1-day Technical Seminar

November 9th, 2015

CPB Christian Pfeiffer

2015 90 YEARS

Cement Grinding
- an overview & improvement possibilities

by Dipl. Ing. Tim Nowack

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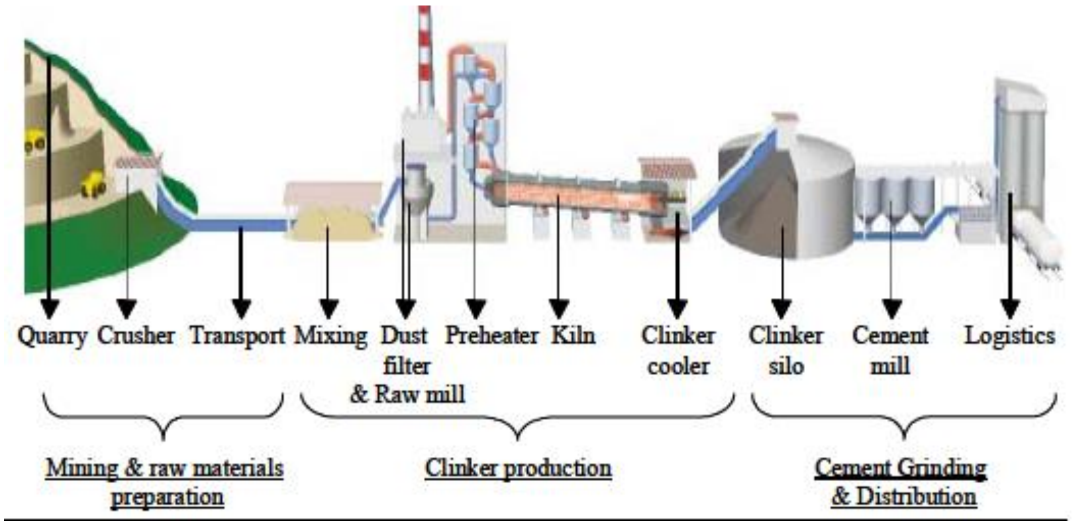
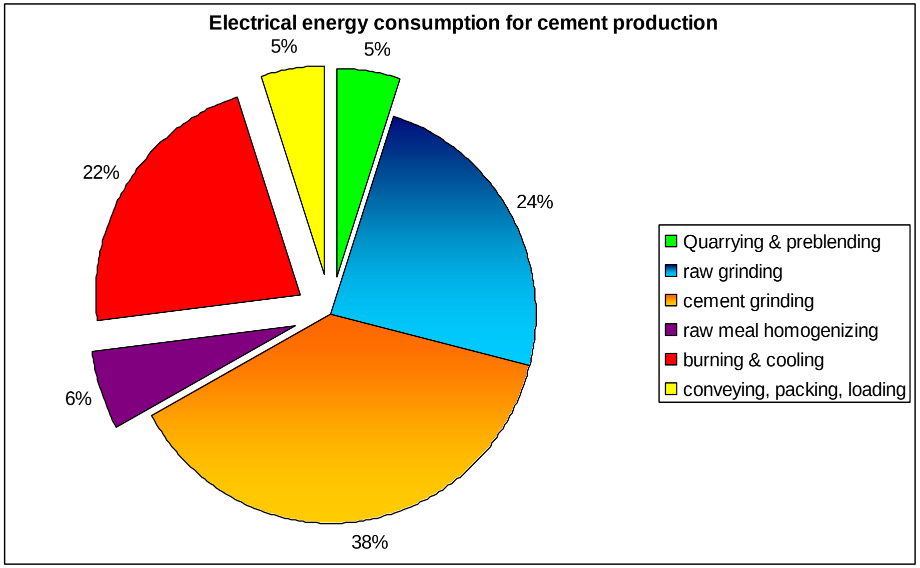
Cement manufacture is highly energy intensive



