit separator

$$V = \frac{d^2 \cdot 1000}{0.1613}$$

V = total airflow [$m^3$/h]

d = nominal diameter [m]

Operation: - pressure drop 10 - 15 [mbar], dedusting efficiency 80 - 95 [%]

- specific air load (feed): 500 - 1000 [g/$m^3$]

### V - Separator

Operational guide values for 1700 [$cm^2$/g] product fineness in closed circuit with roller press:

- specific air load ( feed) ~ 4 [kg/$m^3$]

- specific separator load ~ 6 [$m^3$/s] per [$m^2$] projected open separating area

- maximum fineness 2000 – 2200 [$cm^2$/g]

- pressure drop: 6 - 15 [mbar]

Designation: VS-459 -> 4.59 [$m^2$] projected open separating area

# Grinding – Separator Assessment

## Dynamic Separators (or dynamic classifiers)

### 1st Generation – Separators (Classifiers) with counter-blades and internal fan

| Cement Fineness [$cm^2/g$] | Specific separator load [$t/h,m^2$] |
|---|---|
| ~2500 | 2.2 - 3.6 |
| ~4500 | 1.0 - 1.5 |

$$\text{specific separator load} = \frac{\text{finished product}\,[t/h]}{\text{nominal cross section area}^*\,[m^2]}$$

* nominal cross section area based on inner diameter of cylindrical housing

### 2nd Generation - Separators (Classifiers) with counter-blades and external fan

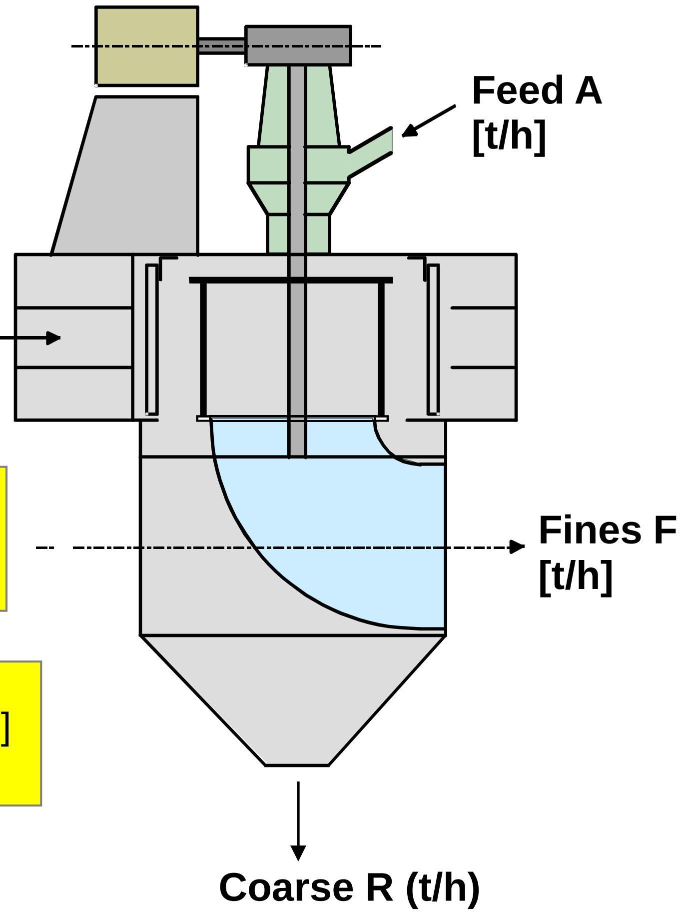
| Cement Fineness [$cm^2/g$] | Specific separator load [$t/h,m^2$] |
|---|---|
| 2600 | ~ 11 |
| 3000 | ~ 8 |

$$\text{specific separator load} = \frac{\text{finished product}\,[t/h]}{\text{nominal cross section area}^*\,[m^2]}$$

* nominal cross section area based on inner diameter of cylindrical housing

# Grinding – Separator Assessment

## 3rd Generation - Rotor Type Separator (Classifier)




**Specific air loads**

$$\frac{\text{Feed}}{\text{Air amount}} \leq 2.5\ [\text{kg/m}^3]$$

$$\frac{\text{Fines}}{\text{Air amount}} \leq 0.75\ [\text{kg/m}^3]$$

**Rotor values**

- Circumferential speed

  $v_u$ ~ 10 – 35 [m/s] for cement*

  $v_u$ ~ 10 – 25 [m/s] for raw meal and coal

- Air speed through rotor

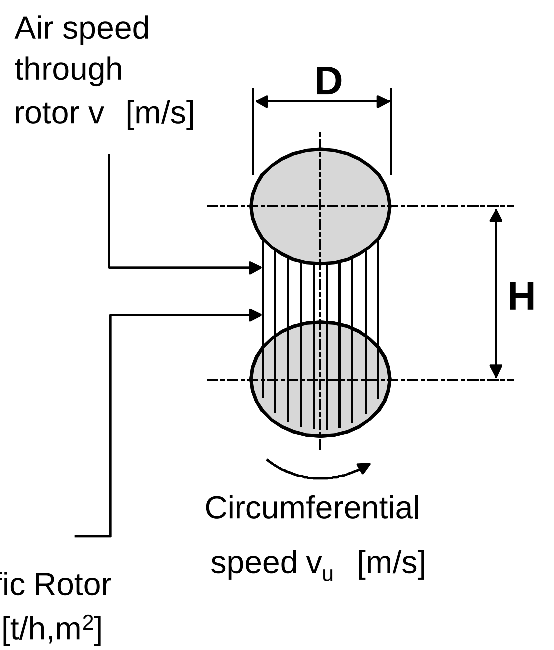
  v ~ 4 [m/s] for cement*

  v ~ 5 [m/s] for raw meal and coal

  **PC 3000 [cm²/g]*

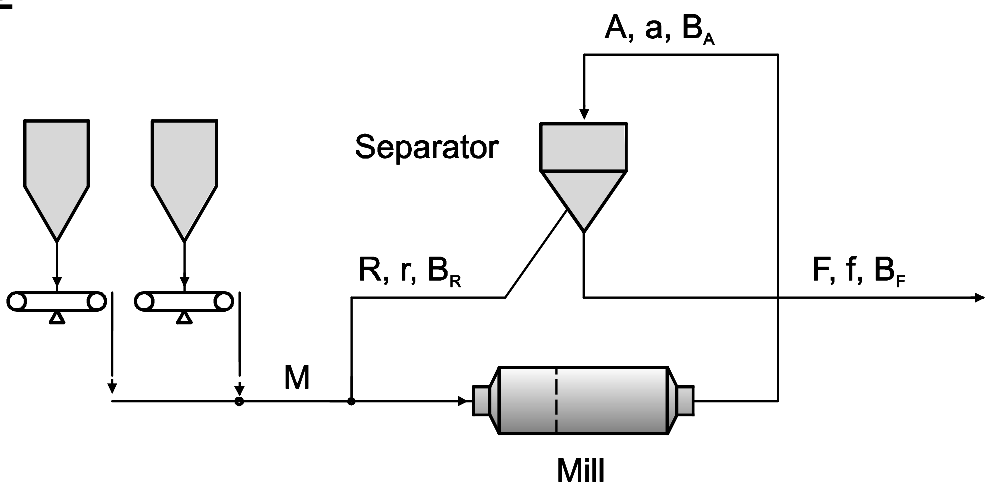
- Specific rotor load

$$= \frac{\text{Fines [t/h]}}{\text{D [m]} \times \pi \times \text{H [m]}} \sim 10\text{-}12\ [\text{t/h,m}^2]$$



# Grinding – Separator Assessment

## Symbols




**Basic equations**

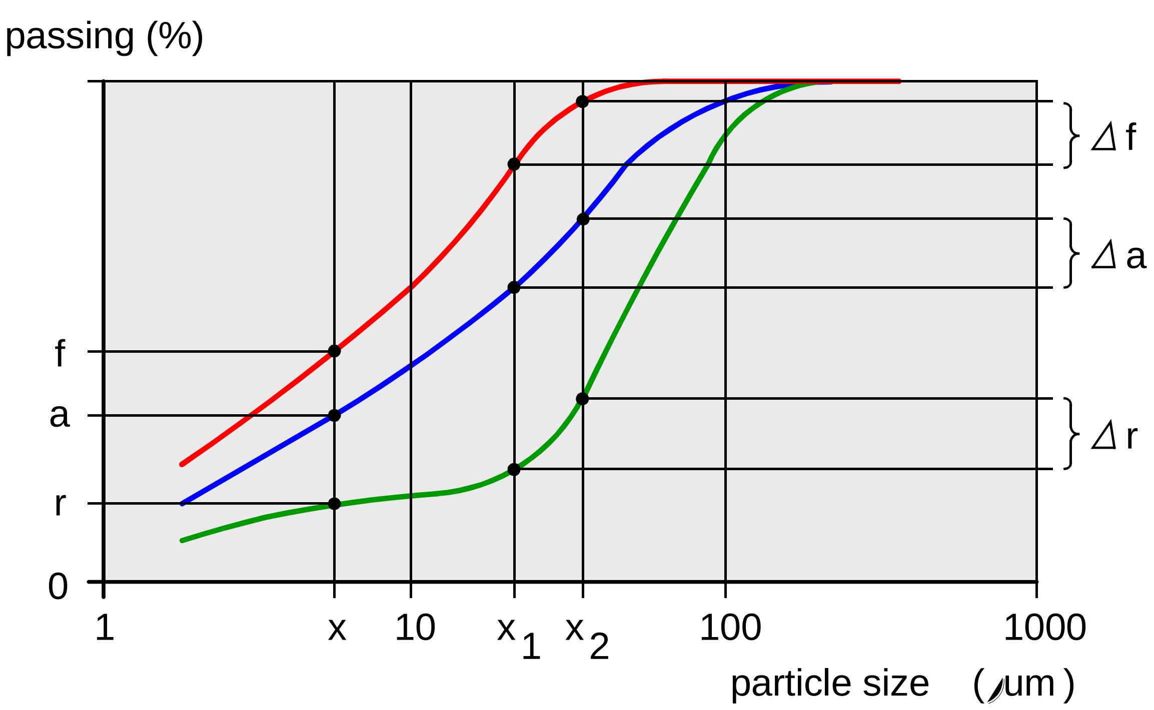
$$A = F + R$$

$$A \cdot a = F \cdot f + R \cdot r$$

$$A \cdot \Delta a = F \cdot \Delta f + R \cdot \Delta r$$

| Description | Mass flow [t/h] | weight fraction < x µm [%] | weight fraction >x1 and <x2 µm [%] |
|---|---|---|---|
| Separator feed | A | a | Δa |
| Fine fraction | F | f | Δf |
| Coarse fraction | R | r | Δr |

## Definitions fineness



# Grinding – Separator Assessment

## Circulating Load

The circulating load u in closed-circuit grinding is defined as the mass flow of the separator feed A divided by the mass flow of the fine fraction F, or:

$$\boxed{u = \frac{A}{F}} \qquad \text{eq. (1)}$$

The actual value of the circulating load depends on various factors, such as mill & separator design, grinding efficiency, product fineness and others.

## Calculation of Circulating Load

If no weighing equipment for separator feed A or rejects R is installed, circulation load u is calculated using particle size analysis data and formula (a) & (b).& eq. (1):

$$A = F + R \quad (a) \qquad A \cdot a = F \cdot f + R \cdot r \quad (b) \qquad u = \frac{A}{F} \quad (eq1)$$

$$\boxed{u = \frac{(f - r)}{(a - r)}} \qquad \text{eq. (2)}$$

a = weight fraction [%] in feed < x [µm]

f = weight fraction [%] in fines < x [µm]

r = weight fraction [%] in rejects < x [µm]

It is recommended to use the u-values calculated by this formula with caution, because inevitable errors in the determination of the particle size distributions affect the result considerably.

Therefore in Holcim for the calculation of the circulating load most frequently the sums of all weight fractions between 0 and $x_i$ are used:

$$\boxed{u = \frac{\left(\sum f_i - \sum r_i\right)}{\left(\sum a_i - \sum r_i\right)}}$$

$a_i$ = weight fraction in feed < $x_i$ (or > $x_i$) [µm]

$f_i$ = weight fraction in fines < $x_i$ (or > $x_i$) [µm]

$r_i$ = weight fraction in rejects < $x_i$ (or > $x_i$) [µm]

$x_i$ = sieve size

# Grinding – Separator Assessment

## Tromp Curve (Classification Curve)

If we ask for the recovery of a feed size class with lower particle size limit x1 and upper particle size limit x2 (x1 greater zero) into the coarse stream, we arrive at the Tromp value for the coarse stream.

$$t_r = \frac{(R \cdot \Delta r)}{(A \cdot \Delta a)} \cdot 100\,[\%]$$

or

$$t_r = \frac{\Delta r}{\Delta a} \cdot \left(1 - \frac{1}{u}\right) \cdot 100\,[\%]$$

eq. (5) eq. (6)

If this ratio is obtained for a number of size classes and plotted against x, the result is the classification curve (see Figure 1 – next page), which is also called the Tromp curve.

## Features of the Tromp Curve (Classification Curve)

### Cut Point

The cut point $d_{50}$ corresponds to 50 [%] of the feed passing to the coarse stream (see Figure 2 – next page). $d_{50}$ is therefore that particle size, which has equal probability of passing either to the coarse or the fine streams.

### By-Pass Effect

Ideally, the Tromp curve is asymptotic to the abscissae at ordinate values of zero and unity.

In practice, it is often the case that the lower asymptote occurs at ordinate values a' greater than zero (see Figure 3 – next page), i.e. a portion of each size fraction bypasses the classifying action. Expressed in an other way, part of the feed reports to the coarse stream independently of its particle size.

Experience has shown that the bypass parameter a' varies with classifier feed rate, and hence it is difficult to describe a single Tromp curve which is representative of the classifier.

### Sharpness of separation

The sharpness of separation k is defined as follows, where $d_{75}$ and $d_{25}$ denote the particle sizes with Tromp values of 75 [%] and 25 [%] (see Figure 2 – next page). For an ideal separation k would be 1.

$$k = \frac{d_{75}}{d_{25}}$$

# Grinding – Separator Assessment

## Features of the Tromp Curve (Classification Curve)

FIG. 1

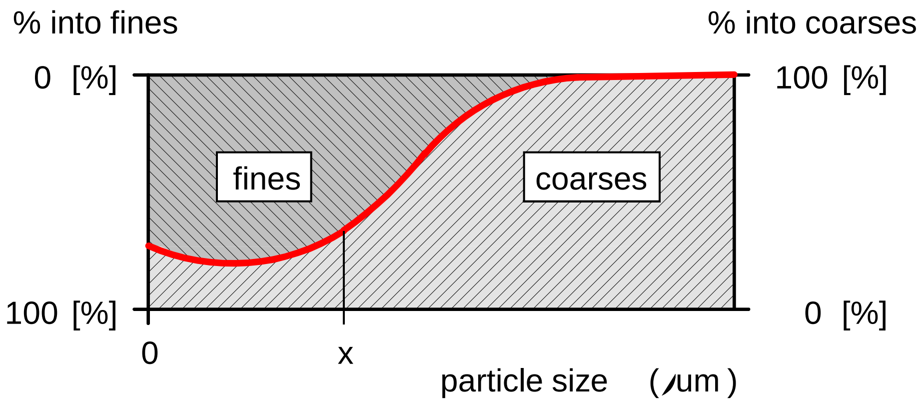



FIG. 2 sharpness of separation k = $d_{75}$ / $d_{25}$

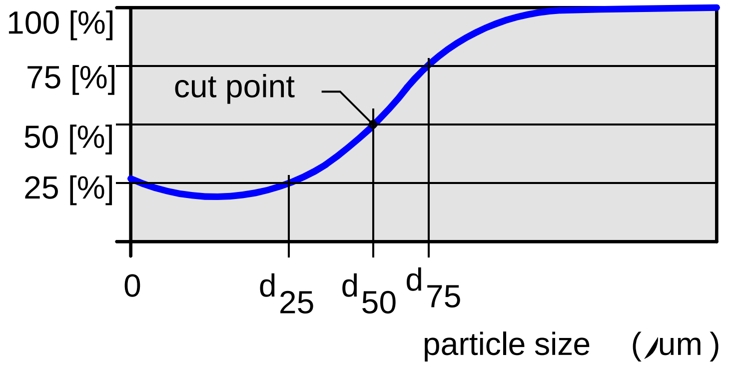
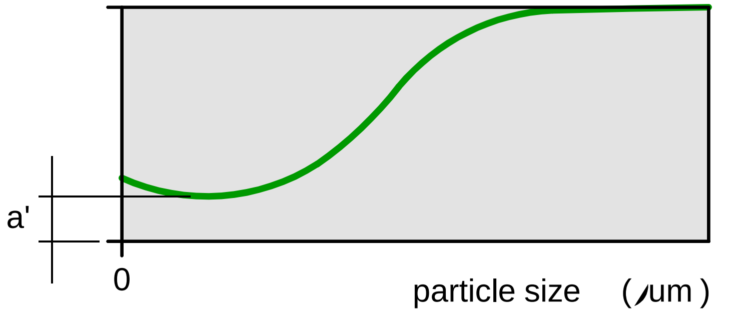