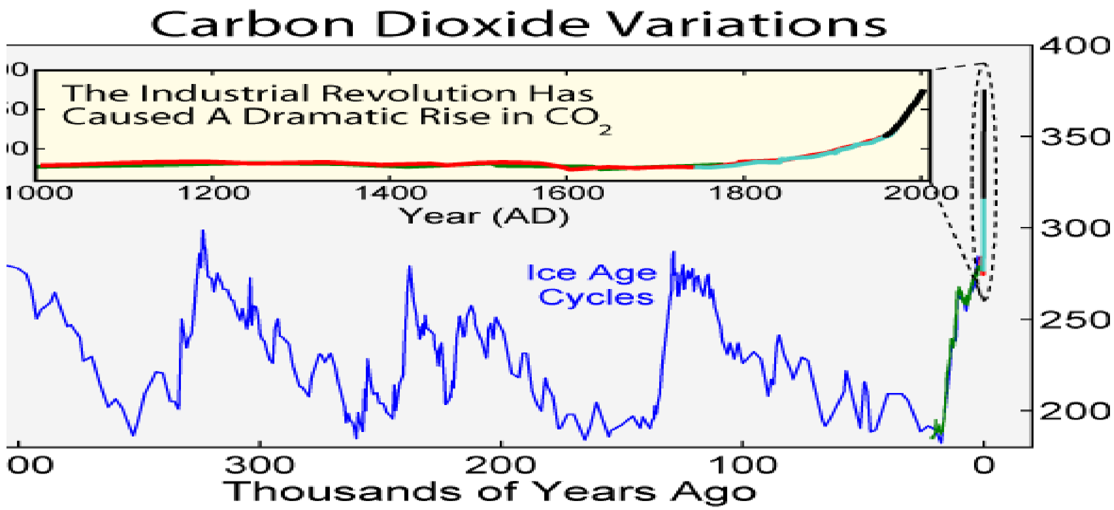
- Modern cement plant typically consumes 3,100 - 3,400 MJ of fuel per t-clinker & 80 -130 kWh electricity per t-cement;
- The industry consumes about 2% of the global primary energy, or 5% of all industrial energy;
- Fuel and electricity are the main costs of cement production.

Electricity is used in every step of the process



- Typically 2/3 of the power consumed for cement production is used for grinding of raw materials, coal (if used as fuel) and cement;
- The single biggest consumer of electricity is the cement mill, which consumes upward of 25 kWh / t of cement ground.

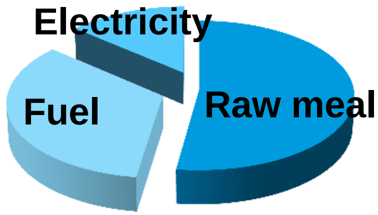
Burning fossil fuels & consuming electricity emits CO_2



- Each tonne of carbon produces 3.67 t of CO_2 when burnt;
- Atmospheric CO_2 risen rapidly since industrial revolution & projected to increase from current level of 380 ppm to 540 – 970 ppm by 2100, depending on the mitigating factors taken.

Cement Industry emits vast quantity of CO_2

- Every tonne of 95/5 OPC generates nearly a tonne of CO_2:

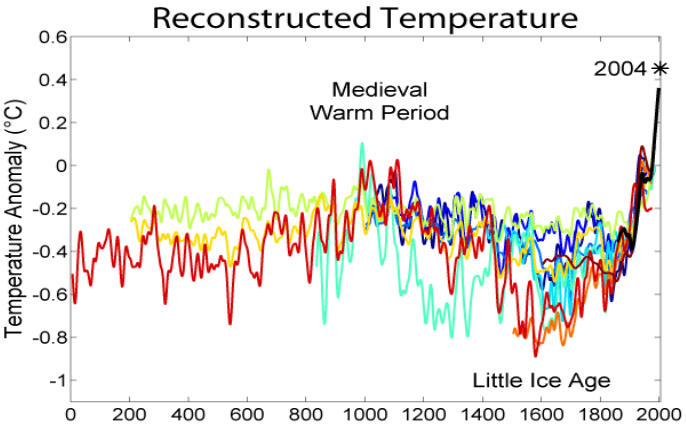


- *50-55%* from raw meal calcination
- *34-36%* from fuel consumption
- *10-15*% from electricity consumption

- Actual CO_2 emission depend mainly on clinker factor and process efficiency, ranging from 0.7 to 1.1 t CO_2 per t-cement globally;

- In 2014, the industry generates almost 10% of the 35 Gt of CO_2 emitted globally.

CO_2 blamed for global warming



- Scientists generally agreed that rising CO_2 is the main cause of global warming and each tonne of CO_2 added increases average global temperature by 1.5×10^{-12} °C;

- 1st critical level of 450 ppm, which is expected to raise the average global surface temperature by 2°C, may be reached in 20-30 years if nothing is done;

- Some countries have introduced carbon tax or ETS to curb fossil fuel burning.