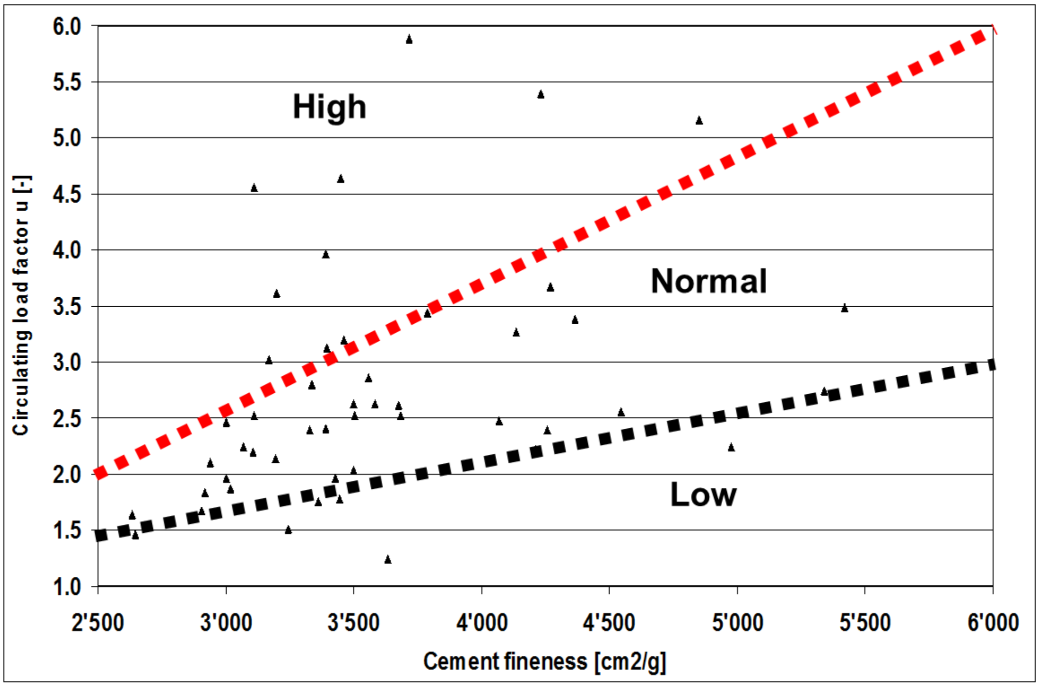

FIG. 3

bypass a'

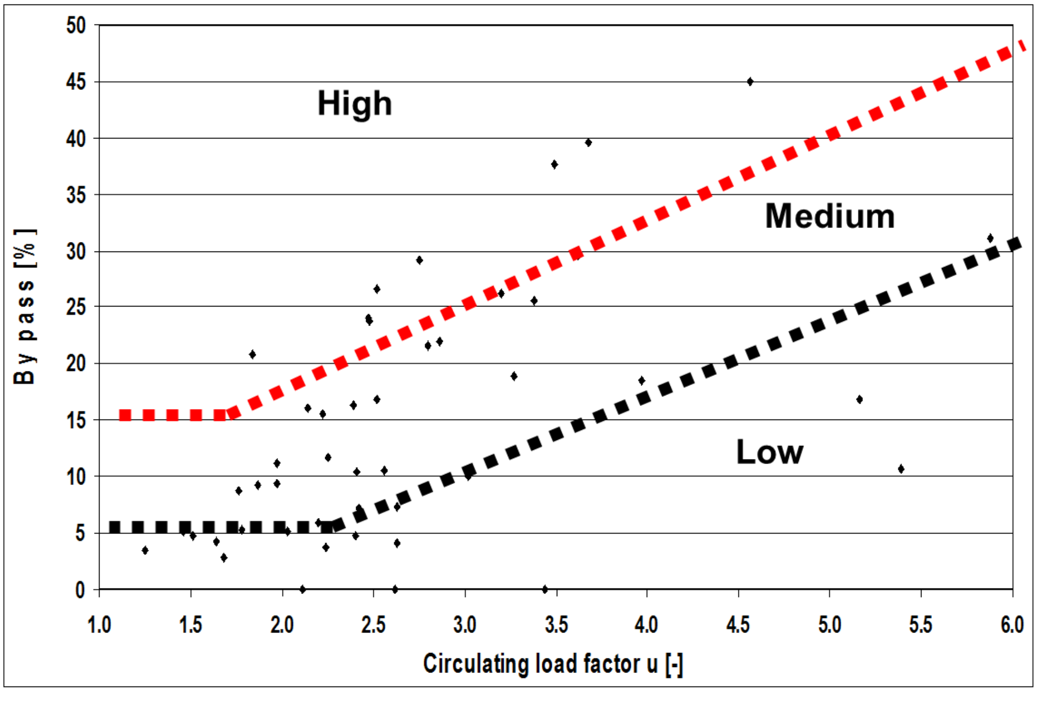


# Grinding – Separator Assessment

## Typical circulating loads vs. product fineness of a High Efficiency Separator (3rd Generation)




## Typical bypass rates vs. circulation load of a High Efficiency Separator (3rd Generation)

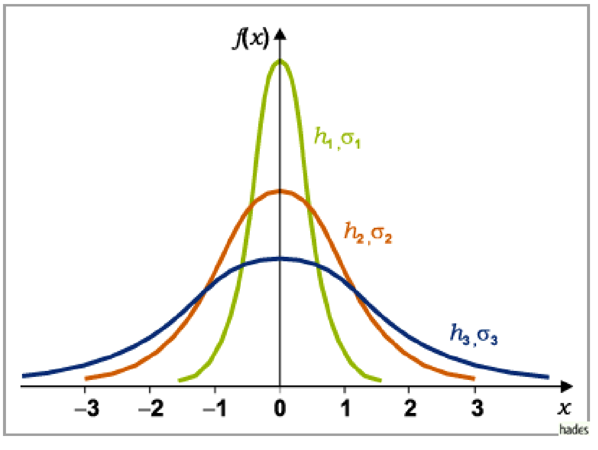


# Grinding – Product Particle Size Distribution

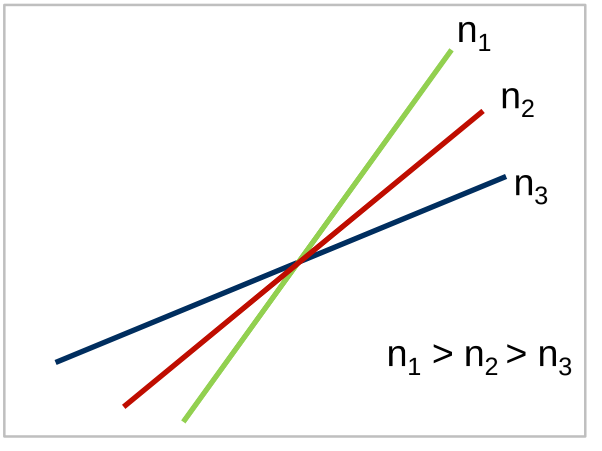
## Particle Size Distribution (PSD) of Product: Rosin-Rammler-Sperling-Bennet (RRSB)

The RRSB distribution is a double logarithmic illustration of the Gauss distributions. The ideal Gauss curves (PSDs normally distributed – valid for pure materials, like OPC, slag, limestone, etc.) convert into straight lines in the double logarithmic illustration of the RRSB diagram. The slope n is a measure for how narrow a particle size distribution is. The higher the slope n, the narrower the particle size distribution and vice versa.

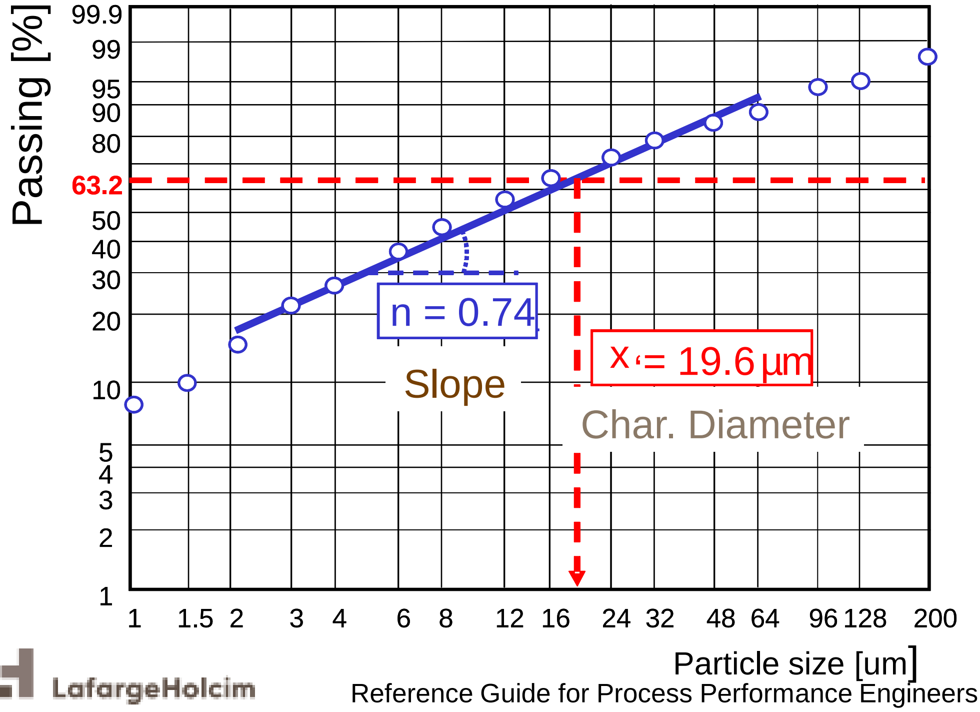
**Bell-shaped Gauss Distribution in linear coordinate plane**




**Gauss Distribution in double logarithmic coordinate plane**




## Key parameters of the Rosin-Rammler-Sperling-Bennet diagram



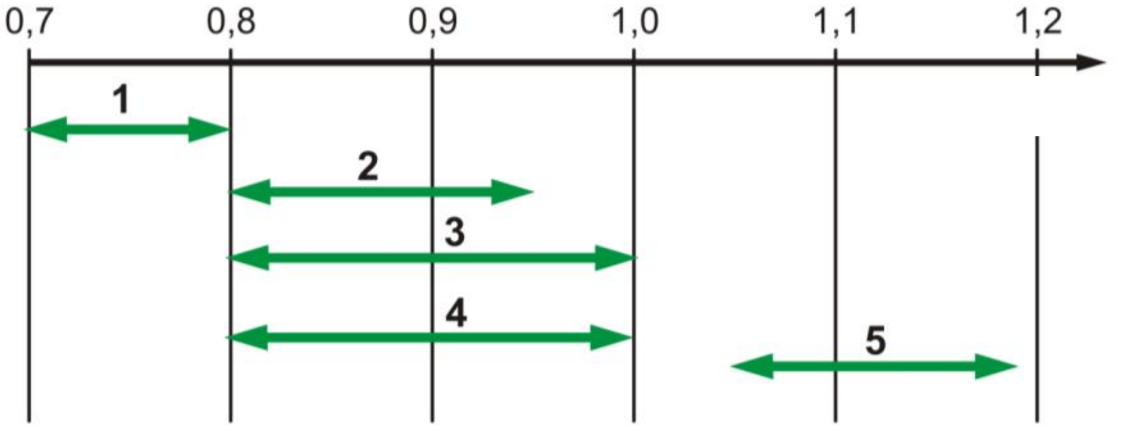

n = slope of the straight line [-]

x' = characteristic diameter, that 63.2 % of all particles pass

# Grinding – Product Particle Size Distribution

## Typical slopes n in the RRSB diagram for different grinding systems

Slope n (for OPC 3500 cm$^2$/g)




1 Open circuit Ball Mill

2 Closed circuit Ball Mill with 1$^{st}$ & 2$^{nd}$ generation separator

3 Closed circuit Ball Mill with 3$^{rd}$ generation separator

4 Vertical Roller Mill / Ball Mill with pregrinding unit (depending on separator)

5 Finish grinding system (e.g. Roller Press)

# Grinding – Heat Balance

## Heat balance - system

Heat balance Energy:
$\sum$ Inputs = $\sum$ Outputs

**Heat Input**

**Separator**

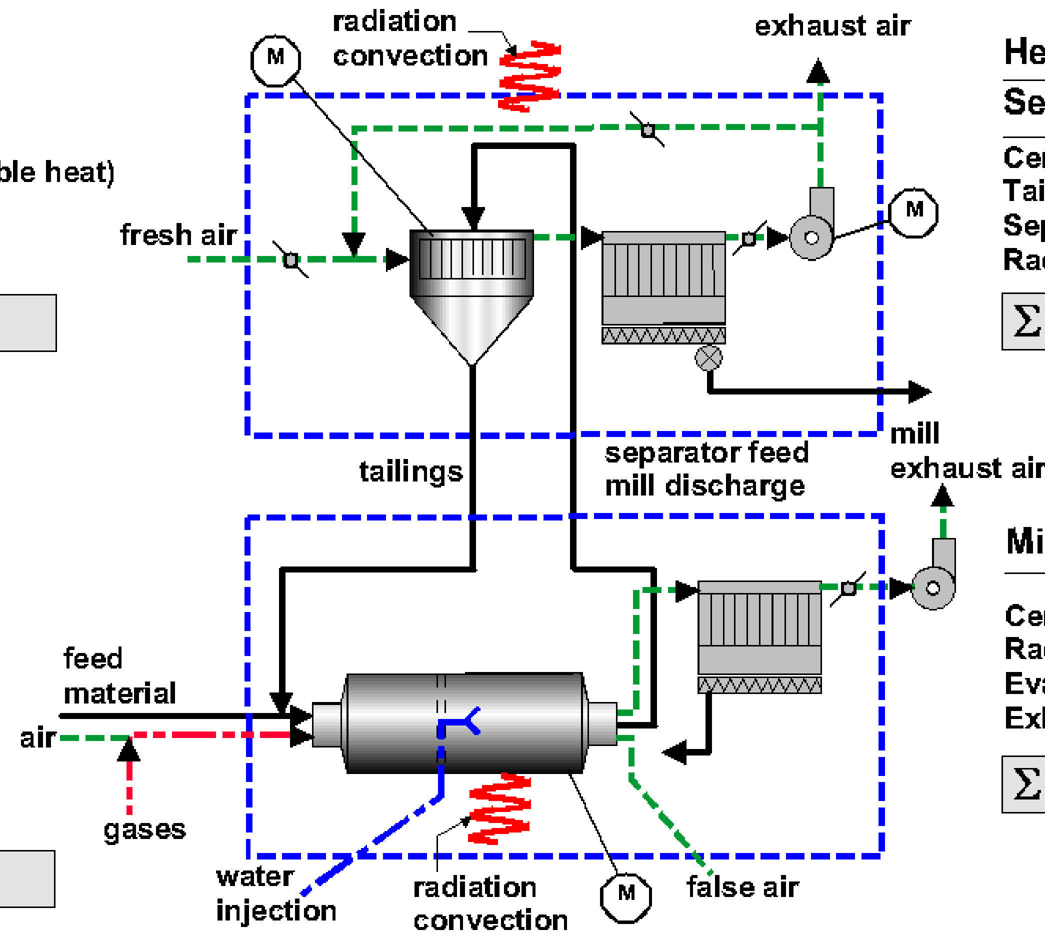
Feed material (sensible heat)
Motors (separ+fan)
Fresh air

$\sum$ Input

**Mill**

Grinding heat
Feed materials
Separator tailings
Water (total)
Gases
Ventilation air
(incl.false air)

$\sum$ Input




**Heat Output**

**Separator**

Cement heat
Tailings heat
Separator exhaust
Radiation / convection

$\sum$ Output

**Mill**

Cement heat
Radiation / convection
Evaporated water
Exhaust air / gas

$\sum$ Output

# Grinding – Heat Balance

## Heat balance example

### Cement grinding system

| | | | | | |
|---|---|---|---|---|---|
| System: | Ball Mill with separator | | | | |
| | Mill diameter | | 4.6 | [m] | |
| | Mill length | | 15.5 | [m] | |
| | Motor power | | 5000 | [kW] abs.@ counter | |
| | Overall drive eff. | | 91 | [%] | |
| Operating data: | | | | | |
| | Production | | 180 | [t/h] | Pozzolana cement |
| | Composition | clinker | 71 | [%] | |
| | | gypsum | 4 | [%] | 4 [%] $H_2O$ |
| | | pozzolana | 25 | [%] | 8 [%] $H_2O$ |
| | Clinker temperature | | 150 | [°C] | |
| | Ambient temperature | | 20 | [°C] | |
| | Water temperature | | 15 | [°C] | |
| | Hot gas temperature | | 450 | [°C] | |
| | Mill inlet temperature | | ~200 | [°C] | |
| | Mill discharge temp. (cement) | | 110 | [°C] | |
| | Mill discharge temp. (gas) | | 105 | [°C] | |
| | Finish product temperature | | 104 | [°C] | |
| | Mill fan flow rate | | 33000 | [$Nm^3$/h] | |

### Index

| | | |
|---|---|---|
| G | [t/h] | mill production |
| u | [ - ] | circulation factor (feed/product) |
| t | [°C] | temperature |
| $P_{abs.}$ | [kW] | absorbed power (counter) |
| η | [ - ] | efficiency of drives |
| cp | [kJ/kg] [kJ/$Nm^3$] | spec. heat value (related to reference temperature) |
| W | [l/h] | water to be evaporated<br>*index:* *in* *moisture in feed material (incl. water injected)*<br>*ev* *evaporated water* |
| V | [$Nm^3$/h] | air/gas flow rate<br>*index:* *g* *gas*<br>*a* *fresh air*<br>*ex* *exhaust air*<br>*s* *fresh air separator* |
| k | [kJ/$m^2$ °C h] | radiation/convection factor |
| A | [$m^2$] | radiation surface |
| q | [kJ/kg $H_2O$] | heat of evaporation |

# Grinding – Heat Balance

## Heat balance example

**Fig. 11 Heat Balance Cement Mill Example**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Heat Balance Mill:*** | | | | | | | |
| Grinding heat | $P_{abs.}$ * η * 3.6 * 1000 | / G * 1000 | 5000 * 0.91 * 3.6 * 1000 / (180 * 1000) | 91.0 | [kJ/kg] | 33.4 | [%] |
| Separator tailings | G * (u-1)) * cp * (t-20) * 1000 | / G * 1000 | 180 * (2-1) * 0.819 * (104-20) / (180 * 1000) | 68.8 | [kJ/kg] | 25.2 | [%] |
| Feed material heat | G * cp * (t-20) | / G * 1000 | 180 * 0.806 * (110-20) / (180 * 1000) | 73.2 | [kJ/kg] | 26.9 | [%] |
| Water (feed + injection) | $W_{in}$ * 4.2 * (t-20) | / G * 1000 | 5410 * 4.2 * (15-20) / (180 * 1000) | -0.7 | [kJ/kg] | -0.2 | [%] |
| Gases | $V_g$ * cp * (t-20) | / G * 1000 | 11'000 * 1.529 * (450-20) / (180 * 1000) | 40.2 | [kJ/kg] | 14.8 | [%] |
| Air (including false air) | $V_a$ * cp * (t-20) | / G * 1000 | 15'290 * 1.3 * (20-20) / (180 * 1000) | 0.0 | [kJ/kg] | 0.0 | [%] |
| ***INPUT :*** | | | | **272.5** | **[kJ/kg]** | **100** | **[%]** |
| Cement heat ex mill | G * u * cp * (t-20) * 1000 | / G * 1000 | 180 * 2 * 0.822 * (110-20) / (180 * 1000) | 148.0 | [kJ/kg] | 54.3 | [%] |
| Radiation / convection | k * A * (t-20) * 3.6 | / G * 1000 | 14.15 * 1030 * (110-20) * 3.6 / (180 * 1000) | 26.2 | [kJ/kg] | 9.6 | [%] |
| Water (evaporated) | $W_{ev}$ * q | / G * 1000 | 5'410 * (2501 + (1.88 * 105)) / (180 * 1000) | 81.1 | [kJ/kg] | 29.8 | [%] |
| Exhaust air /gas | $V_{ex}$ * cp * (t-20) | / G * 1000 | 26'850 * 1.358 * (105-20) / (180 * 1000) | 17.2 | [kJ/kg] | 6.3 | [%] |
| ***OUTPUT :*** | | | | **272.5** | **[kJ/kg]** | **100** | **[%]** |
| ***Heat Balance Separator:*** | | | | | | | |
| Separator Feed | G * u * cp * (t-20) * 1000 | / G * 1000 | 180 *2 * 0.822 * (110-20) * 1000 / (180 * 1000) | 148.0 | [kJ/kg] | 97.0 | [%] |
| Motors separator + fan | $P_{abs.}$ * η * 3.6 * 1000 | / G * 1000 | 282 * 0.8 * 3.6 / (180 * 1000) | 4.5 | [kJ/kg] | 3.0 | [%] |
| Separating air (fresh) | $V_s$ *1.3 * (t-20) | / G * 1000 | 3'032 * 1.3 * (20-20) / (180 * 1000) | 0.0 | [kJ/kg] | 0.0 | [%] |
| ***INPUT :*** | | | | **152.5** | **[kJ/kg]** | **100** | **[%]** |
| Tailings | G * (u-1) * cp * (t-20) * 1000 | / G * 1000 | 180 * (2-1) * 0.819 * (104-20) / (180 * 1000) | 68.8 | [kJ/kg] | 45.1 | [%] |
| Radiation / convection | k * A *(t-20) * 3.6 | / G * 1000 | 14.15 * 550 * (104-20) * 3.6 / (180 * 1000) | 13.1 | [kJ/kg] | 8.6 | [%] |
| System exhaust air | $V_{s\,ex}$ * cp * (t-20) | / G * 1000 | 3'032 * 1.3 * (104-20) / (180 * 1000) | 1.8 | [kJ/kg] | 1.2 | [%] |
| Cement heat | G * cp * (t-20) * 1000 | / G * 1000 | 180 * 0.819 * (104-20) / (180 * 1000) | 68.8 | [kJ/kg] | 45.1 | [%] |
| ***OUTPUT :*** | | | | **152.5** | **[kJ/kg]** | **100** | **[%]** |

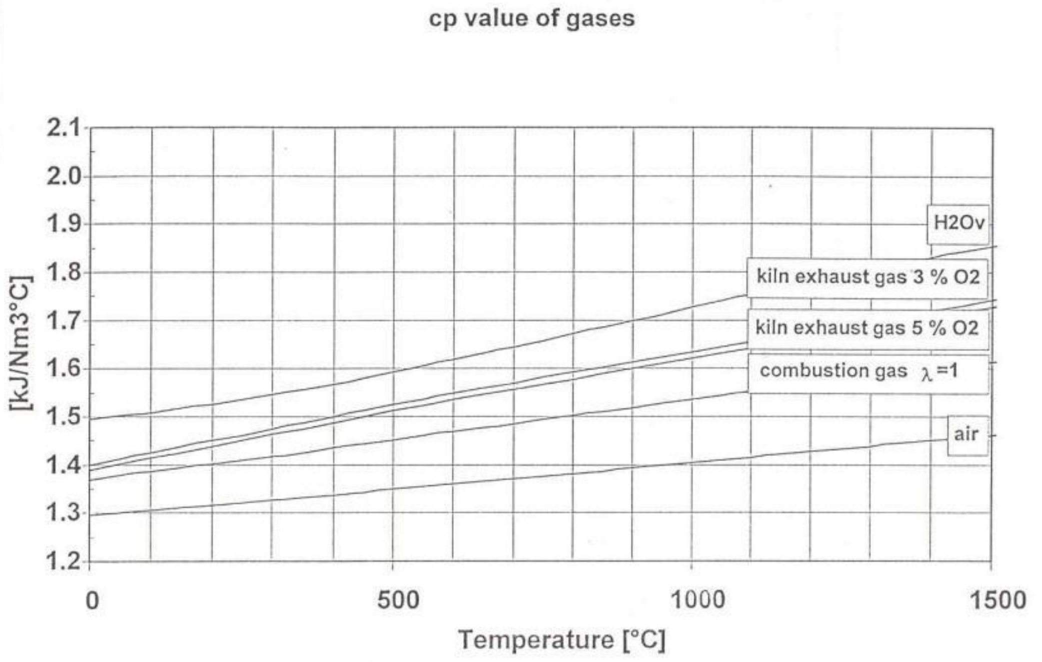
Heat of evporation q = 2501 + (1.88 * t) [kJ/kg $H_2O$] heat of evaporation at exhaust temperature
Radiation / convection factor k = (($\Delta t_{cem}$-10) * 0.055) + 9.75 [kJ/m² °C h]

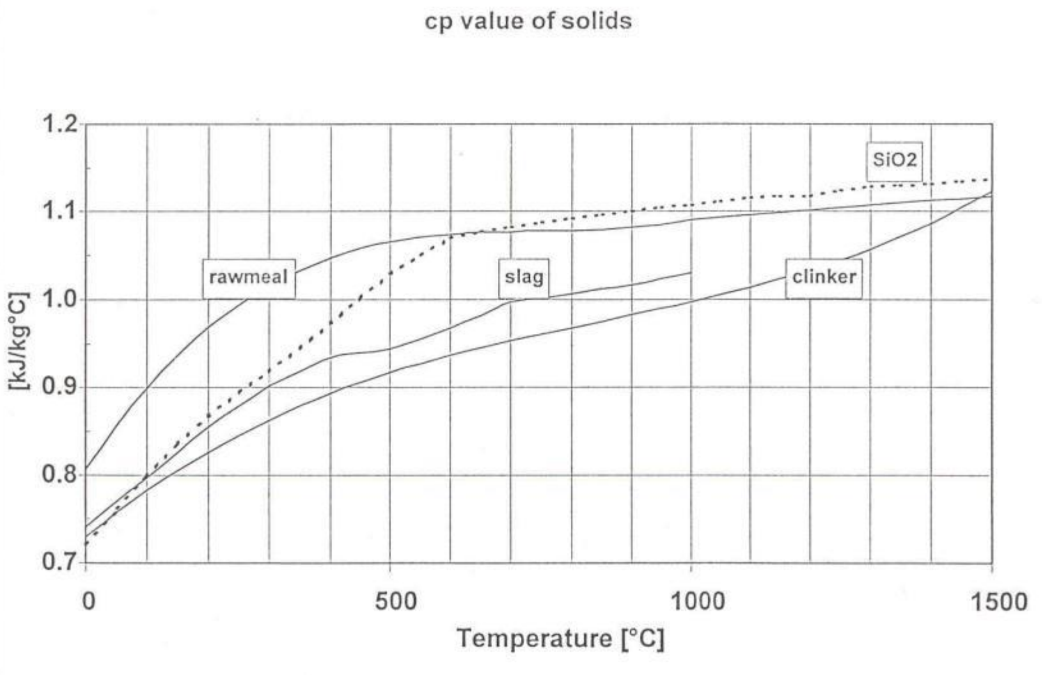
Balance related to : 1 [kg] of cement
Reference temperature 20 [°C]

# Grinding – Heat Balance

## cp values

cp-values




Cooling and Heating

# Grinding – Fineness Corrections

## Fineness Conversions and Corrections for Mills

### Fineness – Conversion of SEEC Mill Drive and Blaine

$$kWh/t_2 = kWh/t_1 \cdot e^{\left(\frac{Blaine_2 - Blaine_1}{1000} \cdot k\right)}$$

k = 0.49 for ordinary Portland cement
k = 0.43 for slag
k = 0.4 for limestone
(Formula valid for 3000 – 5000 Blaine)

### Fineness – Conversion of SEEC Mill Drive and Residue

$$kWh/t_2 = kWh/t_1 \cdot \left(\frac{2 - \log_{10}(R_2)}{2 - \log_{10}(R_1)}\right)$$

$R_1$ and $R_2$ – residues [%] on 32 µm , 45 µm or 90 µm
(Formula valid for 2 – 25 % residue)

### Fineness corrections for additives

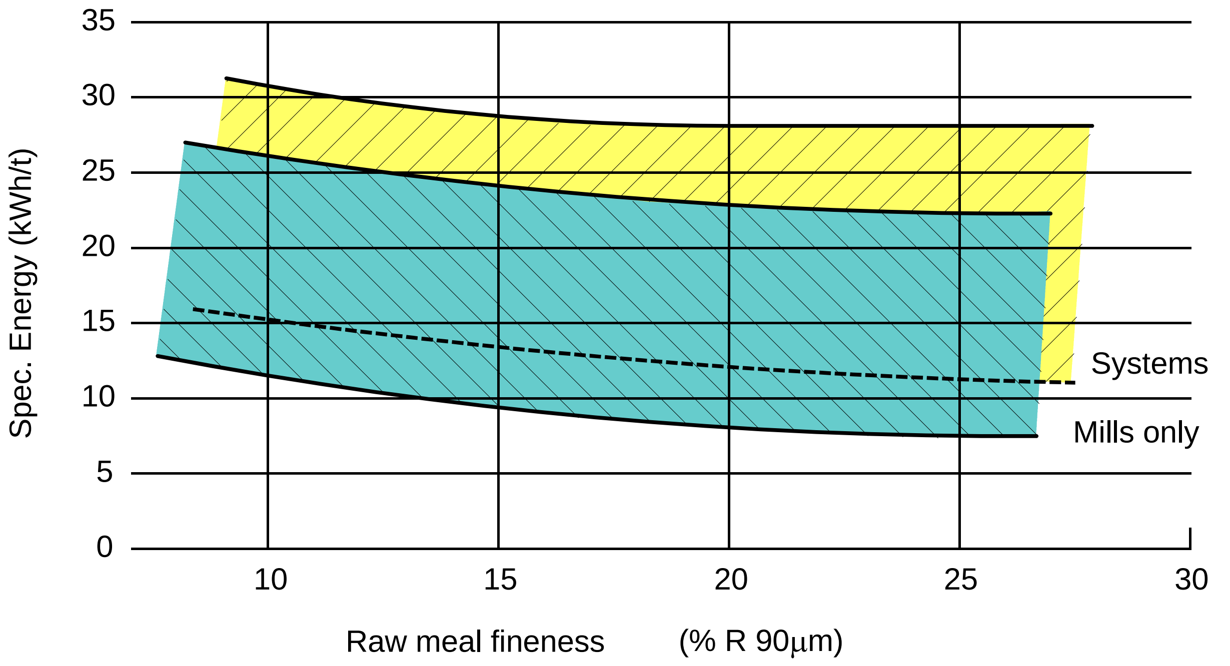
| Additive | Additional Fineness |
|---|---|
| • 1 % Limestone | 50 [cm$^2$/g] Blaine |
| • 1 % Gypsum | 125 [cm$^2$/g] Blaine [1)] |
| • 1 % Fly Ash | 50 [cm$^2$/g] Blaine |
| • 1 % Pozzolana | 50 [cm$^2$/g] Blaine |

[1)] Only applicable, if gypsum content is > 5 %, then the fineness difference [cm$^2$/g] is 125 [cm$^2$/g] x (% gypsum – 5 %)

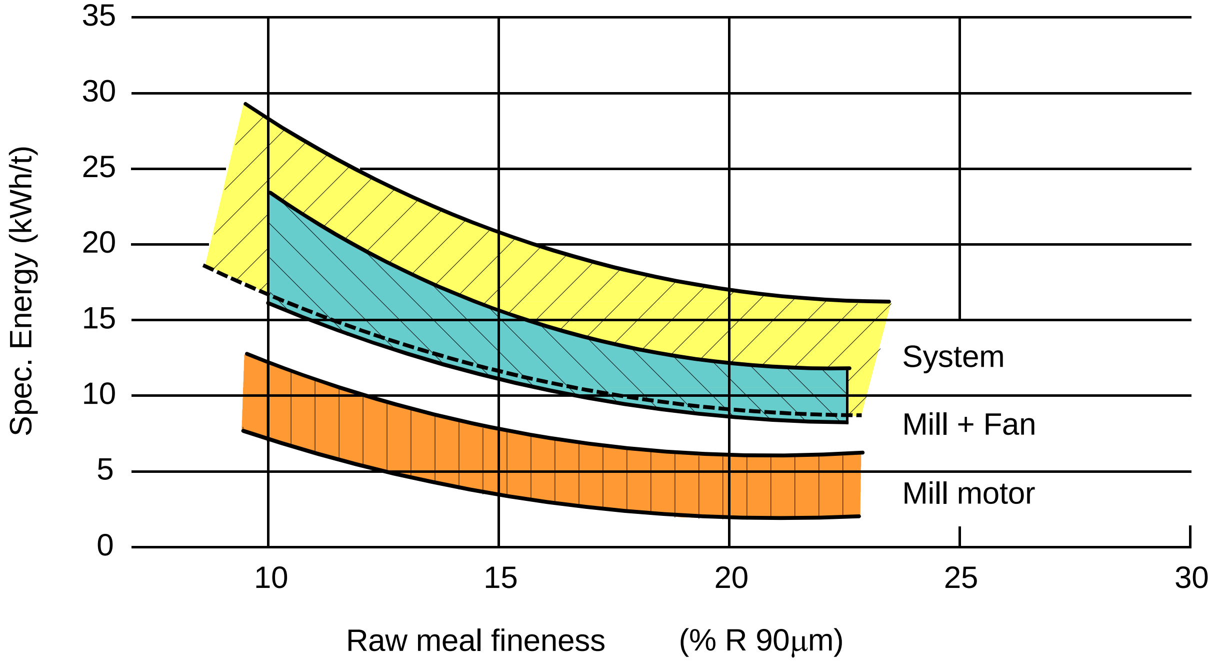
OPC Blaine equivalent [cm$^2$/g] = actual Blaine [cm$^2$/g]
- % limestone x 50 [cm$^2$/g]
- (% gypsum – 5 %) x 125 [cm$^2$/g]
- % fly ash x 50 [cm$^2$/g]
- % pozzolana x 50 [cm$^2$/g]

# Grinding – SEEC Raw Grinding Systems

## Specific electrical energy consumption Ball Mills

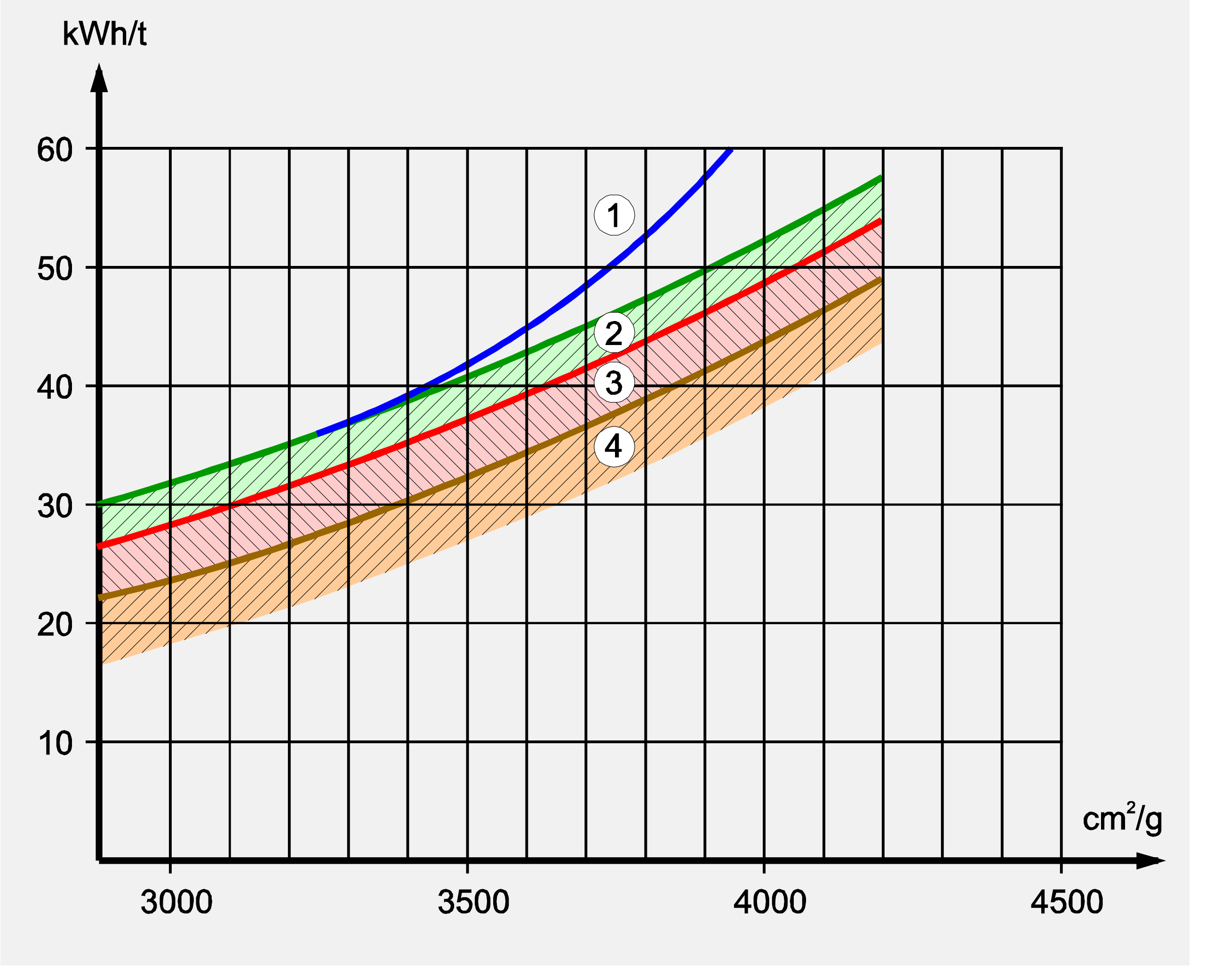



## Specific electrical energy consumption Vertical Roller Mills



# Grinding – SEEC Cement Grinding Systems

## Specific electrical energy consumption (SEEC)



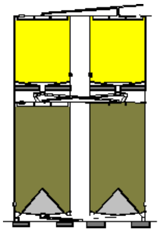

1 Tube mill open circuit
2 Tube mill closed circuit
3 Tube mill with pregrinding unit
4 Finish grinding system **VRM, RP, HRM**

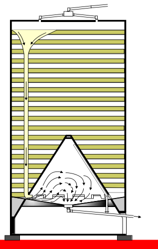
# Raw Meal Handling – Homogenizing

## Homogenizing silos

**Homogenizing silo**

**Storage silo**





| Design & operation guidelines | Batch homogenizing silo | Continuous blending silo / Storage silo |
|---|---|---|
| Capacity (in relation to mill operation) | 10-12 h | 1-3 d |
| Height/diameter ratio | 1.2-1.5 : 1 | Up to 4:1 |
| Net aeration area (% of floor area) | 50-65 | 35-50 |
| Active net aeration air rate | 1.5-3 $m^3/(m^2*min)$ | 1-2 $m^3/(m^2*min)$ |
| Active aeration air pressure | 1.5-2.5 bar | 0.6 bar |
| Passive net aeration air rate | 0.5-1.5 $m^3/(m^2*min)$ | - |
| Passive aeration air pressure | 0.6-0.8 bar | - |
| Aeration sequence | 8x10 min (shorter to avoid segregation) | 5-15 min (do not aerate sectors sequentially; jump) |
| Blending factor | Up to 10:1 | Up to 5:1 |

→ For further information see silo operation guide (available on Holcim portal / iShare)

## Segregation Factor Sf

The higher the segregation, the more attention is to be given to kiln dust handling and materials handling (→ segregation inside silos).