Sustainable Development & Corporate Social Responsibility

- Cement manufacture is generally perceived as a “dirty” industry having a significant impact on the environment;
- Sustainable development of the industry and “license” to operate often hinges on public opinion;
- Hence, many companies -especially MNCs- have embraced Corporate Social Responsibility and embarked on “AFR” -or Alternative Fuels & Raw Materials utilisation- as a means of reducing energy cost and carbon footprint to ensure competitiveness and sustainability;
- Although grinding accounts for < 10% of the industry CO_2 emission, every kWh/t saved reduces global CO_2 emission by ~ 4 Mt annually and helps to improve public perception of the industry.

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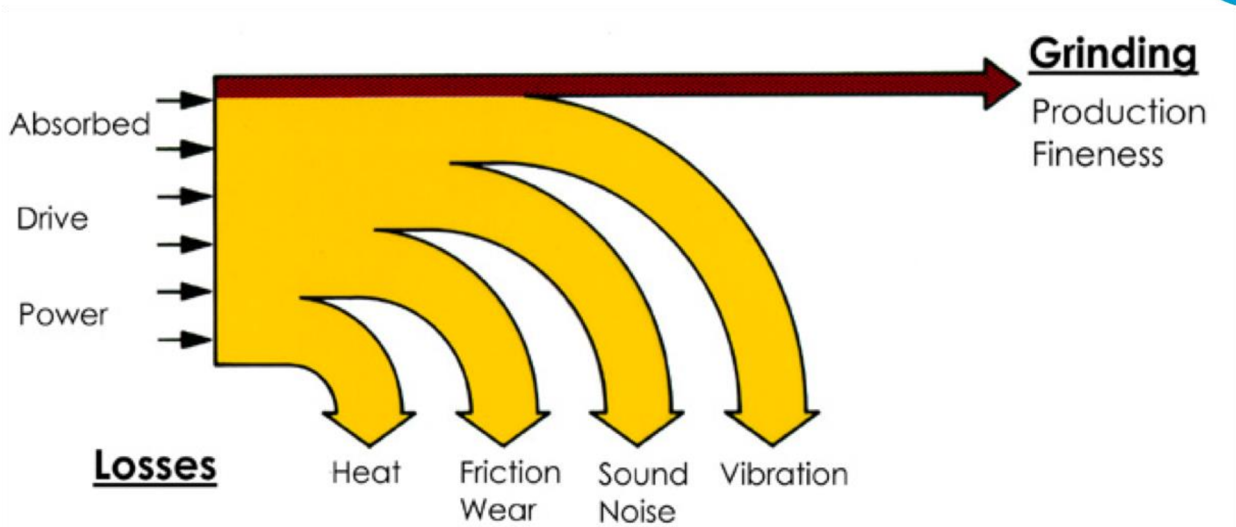
Grinding is inherently an inefficient process



- < 20%, or in the case of ball mills only 3-6%, of the electricity consumed in grinding is converted to useful energy, the bulk is dissipated as heat, noise, vibration and equipment wear;
- While dissipated heat is necessary for the drying and partial dehydration of gypsum, excess amount leads to high mill temperature, which can affect performance as well as cement quality if it is significantly above 120 ºC.

Theory of Comminution

- There is no theoretical formula to determine the energy requirement for grinding other than the empirical laws developed by 3 researchers based on the generalized equation, $dE = -C(dx/x^n)$, viz:

	Laws	Postulations	Equations	Applicable size
1	Rittinger's (1867)	Grinding work is related to the new surface generated	$W = k_1\,(1/x_p - 1/x_f)$	Fine grinding of particle below 0.05 mm (50µm)
2	Kick's (1885)	Equal work is required to achieve equivalent relative reduction in grain size	$W = k_2\,\ln(\frac{x_f}{x_p})$	Crushing of particle above 50 mm
3	Bond's (1952)	Grinding work is related to the length of new cracks formed	$W = k_3(\frac{1}{\sqrt{x_p}} - \frac{1}{\sqrt{x_f}})$	Grinding of particle in 50 – 0.05 mm

- where W = Grinding work required, k = a constant, x_f = grain size of feed & x_p = grain size of product

Bond's Work Index (W)

- For grinding of cement and the particle size involved, Bond's law is the most applicable to correlate the energy required and is generally expressed as:

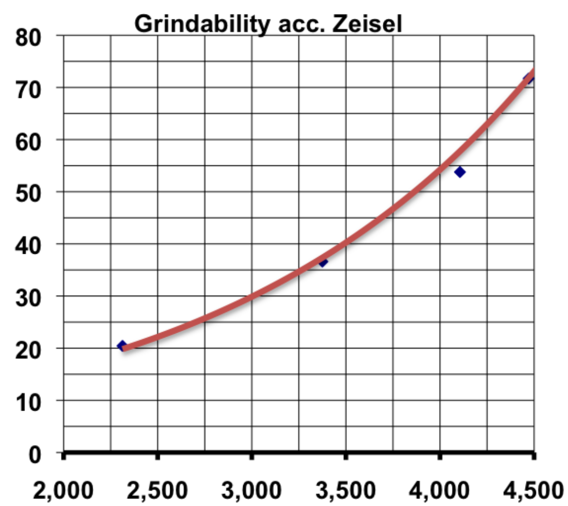
$$E = 10W \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right)$$

where:
E = specific energy required (kWh/t)
W = Bond's work index (kWh/t)
P_{80} = particle diameter of product, 80% passing (µm)
F_{80} = particle diameter of feed, 80% passing (µm)

- The Bond's Work Index of a material, which is commonly used in the British Commonwealth as well as US, is determined in a standard laboratory ball mill but the test is cumbersome to perform.

Grindability

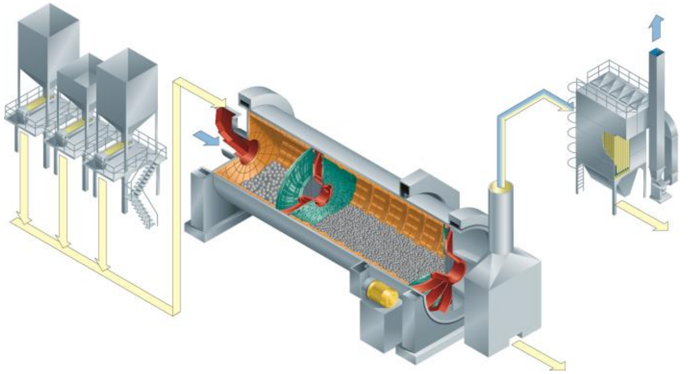
- In Europe, the **Zeisel test** -which is simpler to perform- is normally used to determine the “grindability” of a material for performance evaluation and plant design.

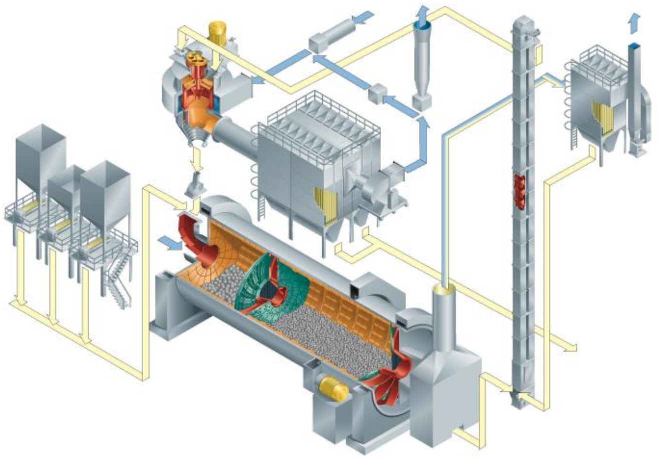


There are 4 types of mill in service today:

1. **Ball Mill** (BM): historically the mill of choice, it still predominates today and accounts for > 85% of all cement mills installed globally;
2. **Vertical Roller Mill** (VRM): commonly used for grinding of granulated slag but increasingly also for cement grinding and accounts for approximately 15% of the global cement mills;
3. **Roller Press** (RP): under development for several years but not known if any commercial plants in service;
4. **Horizontal Mills** (HM): Very few in service (<1%) and no longer a serious consideration.