Analysis of total sample: main elements → LSF
Analysis of < 32 µm fraction : main elements → LSF

for greenfield plants

$$Sf = LSF_{<32\mu m} / LSF_{tot}$$

for existing plants

$$Sf = LSF_{kiln\ dust} / LSF_{kiln\ feed}$$

range of not critical raw meals: <u>0.8 < Sf < 1.2</u> (LSF or SR using the same rules)

Based on the Sf the kiln dust handling concept is chosen → see section “Kiln Dust Management”

# Raw Meal Handling – Homogenizing

## Uniformity targets

The targets used for MPR's are taken as given without any error correction:

| | | **Short term** hourly samples over 24 h | **Long term** daily values over one month |
|---|---|---|---|
| **Kiln feed** (or clinker) | s LSF | < 1.2 | < 1.0 |
| | s SM<br>s AR | < 0.04 | < 0.03 |
| **Raw meal** | s LSF | < 3.6 | < 1.0 |

s = Standard deviation

| Characteristic | Stdv. s |
|---|---|
| CaCO3 | < 0.2 |
| CaO | < 0.11 |
| **LSF** | **< 1.0** |
| SiO2 | < 0.1 |
| Al2O3 | < 0.07 |
| Fe2O3 | < 0.04 |

Table can be used to correlate the LSF target to other characteristics:

$s_{LSF} = 1\% \rightarrow s_{CaCO3} \sim 0.2\% \rightarrow s_{CaO} \sim 0.11\%$

| Location | Procedure | Type of homogenized fluctuations | Blending factor |
|---|---|---|---|
| Selective quarrying | Blending | Long-term to middle-term fluctuations | 5:1 |
| Preblending | Blending | Middle-term to long-term fluctuations | 5:1 |
| Proportioning | Blending | Long-term to middle-term fluctuations | 2:1 |
| Grinding | Mixing | Short-term fluctuations | 2:1 |
| Homogenizing | Mixing / Blending | Short-term to middle-term fluctuations | |
| | | 1) Blending silos | 5:1 |
| | | 2) Homosilos | 10:1 |

Short-term fluctuations: min - hours
Middle-term fluctuations: 1 - 5 days
Long-term fluctuations: 5 - 7 days

# Raw Meal Handling – Homogenizing

## Testing procedure

Sampling frequency adapted to achieve the 30 samples
- Only spot samples
- Period for batch homogenizing silo: should contain 3 batches (e.g. 3 time 8h = 24 h again every 30 min. one sample). Discharge of homogenizing silo even up to every 5 min.
- Period for continuous homogenizing silo: 24 h (e.g. every 30 min. one sample = 48 samples).
- Discharge of silo (kiln feed) normally every 30 minutes

## Minimum sample size

The minimum sample size depends on the granulation and uniformity.
The formula given is a simplification used within Holcim.

$$m = 0.1 * x^{1.5}$$

m = sample quantity [kg]
x = max grain size $x_{90}$ [mm]

| Location | X90 [mm] | m [kg] |
|---|---|---|
| after mill / raw meal | 0.1 | (0.1) |
| before ball mill | 30 | 16 |
| before roller mill | 80 | 70 |

Example for sample size depending on material
In general the sample size for raw meal is about 100 g and differs to the calculation because of the sampling error.

## Number of samples / sample frequency

The minimum number of samples can be calculated depending the required accuracy:

$$n \approx 1 + 0.5 * \left(\frac{Z_\alpha}{\varepsilon}\right)^2$$

n number of samples
$Z\alpha$ probability factor
$\varepsilon$ accuracy (of the stdv)

Example:
For a trust interval of 95% the probability factor $Z_\alpha$ = 2. Therefore the minimum number of samples n is 30 to allow an accuracy of the standard deviation of < 25% .
The preferred number of even 50 samples is asked for performances test with suppliers mainly.

$$1 + 0.5 * \left(\frac{2}{0.25}\right)^2 = 33$$

# Raw Meal Handling – Homogenizing

## Standard deviation

The standard deviation can be roughly estimated by dividing the differences of the min and max values by 6. (Formula for stdv. given in chapter MT)

$$s \approx \frac{(x_{max} - x_{min})}{6}$$

S – standard deviation

$x_{max}$ – max. value

$x_{min}$ – min. value

## Outlier test acc. GRUBB

The outlier test is used to determine samples witch are outside our expectations (confidence). For reasons like sampling and analysis errors

$$(\bar{x} - x_{min}) / s > G$$

$$(x_{max} - \bar{x}) / s > G$$

$\bar{x}$ – average

$x_{max}$ – max. value

$x_{min}$ – min. value

G - critical value acc. GRUBB's

### Critical Values for outlier test acc. GRUBB

| n | G significance level Alpha = 1% |
|---|---|
| 20 | 2,884 |
| 22 | 2,934 |
| 24 | 2,984 |
| 26 | 3,028 |
| 28 | 3,065 |
| 30 | 3,103 |
| 32 | 3,133 |
| 34 | 3,163 |
| 36 | 3,190 |
| 38 | 3,215 |
| 40 | 3,240 |

n = number of samples

# Raw Meal Handling – Homogenizing

## Error evaluation

The error determinations done by double sampling

$$s_{err} = \sqrt{\frac{\pi}{4}\left(\frac{1}{n}\sum |\,di\,|\right)^2}$$

$$s_{cor} = \sqrt{s_{meas}^2 - s_{err}^2}$$

| | |
|---|---|
| $s_{meas}$ | = stdv measured |
| $s_{err}$ | = stdv error |
| $s_{cor}$ | = stdv corrected |
| di | = $(x_{1a}$-$x_{1b})$ differences between the double samples |
| n | = number of double samples |

## Blending factor Bf

The blending factor Bf is the ratio of standard deviation before $s_{in}$ and after $s_{out}$ the homogenizing process

$$Bf = s_{in}/s_{out}$$

Blending factor including error corrections

$$Bf = \frac{s_{in,corr}}{s_{out,corr}} = \frac{\sqrt{s^2{}_{in,measured} - s^2{}_{in,error}}}{\sqrt{s_{out,measured} - s^2{}_{out,error}}}$$

$s_{in}$ = standard deviation of the not homogenized raw material
$s_{out}$ = standard deviation of the homogenized raw material

| LSF stdv | s meas | s err | s cor |
|---|---|---|---|
| Raw meal | 5.5 | 1 | 5.4 |
| Kiln feed | 1.3 | 0.4 | 1.27 |

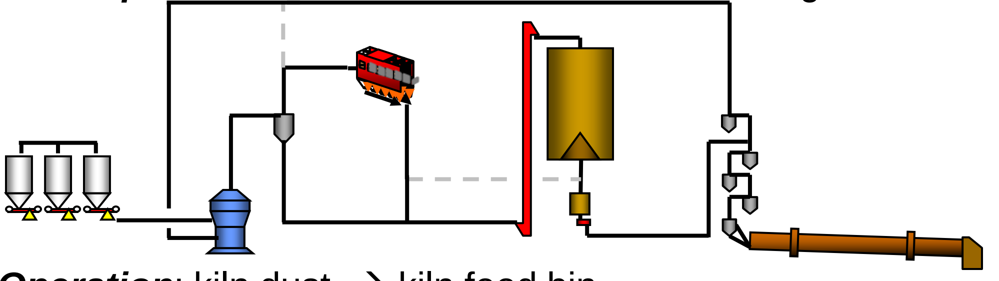
Shown is the not significant influence of the error due to sampling and analyzing based on LSF (San Miguel plant - continuous blending silo)

# Raw Meal Handling – Kiln Dust Management

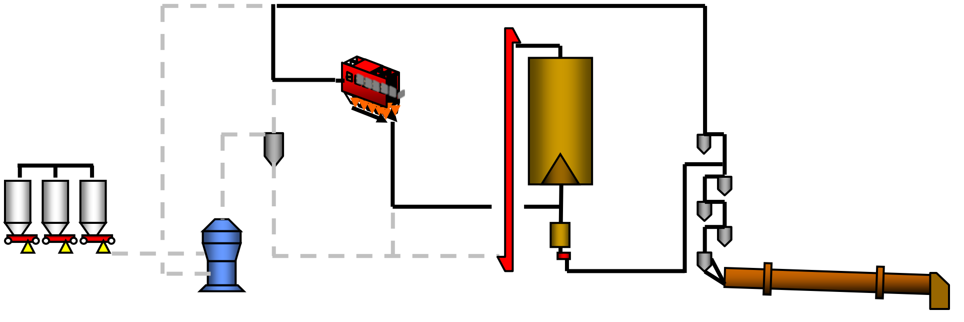
## Option 1 – $S_f$ not critical

***standard arrangement***

***Compound Operation***: Raw mix + kiln dust → blending silo



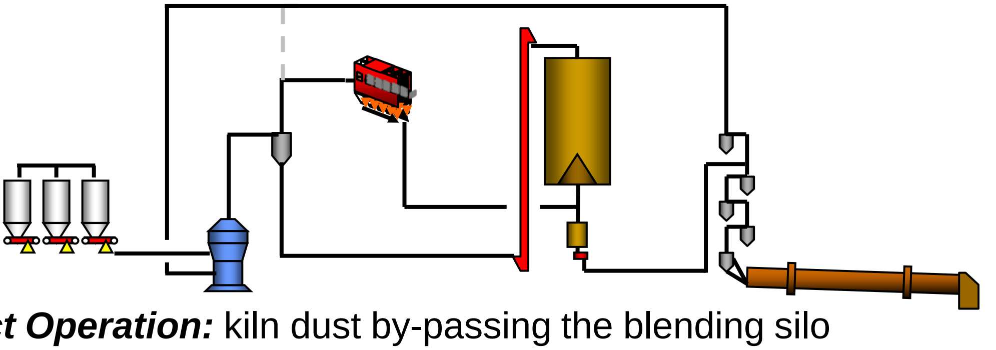
***Direct Operation***: kiln dust → kiln feed bin



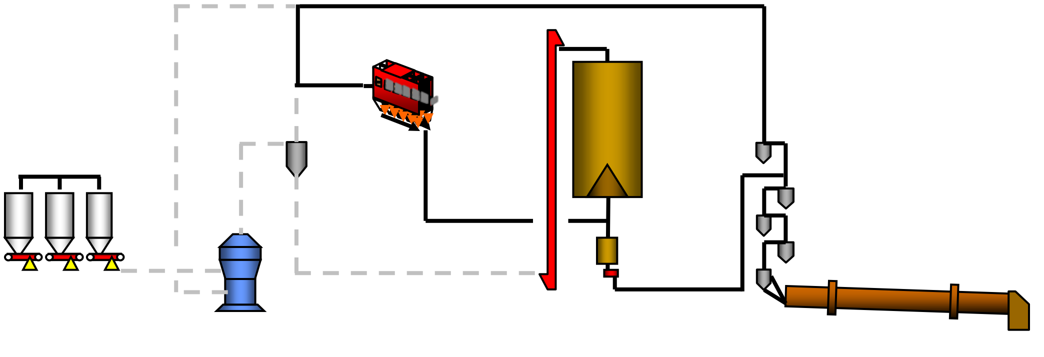
## Option 2 – $S_f$ not critical

***3 fan system / Filter dust must be similar***

***Compound Operation:*** kiln dust by-passing the blending silo



***Direct Operation:*** kiln dust by-passing the blending silo

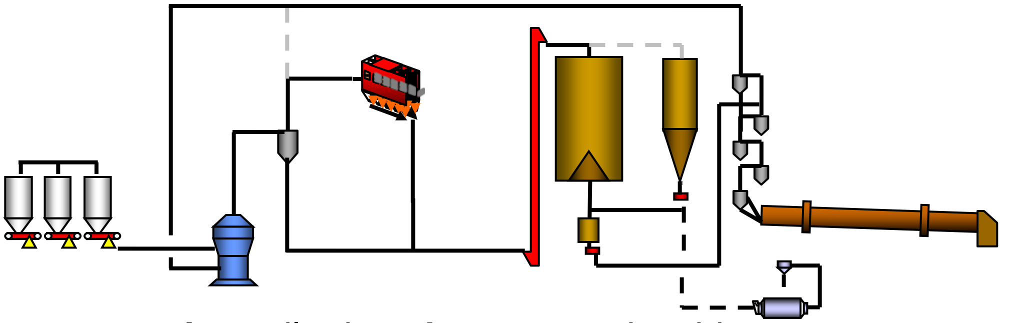


# Raw Meal Handling – Kiln Dust Management

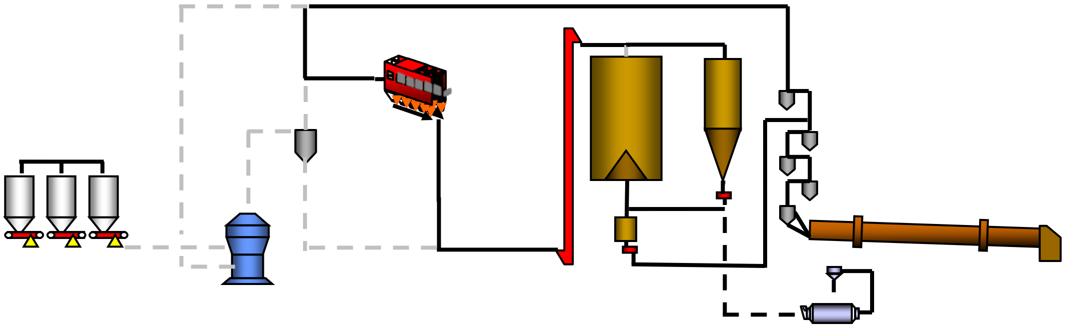
## Option 3 – $S_f$ critical

***Cl bypass optional***

***Compound Operation:*** Raw mix + kiln dust → blending silo



***Direct Operation:*** Kiln dust → separate dust bin



# Transport – Belt Conveyor

## Design Guidelines

For more information please see the TDS manual available on iShare:
**iShare → Communities → Transport, Dedusting & Shipping**

### Belt speed

In general the maximum belt speed shall not exceed 2.0 m/s.
Conveyors handling dry fine material (i.e. raw meal, cement) shall not exceed 1.25 m/s.
Belt speed for conveyors less than 50 meters in length shall not exceed 1.5 m/s.
Conveyors longer than 500 m (overland) can operate faster than 2.0 m/s.

### Belt width

Belt width shall not be less than 800 mm, for special applications 650 mm belts may be used.
Packing plants 500 mm flat belts may be applicable.
The minimum belt width for reversible conveyors shall not be less than 800 mm.

### Conveyor slopes, vertical radius

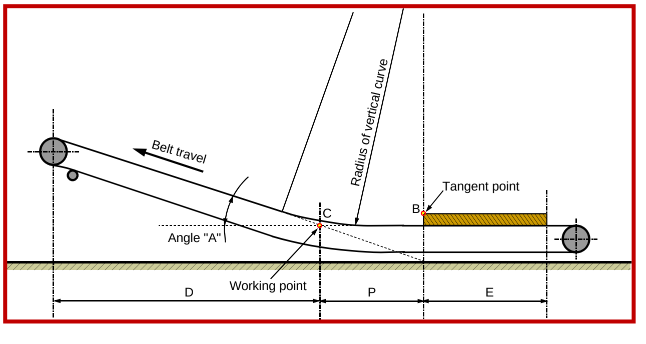
Slope:

| Maximum Slope | Raw Material | Clinker | Cement |
|---|---|---|---|
| General | $16^{O}$ | $10^{O}$ | $6^{O}$ 1) |
| At loading point | $6^{O}$ 2) | $0^{O}$ | $0^{O}$ |

1) Consideration should be given to maximize the horizontal section after the last feed point thus allowing the cement to properly de-aerate and prevent back-flushing on inclined section. Change from horizontal only after a distance equivalent to 60 seconds belt travel from the feed point is desirable. Steeper slopes can be accepted depending on the usage of grinding aids and/or material bed thickness on the belt etc.

2) Steeper slopes may be acceptable depending upon the application.