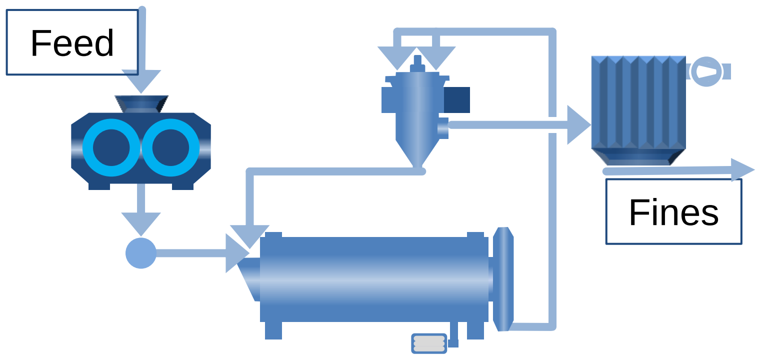
Ball Mill - open or closed circuit

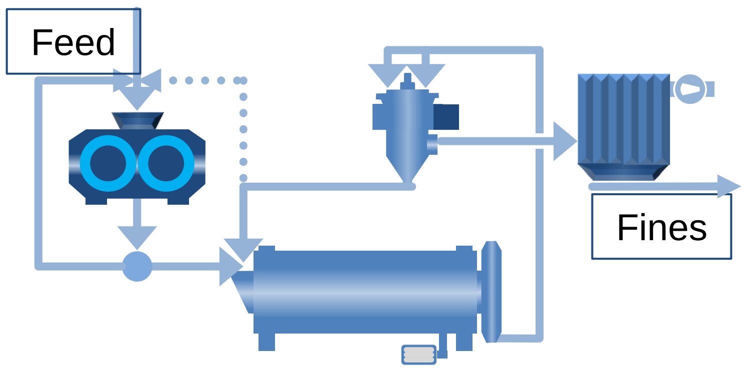




- Started as an open circuit mill until CPB introduced the 1st air separator in 1939 for closed circuit grinding;
- Years of development led to a highly reliable, flexible & easy to operate plant, requiring simple, low maintenance with readily available wear parts and low stocking cost;
- Cement quality is universally accepted and may command a premium over VRM cement in some markets;
- Despite higher energy consumption compared with VRM, it remains popular today and may offers the lowest TCO.

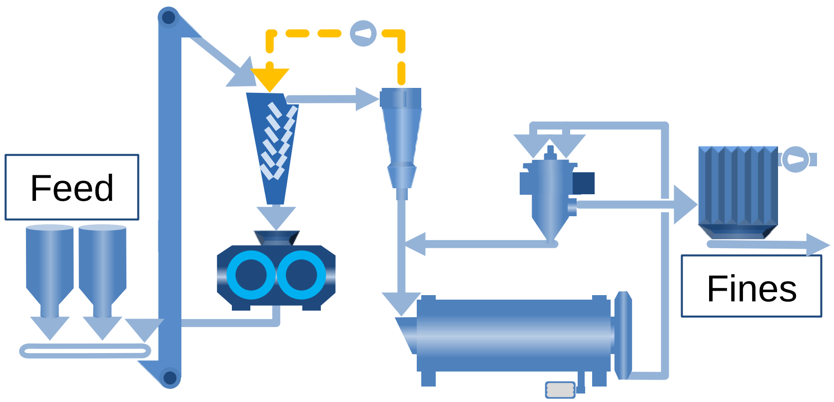
Ball Mill with Roller Press for pre-grinding





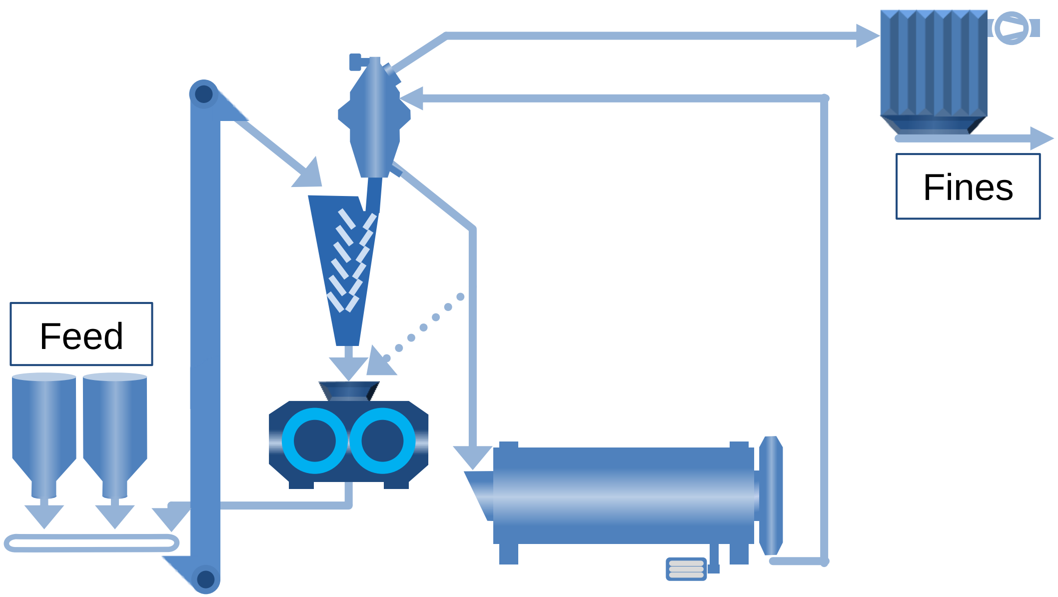
- Gained popularity in the 80's to increase output by up to 30% in open pre-grinding, or 50% in hybrid mode;
- Plant is more complex and sensitive to feed variability / foreign matters, hence reliability / availability often lower compared with ball mill resulting in minimal energy saving;
- Require higher maintenance skills, more costly wear parts, longer delivery time and higher stocking cost are factors to be considered in determining the TCO.