Vertical (concave) curves to be designed to avoid lifting of the belt from the idlers under any conditions (minimum radius 300 m).



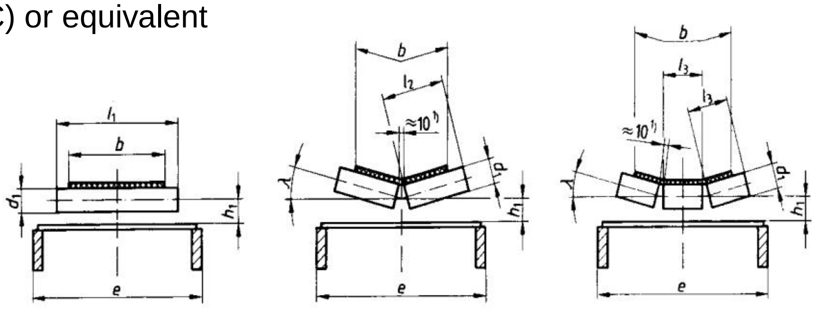

Example vertical curve

# Transport – Belt Conveyor

## Idler design

Trough angle shall not be less than 30°

Carrier and return idler diameter shall be designed according to DIN (15207-1 / 22107) or CEMA (Class C) or equivalent




| Belt width $b$ | Idler diameter $d_1$ | $h_1$ | $l_1$ | Idler length $l_2$ | $l_3$ |
|---|---|---|---|---|---|
| 400 | 63,5 | 62 | 500 | 250 | 160 |
| | 89 | 75 | | | |
| | 108 | 85 | | | |
| 500 | 63,5 | 62 | 600 | 315 | 200 |
| | 89 | 75 | | | |
| | 108 | 85 | | | |
| | 133 | 100 | | | |
| 650 | 63,5 | 62 | 750 | 380 | 250 |
| | 89 | 75 | | | |
| | 108 | 85 | | | |
| | 133 | 100 | | | |
| 800 | 89 | 75 | 950 | 465 | 315 |
| | 108 | 85 | | | |
| | 133 | 100 | | | |
| 1000 | 89 | 75 | 1150 | 600 | 380 |
| | 108 | 85 | | | |
| | 133 | 100 | | | |
| | 159 | 130 | | | |
| 1200 | 108 | 85 | 1400 | 700 | 465 |
| | 133 | 100 | | | |
| | 159 | 130 | | | |
| 1400 | 133 | 100 | 1600 | 800 | 530 |
| | 159 | 130 | | | |
| 1600 | 133 | 100 | 1800 | 900 | 600 |
| | 159 | 130 | | | |
| 1800 | 133 | 100 | 2000 | 1000 | 670 |
| | 159 | 130 | | | |
| 2000 | 133 | 100 | 2200 | 1100 | 750 |
| | 159 | 130 | | | |
| | 194 | 160 | | | |
| 2200 | 159 | 130 | 2500 | 1250 | 800 |
| | 194 | 160 | | | |
| 2400 | 159 | 130 | 2800 | 1400 | 900 |
| | 194 | 160 | | | |
| 2600 | 159 | 130 | 3000 | 1500 | 950 |
| | 194 | 160 | | | |
| 2800 | 159 | 130 | 3150 | 1600 | 1050 |
| | 194 | 160 | | | |
| | 219 | 180 | | | |
| 3000 | 159 | 130 | 3350 | 1700 | 1120 |
| | 194 | 160 | | | |
| | 219 | 180 | | | |

# Transport – Belt Conveyor

## Pulley design

### The Minimum Recommended Pulley Diameters

The Table shows the recommended minimum pulley diameters to limit the stress in the conveyor belting as the belt passes around the pulleys

Fabric Conveyor Belts

| Belt Class | Driving and Head [mm] | Tail/take-up /H.T. Bends [mm] | Low Tension Snubs & Bends [mm] |
|---|---|---|---|
| EP 160 | 200 | 140 | 140 |
| EP 200 | 350 | 250 | 250 |
| EP 250 | 400 | 250 | 250 |
| EP 315 | 400 | 250 | 250 |
| EP 400 | 450 | 300 | 300 |
| EP 500 | 500 | 350 | 330 |
| EP 630 | 540 | 400 | 350 |
| EP 800 | 650 | 450 | 410 |
| EP 1000 | 800 | 570 | 510 |
| EP 1250 | 1000 | 700 | 640 |
| EP 1600 | 1250 | 1000 | 1000 |
| EP 2000 | 1400 | 1000 | 1000 |

Steel Cord Belting

| Belt Rating | High Tension Pulleys, Drive, Discharge, etc [mm] | Low Tension Pulleys, Tail, Take-up, etc [mm] | Snubs [mm] |
|---|---|---|---|
| ST 500 | 600 | 500 | 400 |
| ST 630 | 700 | 550 | 450 |
| ST 800 | 700 | 550 | 450 |
| ST 1000 | 700 | 550 | 450 |
| ST 1250 | 750 | 600 | 500 |
| ST 1600 | 1050 | 900 | 750 |
| ST 2000 | 1050 | 900 | 750 |
| ST 2500 | 1050 | 900 | 750 |
| ST 3150 | 1200 | 900 | 750 |
| ST 4000 | 1350 | 1050 | 900 |
| ST 5000 | 1500 | 1200 | 1050 |

### Pulley lagging

All drive pulleys shall have rubber lagging.
Tail and take-up pulleys: rubber lined or spiral wrapped wing pulleys. Wing type pulleys without spiral are not acceptable

# Transport – Belt Conveyor

## Troughing Transition Distance A for Fabric Belt (Nylon, Polyester, Vinyilon)

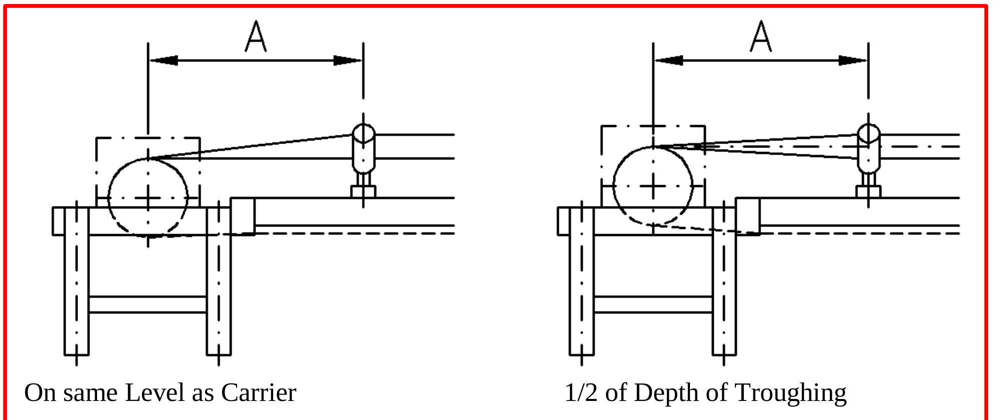
Unit: m

| Position of Pulley Face | | On same level as carrier | | | | 1/2 of depth of troughing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Troughing Angle | | 20° | 30° | 35° | 45° | 20° | 30° | 35° | 45° |
| Belt Width | 600 | 0.55 | 0.80 | 0.95 | 1.20 | 0.30 | 0.40 | 0.50 | 0.60 |
| | 650 | 0.60 | 0.90 | 1.05 | 1.30 | 0.30 | 0.45 | 0.55 | 0.65 |
| | 750 | 0.70 | 1.00 | 1.20 | 1.50 | 0.35 | 0.50 | 0.60 | 0.75 |
| | 800 | 0.75 | 1.10 | 1.25 | 1.60 | 0.40 | 0.55 | 0.65 | 0.80 |
| | 900 | 0.85 | 1.20 | 1.45 | 1.80 | 0.40 | 0.60 | 0.70 | 0.90 |
| | 1000 | 0.95 | 1.35 | 1.60 | 2.00 | 0.45 | 0.70 | 0.80 | 1.00 |
| | 1050 | 0.95 | 1.40 | 1.65 | 2.10 | 0.50 | 0.70 | 0.85 | 1.05 |
| | 1200 | 1.10 | 1.60 | 1.90 | 2.40 | 0.55 | 0.80 | 0.95 | 1.20 |
| | 1400 | 1.30 | 1.90 | 2.20 | 2.80 | 0.65 | 0.95 | 1.10 | 1.40 |
| | 1600 | 1.45 | 2.15 | 2.55 | 3.20 | 0.75 | 1.10 | 1.25 | 1.60 |

## Troughing Transition Distance A for Steel Cord Belt

Unit: m

| Position of Pulley Face | | On same level as carrier | | | | 1/2 of depth of troughing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Troughing Angle | | 20° | 30° | 35° | 45° | 20° | 30° | 35° | 45° |
| Belt Width | 600 | 1.10 | 1.65 | 1.90 | 2.40 | 0.55 | 0.80 | 0.95 | 1.20 |
| | 650 | 1.20 | 1.75 | 2.05 | 2.60 | 0.60 | 0.90 | 1.05 | 1.30 |
| | 750 | 1.40 | 2.05 | 2.40 | 3.00 | 0.70 | 1.00 | 1.20 | 1.50 |
| | 800 | 1.50 | 2.15 | 2.55 | 3.20 | 0.75 | 1.10 | 1.25 | 1.60 |
| | 900 | 1.65 | 2.45 | 2.85 | 3.65 | 0.85 | 1.20 | 1.45 | 1.80 |
| | 1000 | 1.85 | 2.70 | 3.15 | 4.05 | 0.95 | 1.35 | 1.60 | 2.00 |
| | 1050 | 1.95 | 2.85 | 3.35 | 4.25 | 1.00 | 1.45 | 1.65 | 2.10 |
| | 1200 | 2.20 | 3.25 | 3.80 | 4.85 | 1.10 | 1.65 | 1.90 | 2.40 |
| | 1400 | 2.55 | 3.80 | 4.45 | 5.65 | 1.30 | 1.90 | 2.20 | 2.80 |
| | 1600 | 2.95 | 4.30 | 5.05 | 6.45 | 1.45 | 2.15 | 2.55 | 3.20 |