Ball Mill with Roller Press in semi-finishing mode



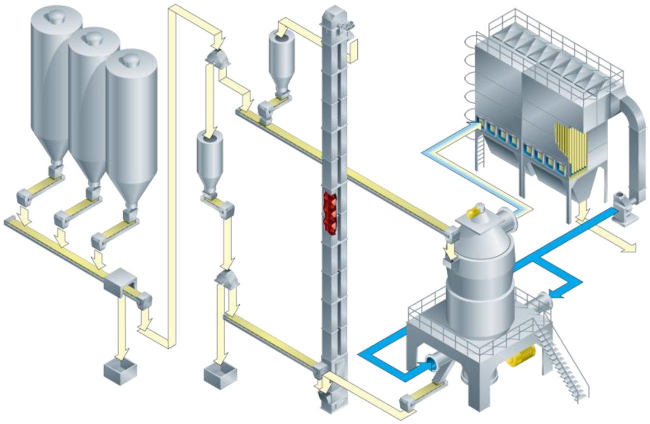
- Combined grinding allows better mill optimization, including use of mono-chamber mill;
- Capacity may almost be doubled and energy reduced by 10 – 20%;
- However, due to lower reliability and operational sensitivity, actual energy saving often minimal or even negative;
- Investment and maintenance costs generally higher and actual TCO may also not be so attractive;
- Cement quality can be an issue in some markets.

Latest CPB Roller Press-Ball Mill with single DSS separator (commissioned in 2015)



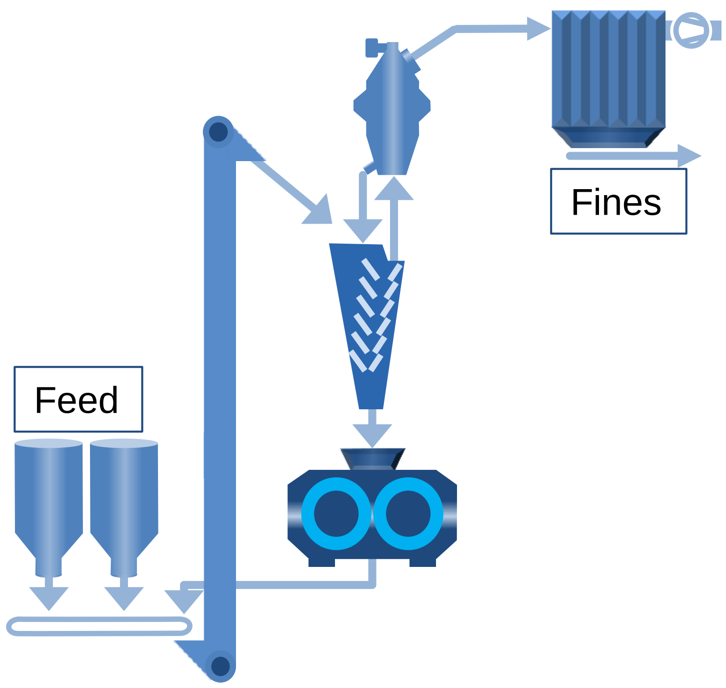
- CPB single dynamic separator system reduces investment cost, plant complexity, and provides higher energy saving potential.

Vertical Roller Mill system



- Used mainly for slag grinding initially but gained popularity for normal cement grinding since last decade due to higher capacity and lower energy consumption;
- However, plant more complex and sensitive in operation, resulting in lower availability and often lower energy saving, especially if hot gas generator is required;
- Cement quality, esp water demand / early strength, may be an issue due to use of water spray to reduce vibration, lower gypsum dehydration and narrower PSD;
- Silo blockage may be aggravated due to higher residual cement moisture.

Roller Press system



- Installed mainly as a pregrinder initially and promoted more recently for stand-alone cement grinding after the advent of the V-separator, improved wear life of the rollers and maintenance needs;
- Potential to offer lowest specific energy consumption;
- However, reliability, operational sensitivity, maintenance needs, cement quality are all unproven and no known plant in commercial service, other than for slag grinding.