Troughing Transition Distance

# Transport – Belt Conveyor

## Nominal volumetric belt capacity [m$^3$/h]

α: Surcharge angle β: Belt troughing angle

| Belt Width | Angle of Surcharge | β = 20 [deg] v [m/s] | | | | | | β = 25 [deg] v [m/s] | | | | | | β = 30 [deg] v [m/s] | | | | | | β = 35 [deg] v [m/s] | | | | | | β = 45 [deg] v [m/s] | | | | | | Angle of Surcharge |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| b [mm] | α[deg] | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 | α[deg] |
| | 0 | 20 | 40 | 59 | 79 | 99 | 119 | 24 | 48 | 72 | 96 | 120 | 144 | 28 | 56 | 84 | 112 | 140 | 168 | 31 | 63 | 94 | 126 | 157 | 189 | 37 | 74 | 110 | 147 | 184 | 221 | 0 |
| | 5 | 24 | 47 | 71 | 95 | 118 | 142 | 28 | 56 | 83 | 111 | 139 | 167 | 32 | 63 | 95 | 126 | 158 | 189 | 35 | 70 | 104 | 139 | 174 | 209 | 40 | 79 | 119 | 159 | 198 | 238 | 5 |
| | 10 | 28 | 55 | 83 | 110 | 138 | 165 | 32 | 63 | 95 | 126 | 158 | 189 | 35 | 70 | 105 | 140 | 175 | 211 | 38 | 76 | 114 | 153 | 191 | 229 | 43 | 85 | 128 | 170 | 213 | 256 | 10 |
| **500** | 15 | 32 | 63 | 95 | 126 | 158 | 189 | 35 | 71 | 106 | 141 | 177 | 212 | 39 | 77 | 116 | 155 | 194 | 232 | 42 | 83 | 125 | 166 | 208 | 249 | 46 | 91 | 137 | 182 | 228 | 273 | 15 |
| | 20 | 36 | 71 | 107 | 142 | 178 | 213 | 39 | 78 | 118 | 157 | 196 | 235 | 42 | 85 | 127 | 170 | 212 | 254 | 45 | 90 | 135 | 180 | 225 | 270 | 48 | 97 | 145 | 194 | 242 | 291 | 20 |
| | 25 | 40 | 79 | 119 | 159 | 198 | 238 | 43 | 86 | 130 | 173 | 216 | 259 | 46 | 92 | 138 | 185 | 231 | 277 | 49 | 97 | 146 | 194 | 243 | 291 | 52 | 103 | 155 | 206 | 258 | 309 | 25 |
| | 30 | 44 | 88 | 132 | 176 | 220 | 264 | 47 | 95 | 142 | 189 | 236 | 284 | 50 | 100 | 150 | 200 | 250 | 300 | 52 | 104 | 157 | 209 | 261 | 313 | 55 | 109 | 164 | 219 | 273 | 328 | 30 |
| | 0 | 36 | 71 | 107 | 143 | 179 | 214 | 43 | 87 | 130 | 174 | 217 | 261 | 51 | 101 | 152 | 202 | 253 | 303 | 57 | 114 | 170 | 227 | 284 | 341 | 66 | 133 | 199 | 266 | 332 | 398 | 0 |
| | 5 | 43 | 85 | 128 | 171 | 213 | 256 | 50 | 100 | 150 | 201 | 251 | 301 | 57 | 114 | 171 | 227 | 284 | 341 | 63 | 125 | 188 | 251 | 314 | 376 | 71 | 143 | 214 | 286 | 357 | 429 | 5 |
| | 10 | 50 | 99 | 149 | 199 | 248 | 298 | 57 | 114 | 171 | 227 | 284 | 341 | 63 | 126 | 190 | 253 | 316 | 379 | 69 | 137 | 206 | 275 | 343 | 412 | 77 | 153 | 230 | 306 | 383 | 460 | 10 |
| **650** | 15 | 57 | 113 | 170 | 227 | 284 | 340 | 64 | 127 | 191 | 255 | 318 | 382 | 70 | 139 | 209 | 279 | 348 | 418 | 75 | 150 | 224 | 299 | 374 | 449 | 82 | 164 | 245 | 327 | 409 | 491 | 15 |
| | 20 | 64 | 128 | 192 | 256 | 320 | 383 | 71 | 141 | 212 | 282 | 353 | 423 | 76 | 152 | 229 | 305 | 381 | 457 | 81 | 162 | 243 | 324 | 405 | 486 | 87 | 174 | 261 | 348 | 435 | 522 | 20 |
| | 25 | 71 | 143 | 214 | 285 | 356 | 428 | 78 | 155 | 233 | 310 | 388 | 466 | 83 | 166 | 249 | 332 | 415 | 498 | 87 | 174 | 262 | 349 | 436 | 523 | 92 | 185 | 277 | 370 | 462 | 555 | 25 |
| | 30 | 79 | 158 | 237 | 316 | 395 | 473 | 85 | 170 | 255 | 340 | 425 | 510 | 90 | 180 | 270 | 360 | 449 | 539 | 94 | 188 | 281 | 375 | 469 | 563 | 98 | 196 | 294 | 392 | 490 | 588 | 30 |
| | 0 | 56 | 113 | 169 | 225 | 282 | 338 | 69 | 137 | 206 | 275 | 343 | 412 | 80 | 159 | 239 | 319 | 399 | 478 | 90 | 179 | 269 | 358 | 448 | 537 | 105 | 209 | 314 | 418 | 523 | 627 | 0 |
| | 5 | 67 | 134 | 202 | 269 | 336 | 403 | 79 | 158 | 237 | 316 | 395 | 474 | 90 | 179 | 269 | 359 | 448 | 538 | 99 | 198 | 296 | 395 | 494 | 593 | 113 | 225 | 338 | 450 | 563 | 675 | 5 |
| | 10 | 78 | 156 | 235 | 313 | 391 | 469 | 90 | 179 | 269 | 358 | 448 | 537 | 100 | 199 | 299 | 398 | 498 | 598 | 108 | 216 | 324 | 433 | 541 | 649 | 121 | 241 | 362 | 482 | 603 | 723 | 10 |
| **800** | 15 | 89 | 179 | 268 | 357 | 446 | 536 | 100 | 200 | 301 | 401 | 501 | 601 | 110 | 219 | 329 | 439 | 548 | 658 | 118 | 235 | 353 | 471 | 588 | 706 | 129 | 257 | 386 | 514 | 643 | 772 | 15 |
| | 20 | 101 | 201 | 302 | 402 | 503 | 603 | 111 | 222 | 333 | 444 | 555 | 666 | 120 | 240 | 360 | 480 | 600 | 720 | 127 | 255 | 382 | 509 | 636 | 764 | 137 | 274 | 411 | 547 | 684 | 821 | 20 |
| | 25 | 112 | 224 | 336 | 448 | 561 | 673 | 122 | 244 | 366 | 488 | 610 | 732 | 130 | 261 | 391 | 522 | 652 | 783 | 137 | 274 | 411 | 549 | 686 | 823 | 145 | 291 | 436 | 581 | 726 | 872 | 25 |
| | 30 | 124 | 248 | 372 | 496 | 620 | 744 | 134 | 267 | 401 | 534 | 668 | 801 | 141 | 283 | 424 | 565 | 707 | 848 | 147 | 295 | 442 | 589 | 737 | 884 | 154 | 308 | 462 | 616 | 770 | 924 | 30 |
| | 0 | 91 | 182 | 274 | 365 | 456 | 547 | 111 | 222 | 333 | 444 | 555 | 666 | 129 | 258 | 387 | 516 | 645 | 774 | 145 | 289 | 434 | 579 | 723 | 868 | 169 | 338 | 507 | 676 | 844 | 1013 | 0 |
| | 5 | 109 | 217 | 236 | 435 | 543 | 652 | 128 | 256 | 383 | 511 | 639 | 767 | 145 | 290 | 434 | 579 | 724 | 869 | 160 | 319 | 479 | 638 | 798 | 958 | 182 | 363 | 545 | 726 | 908 | 1090 | 5 |
| | 10 | 126 | 253 | 379 | 505 | 631 | 758 | 145 | 289 | 434 | 579 | 723 | 868 | 161 | 322 | 482 | 643 | 804 | 965 | 175 | 349 | 524 | 699 | 873 | 1048 | 194 | 389 | 583 | 778 | 972 | 1167 | 10 |
| **1000** | 15 | 144 | 288 | 432 | 576 | 721 | 865 | 162 | 323 | 485 | 647 | 809 | 970 | 177 | 354 | 531 | 708 | 885 | 1062 | 190 | 380 | 570 | 759 | 949 | 1139 | 207 | 415 | 622 | 830 | 1037 | 1244 | 15 |
| | 20 | 162 | 324 | 487 | 649 | 811 | 973 | 179 | 358 | 537 | 716 | 895 | 1075 | 194 | 387 | 581 | 774 | 968 | 1161 | 205 | 411 | 616 | 821 | 1027 | 1232 | 221 | 441 | 662 | 882 | 1103 | 1324 | 20 |
| | 25 | 181 | 362 | 543 | 723 | 904 | 1085 | 197 | 394 | 591 | 788 | 985 | 1181 | 210 | 421 | 631 | 842 | 1052 | 1263 | 221 | 442 | 664 | 885 | 1106 | 1327 | 234 | 468 | 702 | 937 | 1171 | 1405 | 25 |
| | 30 | 200 | 400 | 600 | 800 | 1000 | 1200 | 215 | 431 | 646 | 861 | 1076 | 1292 | 228 | 456 | 684 | 911 | 1139 | 1367 | 238 | 475 | 713 | 950 | 1188 | 1425 | 248 | 496 | 744 | 992 | 1241 | 1489 | 30 |
| | 0 | 134 | 269 | 403 | 537 | 672 | 806 | 164 | 327 | 491 | 654 | 818 | 981 | 190 | 380 | 570 | 759 | 949 | 1139 | 213 | 426 | 639 | 852 | 1065 | 1278 | 249 | 497 | 746 | 994 | 1243 | 1491 | 0 |
| | 5 | 160 | 320 | 480 | 640 | 800 | 960 | 188 | 376 | 564 | 752 | 940 | 1129 | 213 | 426 | 640 | 853 | 1066 | 1279 | 235 | 470 | 705 | 940 | 1175 | 1409 | 267 | 534 | 802 | 1069 | 1336 | 1603 | 5 |
| | 10 | 186 | 372 | 558 | 743 | 929 | 1115 | 213 | 426 | 639 | 851 | 1064 | 1277 | 237 | 473 | 710 | 947 | 1183 | 1420 | 257 | 514 | 771 | 1028 | 1285 | 1542 | 286 | 572 | 858 | 1144 | 1430 | 1716 | 10 |
| **1200** | 15 | 212 | 424 | 636 | 848 | 1060 | 1272 | 238 | 476 | 714 | 952 | 1189 | 1427 | 260 | 521 | 781 | 1042 | 1302 | 1562 | 279 | 558 | 838 | 1117 | 1396 | 1675 | 305 | 610 | 915 | 1220 | 1525 | 1830 | 15 |
| | 20 | 239 | 477 | 716 | 955 | 1193 | 1432 | 263 | 527 | 790 | 1054 | 1317 | 1580 | 285 | 569 | 854 | 1138 | 1423 | 1708 | 302 | 604 | 906 | 1208 | 1510 | 1812 | 324 | 649 | 973 | 1297 | 1621 | 1946 | 20 |
| | 25 | 266 | 532 | 798 | 1064 | 1330 | 1596 | 290 | 579 | 869 | 1158 | 1448 | 1737 | 309 | 619 | 928 | 1238 | 1547 | 1856 | 325 | 650 | 976 | 1301 | 1626 | 1951 | 344 | 688 | 1032 | 1376 | 1720 | 2065 | 25 |
| | 30 | 294 | 588 | 882 | 1176 | 1470 | 1764 | 317 | 633 | 950 | 1266 | 1583 | 1899 | 335 | 670 | 1005 | 1340 | 1675 | 2010 | 349 | 698 | 1048 | 1397 | 1746 | 2095 | 365 | 729 | 1094 | 1458 | 1823 | 2187 | 30 |
| | 0 | 186 | 372 | 557 | 743 | 929 | 1115 | 226 | 452 | 678 | 905 | 1131 | 1357 | 263 | 525 | 788 | 1050 | 1313 | 1575 | 295 | 589 | 884 | 1178 | 1473 | 1767 | 343 | 687 | 1030 | 1374 | 1717 | 2061 | 0 |
| | 5 | 221 | 442 | 664 | 885 | 1106 | 1327 | 260 | 520 | 780 | 1040 | 1300 | 1560 | 295 | 589 | 884 | 1179 | 1474 | 1768 | 325 | 649 | 974 | 1299 | 1624 | 1948 | 369 | 738 | 1108 | 1477 | 1846 | 2215 | 5 |
| | 10 | 257 | 514 | 771 | 1028 | 1284 | 1541 | 294 | 588 | 883 | 1177 | 1471 | 1765 | 327 | 654 | 981 | 1308 | 1635 | 1962 | 355 | 710 | 1065 | 1420 | 1775 | 2130 | 395 | 790 | 1185 | 1580 | 1975 | 2370 | 10 |
| **1400** | 15 | 293 | 586 | 879 | 1172 | 1465 | 1758 | 329 | 657 | 986 | 1315 | 1644 | 1972 | 360 | 720 | 1080 | 1439 | 1799 | 2159 | 386 | 772 | 1157 | 1543 | 1929 | 2315 | 421 | 842 | 1264 | 1685 | 2106 | 2527 | 15 |
| | 20 | 330 | 659 | 989 | 1319 | 1648 | 1978 | 364 | 728 | 1092 | 1456 | 1820 | 2184 | 393 | 786 | 1180 | 1573 | 1966 | 2359 | 417 | 834 | 1251 | 1668 | 2086 | 2503 | 448 | 896 | 1343 | 1791 | 2239 | 2687 | 20 |
| | 25 | 367 | 735 | 1102 | 1469 | 1837 | 2204 | 400 | 800 | 1200 | 1600 | 2000 | 2400 | 427 | 855 | 1282 | 1710 | 2137 | 2564 | 449 | 898 | 1348 | 1797 | 2246 | 2695 | 475 | 950 | 1425 | 1901 | 2376 | 2851 | 25 |
| | 30 | 406 | 812 | 1219 | 1625 | 2031 | 2437 | 437 | 874 | 1312 | 1749 | 2186 | 2623 | 463 | 925 | 1388 | 1851 | 2313 | 2776 | 482 | 965 | 1447 | 1929 | 2411 | 2894 | 503 | 1007 | 1510 | 2013 | 2517 | 3020 | 30 |
| | 0 | 246 | 491 | 737 | 983 | 1228 | 1474 | 299 | 598 | 897 | 1196 | 1494 | 1793 | 347 | 694 | 1041 | 1388 | 1735 | 2082 | 389 | 778 | 1168 | 1557 | 1946 | 2335 | 454 | 908 | 1361 | 1815 | 2269 | 2723 | 0 |
| | 5 | 292 | 585 | 877 | 1169 | 1462 | 1754 | 344 | 687 | 1031 | 1375 | 1718 | 2062 | 389 | 779 | 1168 | 1558 | 1947 | 2337 | 429 | 858 | 1287 | 1716 | 2145 | 2574 | 488 | 975 | 1463 | 1951 | 2438 | 2926 | 5 |
| | 10 | 339 | 679 | 1018 | 1358 | 1697 | 2036 | 389 | 777 | 1166 | 1555 | 1943 | 2332 | 432 | 864 | 1296 | 1728 | 2160 | 2593 | 469 | 938 | 1407 | 1876 | 2345 | 2814 | 522 | 1043 | 1565 | 2087 | 2608 | 3130 | 10 |
| **1600** | 15 | 387 | 774 | 1161 | 1548 | 1935 | 2322 | 434 | 868 | 1303 | 1737 | 2171 | 2605 | 475 | 951 | 1426 | 1901 | 2377 | 2852 | 510 | 1019 | 1529 | 2038 | 2548 | 3057 | 556 | 1112 | 1668 | 2225 | 2781 | 3337 | 15 |
| | 20 | 435 | 871 | 1306 | 1742 | 2177 | 2613 | 481 | 961 | 1442 | 1923 | 2403 | 2884 | 519 | 1039 | 1558 | 2077 | 2597 | 3166 | 551 | 1102 | 1653 | 2203 | 2754 | 3305 | 591 | 1183 | 1774 | 2365 | 2956 | 3548 | 20 |
| | 25 | 485 | 970 | 1455 | 1940 | 2426 | 2911 | 528 | 1056 | 1585 | 2113 | 2641 | 3169 | 564 | 1129 | 1693 | 2258 | 2822 | 3386 | 593 | 1186 | 1779 | 2373 | 2966 | 3559 | 627 | 1255 | 1882 | 2509 | 3136 | 3764 | 25 |
| | 30 | 536 | 1073 | 1609 | 2145 | 2682 | 3218 | 577 | 1155 | 1732 | 2309 | 2887 | 3464 | 611 | 1222 | 1833 | 2444 | 3055 | 3666 | 637 | 1274 | 1910 | 2547 | 3184 | 3821 | 664 | 1329 | 1993 | 2658 | 3322 | 3986 | 30 |
| | 0 | 314 | 628 | 941 | 1255 | 1569 | 1883 | 382 | 764 | 1145 | 1527 | 1909 | 2291 | 443 | 886 | 1330 | 1773 | 2216 | 2659 | 497 | 994 | 1491 | 1988 | 2485 | 2982 | 579 | 1159 | 1738 | 2318 | 2897 | 3476 | 0 |
| | 5 | 373 | 747 | 1120 | 1494 | 1867 | 2240 | 439 | 878 | 1317 | 1755 | 2194 | 2633 | 497 | 995 | 1492 | 1989 | 2486 | 2984 | 548 | 1096 | 1643 | 2191 | 2739 | 3287 | 623 | 1245 | 1868 | 2490 | 3113 | 3735 | 5 |
| | 10 | 433 | 867 | 1300 | 1733 | 2167 | 2600 | 496 | 993 | 1489 | 1985 | 2481 | 2978 | 552 | 1103 | 1655 | 2207 | 2759 | 3310 | 599 | 1198 | 1797 | 2395 | 2994 | 3593 | 666 | 1332 | 1998 | 2664 | 3330 | 3996 | 10 |
| **1800** | 15 | 494 | 988 | 1482 | 1976 | 2470 | 2964 | 554 | 1109 | 1663 | 2218 | 2772 | 3326 | 607 | 1214 | 1820 | 2427 | 3034 | 3641 | 651 | 1301 | 1952 | 2602 | 3253 | 3903 | 710 | 1420 | 2130 | 2839 | 3549 | 4259 | 15 |
| | 20 | 556 | 1112 | 1668 | 2223 | 2779 | 3335 | 614 | 1227 | 1841 | 2454 | 3068 | 3682 | 663 | 1326 | 1989 | 2652 | 3315 | 3978 | 703 | 1406 | 2109 | 2813 | 3516 | 4219 | 755 | 1509 | 2264 | 3018 | 3773 | 4528 | 20 |
| | 25 | 619 | 1238 | 1858 | 2477 | 3096 | 3715 | 674 | 1349 | 2023 | 2697 | 3371 | 4046 | 720 | 1441 | 2161 | 2882 | 3602 | 4323 | 757 | 1514 | 2271 | 3028 | 3785 | 4543 | 800 | 1601 | 2401 | 3202 | 4002 | 4803 | 25 |
| | 30 | 685 | 1369 | 2054 | 2738 | 3423 | 4108 | 737 | 1474 | 2211 | 2947 | 3684 | 4421 | 780 | 1560 | 2339 | 3119 | 3899 | 4679 | 813 | 1625 | 2438 | 3251 | 4064 | 4876 | 848 | 1696 | 2543 | 3391 | 4239 | 5087 | 30 |

# Transport – Belt Conveyor

## Transfer Chute Design

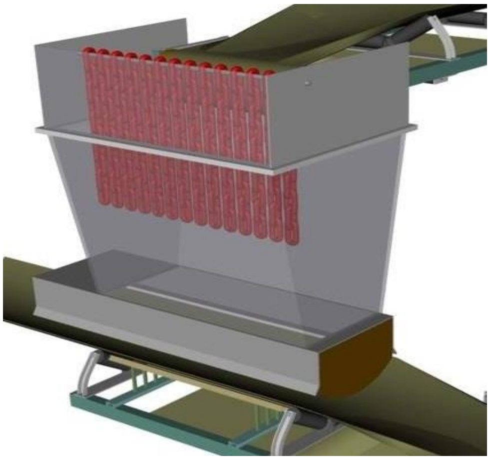
Chute design depends on material characteristics, especially flowability and abrasiveness.

The following examples show general tendencies / concepts for typical materials and shall serve as a guidance. However, the design always has to be adapted to the specific material.

Always keep the material flow trajectory in mind (depending on belt speeds) and feed into the centre of the receiving belt to avoid belt misalignment.

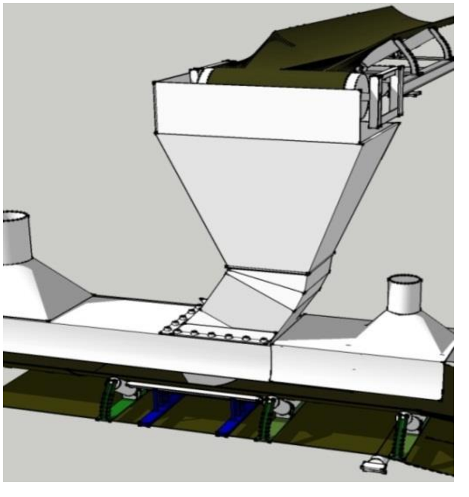
### Sticky material

Build chutes as straight, steep and simple as possible to ensure material flow without obstacles. If impact is not avoidable, prefer flexible structures such as rubber curtains or chains.



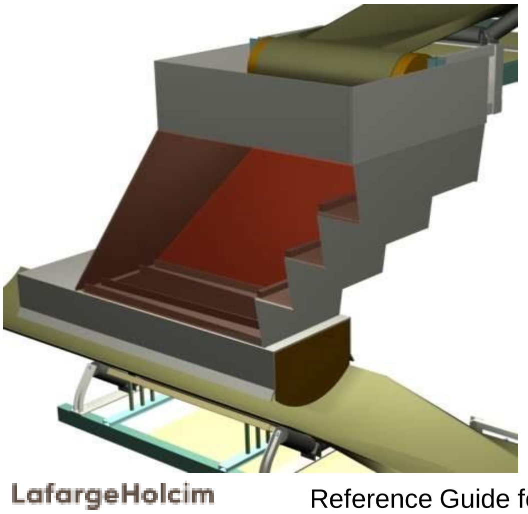
### Fine material

Flow guidance in direction of travel as far as possible, to ensure smooth flow with creating as little dust as possible.



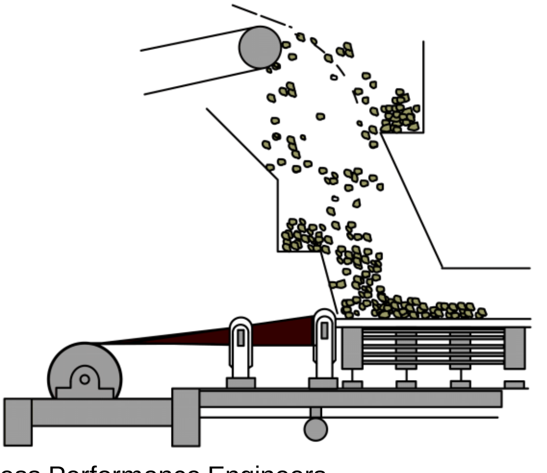
### Abrasive material

As much as possible “self-protection”, meaning material falling on material rather than chute structures. → Rock box design



### Coarse material

Low impact on the equipment

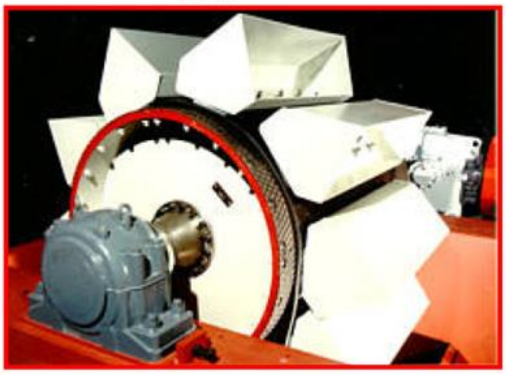


# Transport – Bucket Elevator

## Bucket Elevator Types

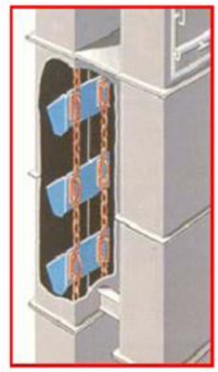
- Belt bucket elevator
- Central chain bucket elevator
- Round-link chain bucket elevator

Belt



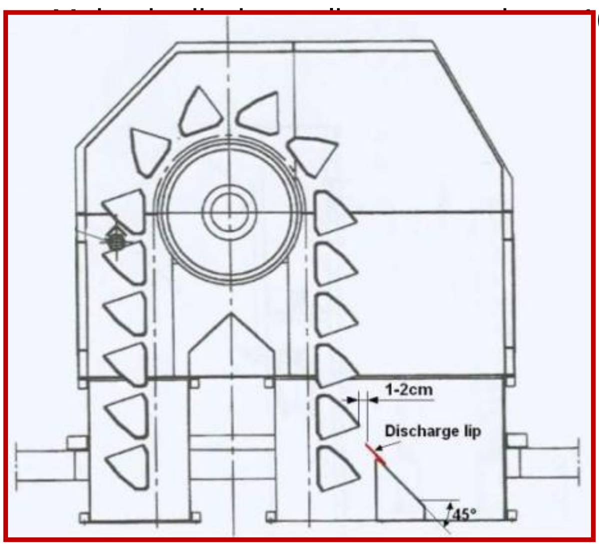
Central chain

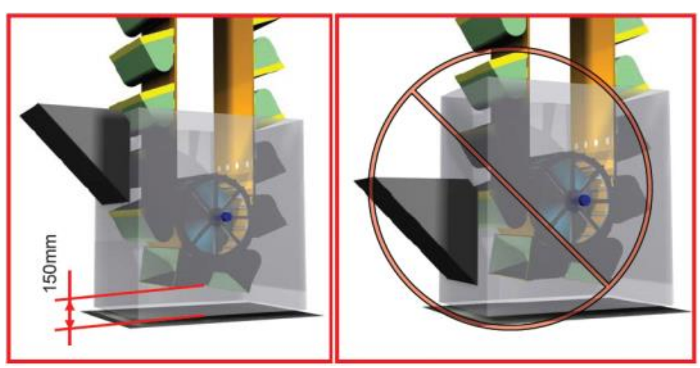
Roundlink chain



## Bucket Elevator Design & Maintenance

- There is a fixed speed for each bucket elevator that allows for proper material discharge and should not be changed!
- Feed material mostly directly into buckets instead of scooping out the bucket elevator boot.
- …0-20 mm in order to ensure effective discharge




For more information please see the TDS manual available on iShare:

**iShare → Communities → Transport, Dedusting & Shipping**

# Dedusting – Nuisance Dust Collection

## Design Guidelines

For more information please see the TDS manual available on iShare:
**iShare → Communities → Transport, Dedusting & Shipping**

### Air-to-cloth ratio (A/C ratio)

**1.2 $m^3/m^2$ x min** for slag, coal and clinker dust

**1.5 $m^3/m^2$ x min** for limestone and cement dust

### Can velocity

Can velocity (theoretical calculated raw gas velocity between the filter bags at the lower bag ends), valid independent of raw gas inlet arrangement, shall not exceed 1.3 m/s

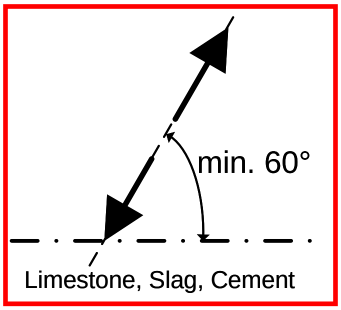
### Amount of vent points per filter

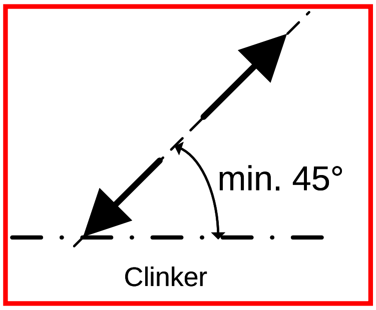
No more than eight (8) venting points should be connected to one dust collector.
.