Comparison of specific energy consumption of the 3 main cement mill systems in service

Basis: 3,200 g/cm² OPC		Ball Mill	Ball Mill + Roller Press	Vertical Roller Mill
Mill machinery		**Ø4.6x14.25 m**	**Ø4.0x8.75 m +RP 16/10**	**Type 46**
Main power absorbed	[kW]	4,350	3,400	2,900
Output	[t/h]	150	150	150
Mill Power absorbed	[kWh/t]	29.0	22.7	19,3
Mill Power absorbed relative to ball mill	[%]	**100**	**78**	**67**
Ancilaries	[kWh/t]	5.0	8.0	11.6
Plant total	[kWh/t]	34.0	30.7	30.9
Plant total relative to ball mill installation	[%]	**100**	**90**	**91**

Comparison of the Total Cost of Ownership of the 3 main cement mill systems in service

		Ball Mill	Ball Mill + Roller Press	Vertical Roller Mill
Investment cost	[%]	100	125	130
Annual plant availability	[%]	97 - 99	85 - 90	88 - 90
Operating cost (energy + maintenance)	[%]	**100**	**116**	**107**
Spares holding cost	[%]	100	115-125	115-125
Cement quality		General acceptance	General acceptance	May have issues

- Well designed, simple closed circuit ball mill can often offers the lowest TCO

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Factors affecting mill performance are:

1. Characteristics or “grindability” of the feed;
2. Fineness of the product;
3. Engineering and design of the plant and equipment;
4. Use of additives and admixtures;
5. Operation and maintenance.

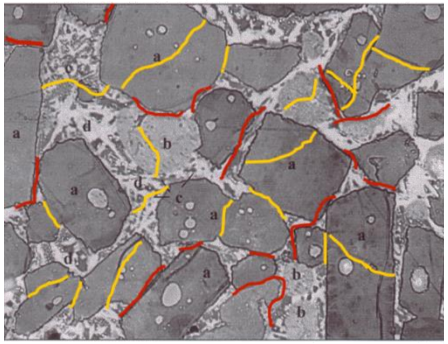
Characteristics & grindability of materials

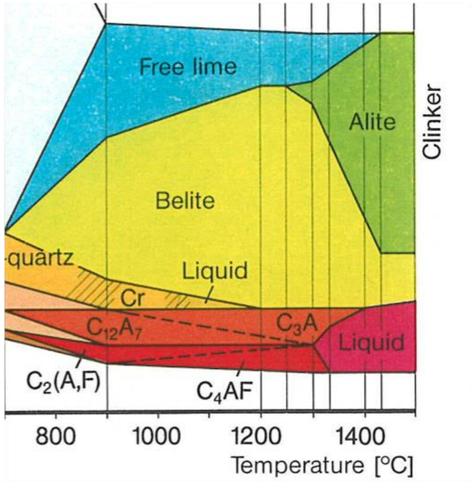
Materials	Appearance	Particle Size	Moisture	Grindability
Clinker	Hard, abrasive	< 30 mm	Dry	High
Gypsum – natural	Mainly hard	< 50 mm	Upto 10%	Low
Gypsum - synthetic	Soft, sticky	< 50 mm	Upto 25 %	Low
Granulated Glass Blastfurnace Slag	Glassy, abrasive	< 5 mm	Upto 15 %	High
Limestone	Hard	< 50 mm	5 - 10 %	Medium
Pozzolana	Hard or soft	10 - 50 mm	Upto 25 %	Medium
Fly ash - dry	Powdery	2,000 – 5,500 cm^2/g	Dry	Low
Fly ash - moist	Sticky	Lumpy	Upto 25 %	Low