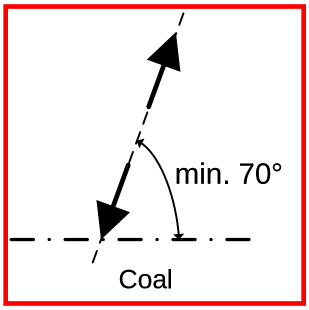
### Ductwork

Up- and downward sloping ducts for dust-laden air shall have a slope of
- $30^0$ for limestone, slag, and cement,
- $45^0$ for clinker
- 20° for coal

to avoid dust accumulation (measured from vertical axis).
Horizontal ducts should be avoided!



# Dedusting – Nuisance Dust Collection

## Filter bag dimension

The filter bag dimension depends on the cleaning system efficiency and the geometrical allocation of the filter bags. The diameter of the bags is usually between 120 and 160 mm.

The following bag lengths should not be exceeded:

| | new installation | conversion |
|---|---|---|
| reverse air | 11.0 m | 11.0 m |
| low pressure pulse-jet | 6.0 m | 8.0 m |
| high pressure pulse-jet | 4.5 m | 6.0 m |

## Distance between the bags

The minimum distance between the bags should be 50 mm.

## Number of bags per row

The maximum number of bags per row should not be more than 16 bags.

## Filter cloth

The filter cloth specification and design data to be provided by the supplier has to be carefully checked by the user.

- For general application (dry gas) up to $120^0$ C (long time operation): needle felt fabric made from high quality Polyester fibers
- For an application in drying/grinding (humid gas) up to $120^0$ C (long time operation): Polyacrylnitrile or similar fiber cloth
- Application for temperatures above $120^0$ C: Polyamide (Nomex), Polyphenylene, Glass-fiber, Teflon/graphite coated or similar.

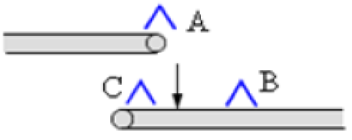
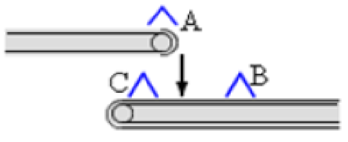
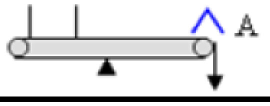
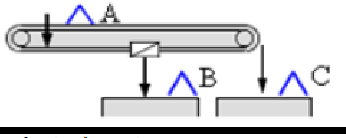
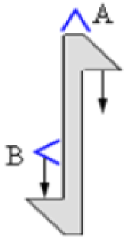
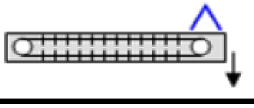
## Pulse cycle

The cleaning cycle for pulse-jet collectors should be designed so that the pulse duration produces a short, crisp pulse in order to create an effective shock wave in the bag. This duration is generally set to fire for 0.10 to 0.15 second.
The frequency of pulse-jet cleaning is also vital for a proper dust cake retention. This frequency can vary from 7 to 30 seconds or more and is adjusted by means of a potentiometer on the timer panel. The frequency should be adjusted, so that the differential pressure across the collector ranges from 75 - 150 mm WG.

To ensure proper cleaning frequency, an automatic "cleaning-on-demand" system utilizing a pressure switch gauge can be installed. Good practice is to put the low set point at about 10 mbar and the set point high at 12.5 mbar.

# Dedusting – Nuisance Dust Collection

## Dedusting Air Quantities

| Machine | Size (mm) | Air quantity ($m^3/h$) | Details | | | |
|---|---|---|---|---|---|---|
| Belt conveyor | | | A | B | C | |
|  | 650 | 4'000 | 1'500 | 1'500 | 1'000 | |
| | 800 | 5'250 | 2'000 | 2'250 | 1'000 | |
| | 1'000 | 6'500 | 2'500 | 2'750 | 1'250 | $m^3/h$ |
| | 1'200 | 7'750 | 3'000 | 3'250 | 1'500 | |
| | 1'400 | 8'750 | 3'500 | 3'750 | 1'500 | |
| | 1'600 | 10'000 | 4'000 | 4'250 | 1'750 | |
| Apron conveyor | | | A | B | C | |
|  | 800 | 6'500 | 3'500 | 2'000 | 1'000 | |
| | 1'000 | 7'500 | 4'000 | 2'500 | 1'000 | |
| | 1'200 | 8'750 | 4'500 | 3'000 | 1'250 | $m^3/h$ |
| | 1'400 | 9'500 | 4'750 | 3'250 | 1'500 | |
| | 1'600 | 10'000 | 5'000 | 3'500 | 1'500 | |
| Weigh feeder | | | A | | | |
|  | < 2'000 | | 1'500 | | | $m^3/h$ |
| | > 2'000 | | 2'000 | | | |
| Pivoting apron conveyor | | | A | B | C | |
|  | 800 | | 2'500 | 9'000 | 9'000 | |
| | 1'000 | | 3'000 | 10'000 | 10'000 | $m^3/h$ |
| | 1'200 | | 3'500 | 11'000 | 11'000 | |
| | 1'400 | | 4'000 | 12'000 | 12'000 | |
| Bucket elevator | | | Chain | | Belt | |
| | | | A | B | A | B |
|  | 400 | | 1'400 | 1'250 | 1'800 | 1'250 |
| | 500 | | 1'600 | 1'250 | 2'250 | 1'250 |
| | 630 | | 2'000 | 1'250 | 2'500 | 1'250 |
| | 800 | | 2'500 | 1'250 | 3'000 | 1'250 |
| | 1'000 | | 3'000 | 1'500 | 3'500 | 1'500 |
| | 1'250 | | 3'500 | 1'500 | 4'500 | 1'500 |
| | 1'600 | | 4'000 | 1'500 | 6'000 | 1'500 |
| Trough chain & screw conveyor  | ≤ 500 | 500 | per 15m length | | | |
| | > 500 | 1'000 | per 15m length | | | |
| Air slide | | | 125% of the air blower | | | |
| Classifying screen | | 50 | per t/h | | | |
| Vibratory screen | | 450 | per $m^2$ (closed) | | | |
| Swing screen | | 600 | per $m^2$ (closed) | | | |

# Dedusting – Nuisance Dust Collection

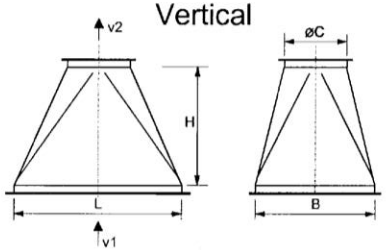
## Dedusting Air Quantities

| Machine unit | Size | $m^3/h$ | Remarks |
|---|---|---|---|
| Vibrating feeder | 600 mm | 900 | |
| | 800 mm | 1'500 | |
| | 1'000 mm | 2'400 | |
| | 1'200 mm | 3'600 | |
| Screen | | | |
| Classifing screen | | 50 | Per t/h (open) |
| Vibratory screen | | 450 | Per $m^2$ (close) |
| Swing screen | | 600 | Per $m^2$ (close) |
| Pneumatic transport | | | 1.5-times of the expanded compressed air volume |
| Crusher | | | |
| Roller crusher | | 15 - 20 | Guide values per t (Depending on supplier, and rpm) |
| Jaw crusher | | 8 - 15 | |
| Hammer crusher | | 30 - 50 | |
| Impact crusher | | 35 - 75 | |
| Gyratory crusher | | 30 - 60 | |
| Silo | | | |
| Clinker silo | | 15'000 | Per 30'000 $m^3$ of silo volume |
| Clinker dome | | 40 - 60'000 | |
| All other silos | | 5'000 | Net. Feeding arrangement dedusting to be added on top. |
| Bin | | | |
| Small bin | < $50m^3$ | 1'000 | Mechanical feeding |
| Medium bin | < $500m^3$ | 3'000 | Mechanical feeding |
| Large bin | >500 $m^3$ | 5'000 | Mechanical feeding |
| Packing machine | | 1'000 | Packing machine feed |
| | | 6'000 | 6-spouts rotary packer |
| | | 8'000 | 8-spouts rotary packer |
| | | 10'000 | 12-spouts rotary packer |
| | | 12'000 | 16-spouts rotary packer |
| | | 2'500 | Per spout in-line packer collecting funnel |
| | | 1'500 | Niagara-swing screen 1 x 2.5 m |
| | | 2'000 | Takeaway belt conveyor |
| | | 2'500 | Bag cleaning unit |
| Loading mobile | | 5'000 | Air slide 400 mm |
| | | 5'000 | Screw 1630/1800 |
| | | 1'500 | Hopper mobile |
| | | 4'000 | Double articulated (air slide or screw) |
| Loading head | | 900 | Cement 300 $m^3/h$ |
| | | 1'500 | Cement 600 $m^3/h$ |
| | | 10'000 | Clinker 300 - 1000 $m^3/h$ |
| Tanker vehicles | | 540 - 660 | Road 60 t/h at 2.5 bar |
| | | 660 | Rail 60 t/h at 2.5 bar |

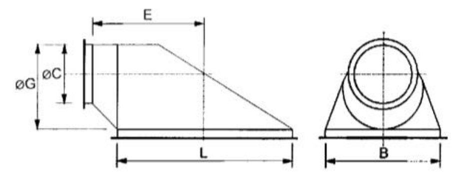
# Dedusting – Nuisance Dust Collection

## Venting Hood Design

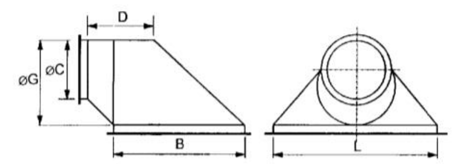
Vertical




Longitudinal




Transversal

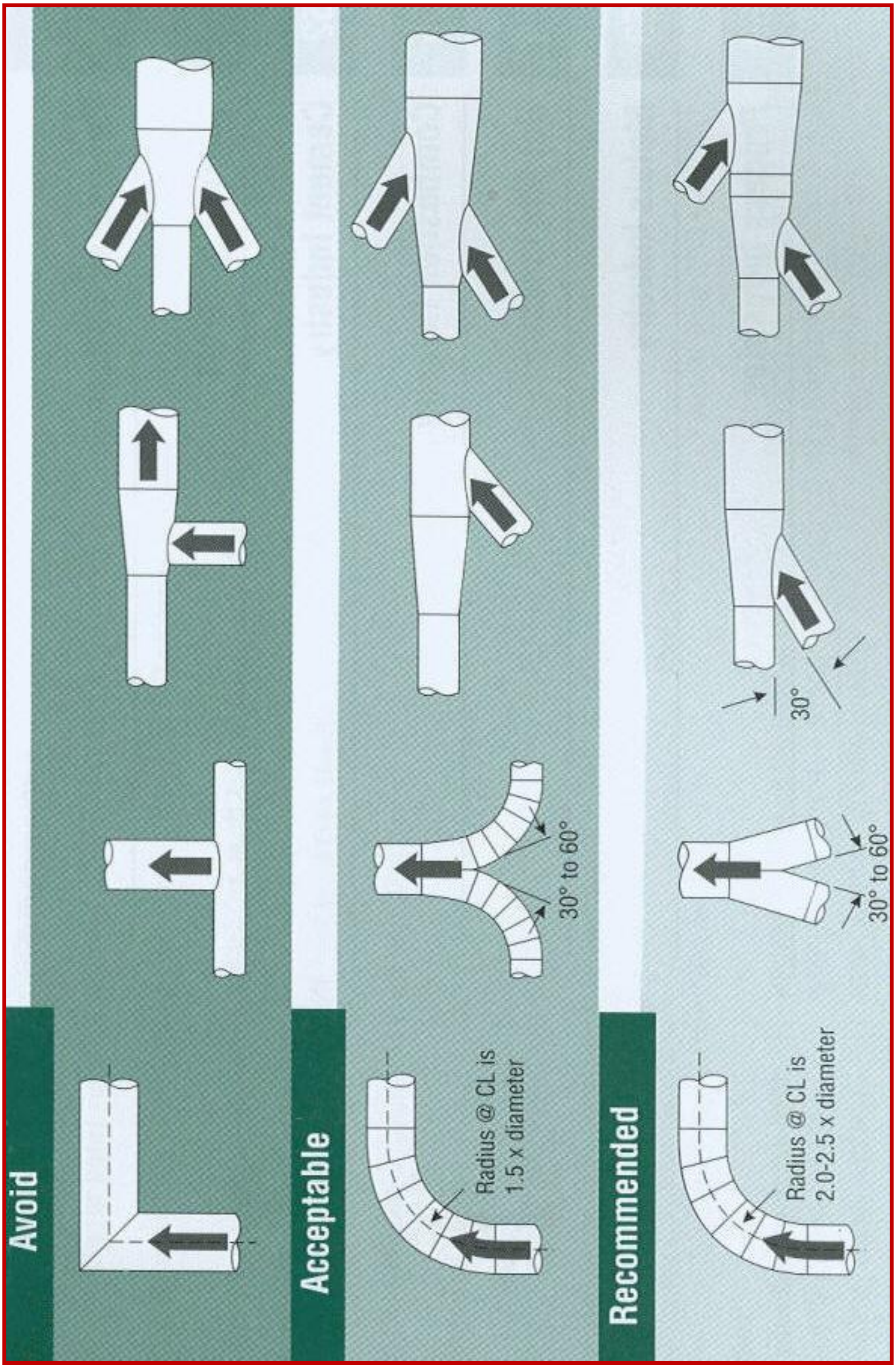



| Air Quantity | | v1 | v2 | L | B | H | Ø C | | Ø G | L | B | E | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| m³/h | m³/min | ms-1 | ms-1 | mm | mm | mm | mm | | mm | mm | mm | mm | mm |
| 250 | 4.2 | 1.40 | 18.0 | 260 | 190 | 165 | 70.0 * | | 97 | 260 | 190 | 157.0 | 122.0 |
| 500 | 8.3 | 1.40 | 17.5 | 370 | 270 | 235 | 100.5 * | | 143 | 370 | 270 | 227.0 | 177.5 |
| 750 | 12.5 | 1.40 | 17.0 | 450 | 330 | 280 | 125.0 * | | 178 | 450 | 330 | 278.0 | 218.0 |
| 1000 | 16.6 | 1.40 | 17.2 | 520 | 380 | 325 | 143.5 * | | 207 | 520 | 380 | 323.5 | 253.5 |
| 1250 | 20.8 | 1.40 | 17.7 | 580 | 425 | 365 | 158.0 | | 233 | 580 | 425 | 365.0 | 287.5 |
| 1500 | 25.0 | 1.44 | 17.9 | 630 | 460 | 400 | 172.0 | | 253 | 630 | 460 | 396.0 | 311.0 |
| 1750 | 29.2 | 1.43 | 17.9 | 680 | 500 | 430 | 186.0 | | 276 | 680 | 500 | 430.0 | 340.0 |
| 2000 | 33.3 | 1.39 | 17.9 | 740 | 540 | 470 | 198.0 | | 299 | 740 | 540 | 471.0 | 371.0 |
| 2500 | 41.6 | 1.41 | 18.0 | 820 | 600 | 520 | 222.0 | | 334 | 820 | 600 | 522.0 | 412.0 |
| 3000 | 50.0 | 1.40 | 17.9 | 900 | 660 | 570 | 244.0 | | 368 | 900 | 660 | 574.0 | 454.0 |
| 3500 | 58.3 | 1.44 | 17.8 | 960 | 700 | 610 | 262.0 | | 391 | 960 | 700 | 609.0 | 479.0 |
| 4000 | 66.6 | 1.40 | 18.0 | 1040 | 760 | 660 | 280.0 | | 426 | 1040 | 760 | 666.0 | 526.0 |
| 4500 | 75.0 | 1.42 | 17.9 | 1100 | 800 | 700 | 298.0 | | 449 | 1100 | 800 | 701.0 | 557.0 |
| 5000 | 83.3 | 1.42 | 17.9 | 1150 | 850 | 740 | 314.0 | | 475 | 1150 | 850 | 739.0 | 589.0 |
| 6000 | 100.0 | 1.42 | 17.9 | 1260 | 930 | 800 | 344.0 | | 524 | 1260 | 930 | 810.0 | 645.0 |

*Commercial Pipes and Bends
Sheet Thickness for Suction Hoods and Ducts: 3-4mm
Intake Velocity at Hoods according to Above Table: $V_1$ = ~ 1.4m/s
Air Velocity in Dedusting Duct : $V_2$ = > 18m/s

# Dedusting – Nuisance Dust Collection

## Duct Elbow, Joint and Branch Design



# Dispatch – Roto Packer and Palletizing

## Packer capacity per spout (guide value)

| Packer capacity per spout (design capacity)<br>(valid for cement fines < 4000 Blaine) | | |
|---|---|---|
| 25 kg Bags | 360 | bags/spout |
| 35 kg Bags | 330 | bags/spout |
| 40 kg Bags | 320 | bags/spout |
| 50 kg Bags | 300 | bags/spout |

## Packer machine capacity (guide value)

| Packer machine capacity (design capacity)<br>(valid for cement fines < 4000 Blaine) | | | | |
|---|---|---|---|---|
| | 25 kg Bags | 35 kg Bags | 40 kg Bags | 50 kg Bags |
| 4 Spout packer | 1440 | 1320 | 1280 | 1200 |
| 6 Spout packer | 2160 | 1980 | 1920 | 1800 |
| 8 Spout packer | 2880 | 2640 | 2560 | 2400 |
| 10 Spout packer | 3600 | 3300 | 3200 | 3000 |
| 12 Spout packer | 4320 | 3960 | 3840 | 3600 |
| 14 Spout packer | 5040 | 4620 | 4480 | 4200 |
| 16 Spout packer | 5760 | 5280 | 5120 | 4800 |

## Holcim bench mark for packing / palletizing / loading systems

- OEE 70 -75% (Proven OEE in packing plant) if manual loading
- OEE 85 -90% (Proven OEE in packing plant) if automated loading

Valid for packing, palletizing and shrinking and packing/direct loading systems

## Packer machine capacity reduction (guide value)

5000 Blaine: ~ 7% reduction of Packer machine capacity (guide value)

6000 Blaine: ~ 14% reduction of Packer machine capacity (guide value)

8000 Blaine: ~ 23% reduction of Packer machine capacity (guide value)

# Unit Conversion Table

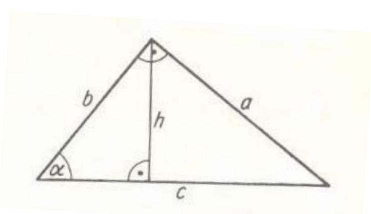
**Power of ten**

| Prefix | Power of Ten | Abreviation |
|---|---|---|
| Peta- | $10^{15}$ | P |
| Tera- | $10^{12}$ | T |
| Giga- | $10^{9}$ | G |
| Mega- | $10^{6}$ | M |
| Kilo- | $10^{3}$ | k |
| Hecto- | $10^{2}$ | h |
| Deca- | 10 | da |
| Deci- | $10^{-1}$ | d |
| Centi- | $10^{-2}$ | c |
| Milli- | $10^{-3}$ | m |
| Micro- | $10^{-6}$ | µ |
| Nano- | $10^{-9}$ | n |
| Pico- | $10^{-12}$ | p |
| Femto- | $10^{-15}$ | f |
| Atto- | $10^{-18}$ | a |

**Density of fuels**

| | |
|---|---|
| 1 ltr. light fuel oil | ≙ 0.84 kg at 15°C |
| 1 ltr. heavy fuel oil | ≙ 0.94 kg at 90°C |
| 1 $m^3$ natural gas | ≙ 0.80 kg (Approx. value) |
| 1 $m^3$ propane gas | = 2.019 kg |
| 1 $m^3$ butane gas | = 2.7 kg |

## Triangle:




$$\sin\alpha = \frac{a}{c}$$

$$\cos\alpha = \frac{b}{c}$$

$$\tan\alpha = \frac{a}{b}$$

$$\cot\alpha = \frac{b}{a}$$

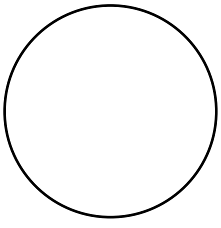
$$A = \frac{ab}{2}$$

A = surface

$$h = \frac{ab}{c}$$

$$a^2 + b^2 = c^2$$

## Circle:



$$u = 2\pi r = \pi d$$

$$A = \pi r^2 = \frac{\pi d^2}{4}$$

A = surface
u = circumference
r = radius
d = diameter

# Unit Conversion Table

## Area

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| square centimeter | $cm^2$ | $1 \cdot 10^{-4}$ $m^2$ |
| square meter | $m^2$ | 1 $m^2$ |
| are | are | $1 \cdot 10^{2}$ $m^2$ |
| hectare | ha | $1 \cdot 10^{4}$ $m^2$ |
| square kilometer | $km^2$ | $1 \cdot 10^{6}$ $m^2$ |
| square inch | $inch^2$ | $6.4516 \cdot 10^{-4}$ $m^2$ |
| square foot | $ft^2$ | $9.2903 \cdot 10^{-2}$ $m^2$ |
| square yard | $yard^2$ | $8.36127 \cdot 10^{-1}$ $m^2$ |

## Density [Mass]

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| kilogram per cubic meter | $kg/m^3$ | 1 $kg/m^3$ |
| gram per cubic centimeter | $g/cm^3$ | $1 \cdot 10^{3}$ $kg/m^3$ |
| pound per cubic foot | $lb/ft^3$ | $1.60185 \cdot 10^{1}$ $kg/m^3$ |
| pound per cubic inch | $lb/inch^3$ | $2.76799 \cdot 10^{4}$ $kg/m^3$ |
| grains per cubic foot | $grains/ft^3$ | $2.28835 \cdot 10^{-3}$ $kg/m^3$ |

## Energy

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| joule | J | 1 N·m |
| Newton meter | N·m | 1 N·m |
| kilojoule | kJ | $1 \cdot 10^{3}$ N·m |
| calorie | cal | 4.1868 N·m |
| kilocalorie | kcal | $4.1868 \cdot 10^{3}$ N·m |
| British termal unit | Btu | $1.05506 \cdot 10^{3}$ N·m |
| kilowatt hour | kW·h | $3.6 \cdot 10^{6}$ N·m |
| horse power hour | hp·h | $2.6845 \cdot 10^{6}$ N·m |
| gigajoule | GJ | $1 \cdot 10^{9}$ N·m |

## Flowrate [Volume]

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| cubic meter per second | $m^3/s$ | 1 $m^3/s$ |
| cubic meter per hour | $m^3/hr$ | $2.77778 \cdot 10^{-4}$ $m^3/s$ |
| cubic meter per day | $m^3/d$ | $1.15741 \cdot 10^{-5}$ $m^3/s$ |
| cubic foot per second | $ft^3/s$ | $2.83168 \cdot 10^{-2}$ $m^3/s$ |
| cubic foot per hour | $ft^3/hr$ | $7.86579 \cdot 10^{-6}$ $m^3/s$ |
| cubic foot per day | $ft^3/d$ | $3.27741 \cdot 10^{-7}$ $m^3/s$ |
| US gallon per second | USgal/s | $3.78541 \cdot 10^{-3}$ $m^3/s$ |
| US gallon per hour | USgal/hr | $1.0515 \cdot 10^{-6}$ $m^3/s$ |
| US gallon per day | USgal/d | $4.38126 \cdot 10^{-8}$ $m^3/s$ |
| liter per minute | l/min | $1.66667 \cdot 10^{-5}$ $m^3/s$ |

## Force

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| Newton | N | 1 N |
| pound force | $lb_f$ | 4.44822 N |
| kilogram force | $kg_f$ | 9.80665 N |
| Kilo Newton | kN | $1 \cdot 10^{3}$ N |
| ton force US | $tn_f$ US | $8.89644 \cdot 10^{3}$ N |
| ton force UK | $tn_f$ UK | $9.96402 \cdot 10^{3}$ N |

## Length

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| Ångstrom | Å | $1 \cdot 10^{-10}$ m |
| micron | µm | $1 \cdot 10^{-6}$ m |
| millimeter | mm | $1 \cdot 10^{-3}$ m |
| centimeter | cm | $1 \cdot 10^{-2}$ m |
| meter | m | 1 m |
| kilometer | km | $1 \cdot 10^{3}$ m |
| inch | " | $2.54 \cdot 10^{-2}$ m |
| foot | ft | $3.048 \cdot 10^{-1}$ m |

# Unit Conversion Table

## Mass

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| milligram | mg | $1 \cdot 10^{-6}$ kg |
| Carat (Metric) | carat | $2 \cdot 10^{-4}$ kg |
| gram | g | $1 \cdot 10^{-3}$ kg |
| kilogram | kg | 1 kg |
| quintal | quintal | $1 \cdot 10^{2}$ kg |
| ton (metric) | t | $1 \cdot 10^{3}$ kg |
| Atomic unit mass | u | $1.66054 \cdot 10^{-27}$ kg |
| grain | gr | $6.47989 \cdot 10^{-5}$ kg |
| dram | dram | $1.77185 \cdot 10^{-3}$ kg |
| ounce | oz | $2.83495 \cdot 10^{-2}$ kg |
| pound | lb | $4.53592 \cdot 10^{-1}$ kg |
| stone | stone | 6.35029 kg |
| Quarter | Quarter | $1.27006 \cdot 10^{1}$ kg |
| hundredweight US | hundredweight US | $4.53592 \cdot 10^{1}$ kg |
| Hundredweight UK | Hundredweight UK | $5.08023 \cdot 10^{1}$ kg |
| Uston | Uston | $9.07185 \cdot 10^{2}$ kg |
| Ukton | Ukton | $1.01605 \cdot 10^{3}$ kg |

## Plane angle

| | | |
|---|---|---|
| degree | ° | 1 ° |
| minute | min | $1.66667 \cdot 10^{-2}$ ° |
| second | s | $2.77778 \cdot 10^{-4}$ ° |
| radian | rad | $5.72958 \cdot 10^{1}$ ° |

## Power

| | | |
|---|---|---|
| joule per second | J/s | 1 J/s |
| watt | W | 1 J/s |
| kilowatt | kW | $1 \cdot 10^{3}$ J/s |
| megawatt | MW | $1 \cdot 10^{6}$ J/s |
| kilojoule per hour | kJ/hr | $2.77778 \cdot 10^{-1}$ J/s |
| kilogram force meter per second | $kg_f \cdot m/s$ | 9.80665 J/s |
| calorie per second | cal/s | 4.1868 J/s |
| calorie per hour | cal/hr | $1.163 \cdot 10^{-3}$ J/s |
| British thermal units per second | BTU/s | $1.05506 \cdot 10^{3}$ J/s |
| British thermal units per hour | BTU/hr | $2.93072 \cdot 10^{-1}$ J/s |
| tons | Ton (RT) | $3.51687 \cdot 10^{3}$ J/s |
| metric horse power | pk (Metric hp) | $7.35499 \cdot 10^{2}$ J/s |
| horse power | hp | $7.457 \cdot 10^{2}$ J/s |
| electric horse power | ehp | $7.46 \cdot 10^{2}$ J/s |

## Pressure

| | | |
|---|---|---|
| pascal | Pa | 1 Pa |
| kilopascal | kPa | $1 \cdot 10^{3}$ Pa |
| newton per square meter | $N/m^2$ | 1 Pa |
| bar | Bar | $1 \cdot 10^{5}$ Pa |
| millibar | mBar | $1 \cdot 10^{2}$ Pa |
| kilogram force per square centimeter | $kg_f/cm^2$ | $9.80665 \cdot 10^{4}$ Pa |
| atmosphere | atm | $1.01325 \cdot 10^{5}$ Pa |
| pound per square inch | psi | $6.89476 \cdot 10^{3}$ Pa |
| meter of water @ 4°C | m $H_2O$ 4°C | $9.80665 \cdot 10^{3}$ Pa |
| centimeter of water @ 4°C | cm $H_2O$ 4°C | $9.80665 \cdot 10^{1}$ Pa |
| foot of water @ 4°C | ft $H_2O$ 4°C | $2.98907 \cdot 10^{3}$ Pa |
| inch of water @ 4°C | inch $H_2O$ 4°C | $2.49089 \cdot 10^{2}$ Pa |
| millimeter of mecury @ 0°C | mm Hg 0°C | $1.33322 \cdot 10^{2}$ Pa |
| inch of mercury @ 0°C | inch Hg 0°C | $3.38639 \cdot 10^{3}$ Pa |
| | | |

# Unit Conversion Table

## Specific heat [Mass]

| Unit name | Symbol | SI Equivalent |
|---|---|---|
| joule per kilogram per kelvin | J/(kg·K) | 1 J/(kg·K) |
| kilojoule per kilogram per kelvin | kJ/(kg·K) | $1 \cdot 10^{3}$ J/(kg·K) |
| calorie per gram per degree celcius | cal/(g·$^{o}$C) | $4.1868 \cdot 10^{3}$ J/(kg·K) |
| kilocalorie per gram per degree celcius | kcal/(g·$^{o}$C) | 4.1868 J/(kg·K) |
| British thermal unit per pound mass per degree farenheit | Btu/(lb$_{m}$·$^{o}$F) | $4.1868 \cdot 10^{3}$ J/(kg·K) |
| calorie per gram per kelvin | cal/(g·K) | $4.1868 \cdot 10^{3}$ J/(kg·K) |

## Temperature

| | | |
|---|---|---|
| **Kelvin (K)** | | |
| (K-273.15) | = | °C |
| (9/5)K-459.67 | = | °F |
| | | |
| **Celcius (°C)** | | |
| (°C+273.15) | = | K |
| (9/5)°C+32 | = | °F |
| | | |
| **Fahrenheit (°F)** | | |
| (5/9)(°F+459.67) | = | K |
| (5/9)(°F-32) | = | °C |

## Velocity

| | | |
|---|---|---|
| centimeter per second | cm/s | $1 \cdot 10^{-2}$ m/s |
| meter per second | m/s | 1 m/s |
| kilometer per second | km/s | $1 \cdot 10^{3}$ m/s |
| kilometer per hour | km/hr | $2.77778 \cdot 10^{-1}$ m/s |
| foot per second | ft/s | $3.048 \cdot 10^{-1}$ m/s |
| foot per hour | ft/hr | $8.46667 \cdot 10^{-5}$ m/s |
| inch per second | inch/s | $2.54 \cdot 10^{-2}$ m/s |
| mile per hour | mph | $4.4704 \cdot 10^{-1}$ m/s |
| speed of light in vacuum | (speed of light in vacuum) m/s | $2.99792 \cdot 10^{8}$ m/s |
| Mach | M | $3.316 \cdot 10^{2}$ m/s |

## Angular velocity

| | | |
|---|---|---|
| degrees per minute | $^{o}$/min | $2.90888 \cdot 10^{-4}$ rad/s |
| degrees per second | $^{o}$/s | $1.74533 \cdot 10^{-2}$ rad/s |
| radian per minute | rad/minute | $1.66667 \cdot 10^{-2}$ rad/s |
| radian per second | rad/s | 1 rad/s |
| revolutions per minute | rpm | $1.0472 \cdot 10^{-1}$ rad/s |
| revolutions per second | rps | 6.28319 rad/s |

## Viscosity [Dynamic]

| | | |
|---|---|---|
| pascal second | Pa·s | 1 Pa·s |
| millipascal second | mPa·s | $1 \cdot 10^{-3}$ Pa·s |
| centipoise | cP | $1 \cdot 10^{-3}$ Pa·s |
| kilogram force second per square meter | kg$_{f}$·s/m$^{2}$ | 9.80665 Pa·s |
| pound force second per square foot | lb$_{f}$·s/ft$^{2}$ | $4.78803 \cdot 10^{1}$ Pa·s |
| pounf mass per foot second | lb$_{m}$/(ft·s) | 1.48816 Pa·s |
| kilogram per (meter second) | kg/(m·s) | 1 Pa·s |
| gram per (centimeter second) | g/(cm·s) | $1 \cdot 10^{-1}$ Pa·s |
| Poise | P | $1 \cdot 10^{-1}$ Pa·s |

# Unit Conversion Table

| Viscosity [Kinematic] | | |
|---|---|---|
| **Unit name** | **Symbol** | **SI Equivalent** |
| centistokes | cSt | $1 \cdot 10^{-6}$ $m^2/s$ |
| square centimeter per second | $cm^2/s$ | $1 \cdot 10^{-4}$ $m^2/s$ |
| square foot per hour | $ft^2/hr$ | $2.58064 \cdot 10^{-5}$ $m^2/s$ |
| square foot per second | $ft^2/s$ | $9.2903 \cdot 10^{-2}$ $m^2/s$ |
| square meter per hour | $m^2/h$ | $2.77778 \cdot 10^{-4}$ $m^2/s$ |
| square meter per hour | $m^2/s$ | 1 $m^2/s$ |
| stokes | St | $1 \cdot 10^{-4}$ $m^2/s$ |
| **Volume** | | |
| cubic centimeter | $cm^3$ | $1 \cdot 10^{-6}$ $m^3$ |
| cubic decimeter | $dm^3$ | $1 \cdot 10^{-3}$ $m^3$ |
| cubic meter | $m^3$ | 1 $m^3$ |
| liter | l | $1 \cdot 10^{-3}$ $m^3$ |
| cubic inch | $inch^3$ | $1.63871 \cdot 10^{-5}$ $m^3$ |
| cubic foot | $ft^3$ | $2.83168 \cdot 10^{-2}$ $m^3$ |
| cubic yard | $yard^3$ | $7.64555 \cdot 10^{-1}$ $m^3$ |
| US gallon | US gal | $3.78541 \cdot 10^{-3}$ $m^3$ |
| UK gallon | UK gal | $4.54609 \cdot 10^{-3}$ $m^3$ |
| barrel US petrol | bbl US petrol | $1.58987 \cdot 10^{-1}$ $m^3$ |
| UK pint | UK pint | $5.68262 \cdot 10^{-4}$ $m^3$ |

# Notes

# Notes

**LafargeHolcim**
**Cement Industrial Performance**

Edition 12
April 2016