Grindability of clinker

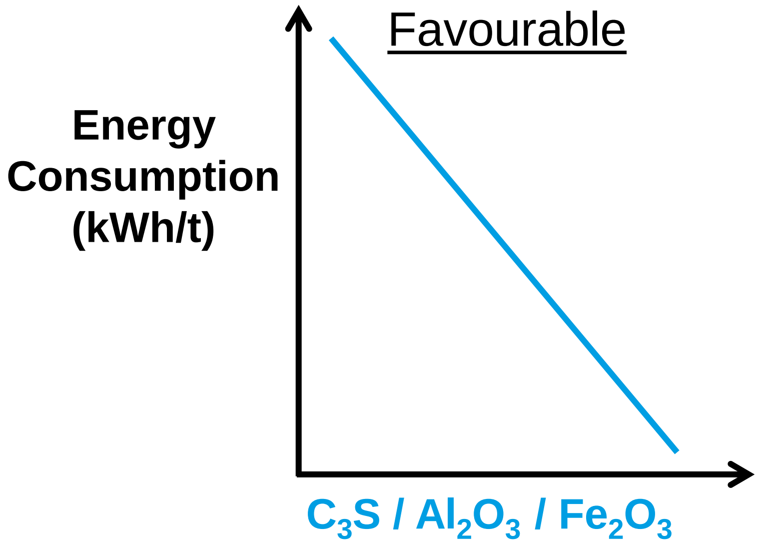
A common factor affecting mill performance, clinker grindability varies according to the:

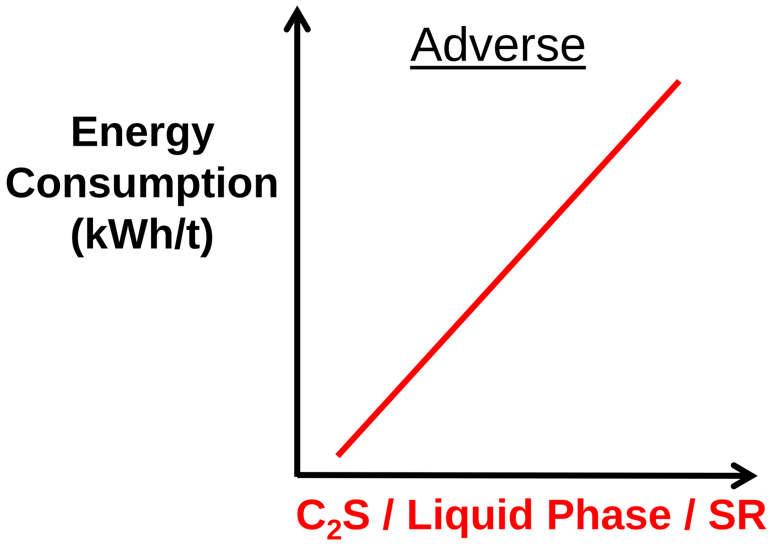
- Clinker mineralogy and composition, in particular the amount of C_2S / C_2S, crystal size and extent of micro fracturing;
- Thermal history, ie. temperature and duration of sintering-cooling, which determines the crystal size and micro cracking;
- Hence, quarry development, raw meal preparation, kiln burning / cooling, fuel quality, etc, can all affect the cement mill performance.





Effect of clinker composition on mill performance

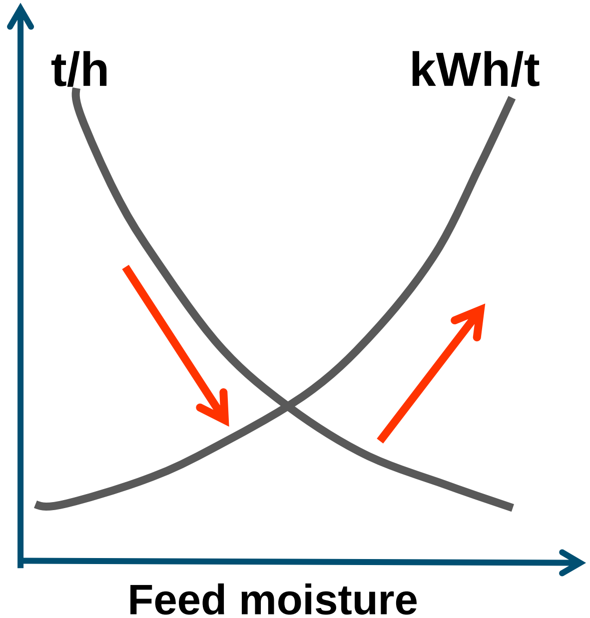




"Rule-of-thumb":

- Every 1% increase in **C_3S**, the grindability decreases by ~1.5%;
- Every 1% increase in **C_2S**, the grindability increases by ~2.5%.

Effect of feed moisture on mill performance



- Moisture content below 0.5% has a beneficial effect on mill performance, but for every 1% increase in moisture above 0.5%, mill energy consumption increases by >10%, especially at higher product fineness
- At moisture above 3 - 4%, a ball mill without drying chamber may not be operable

> Excessive moisture in waste gypsum or additives can adversely affect the mill performance if the total moisture level approaches the critical level of 3-4%

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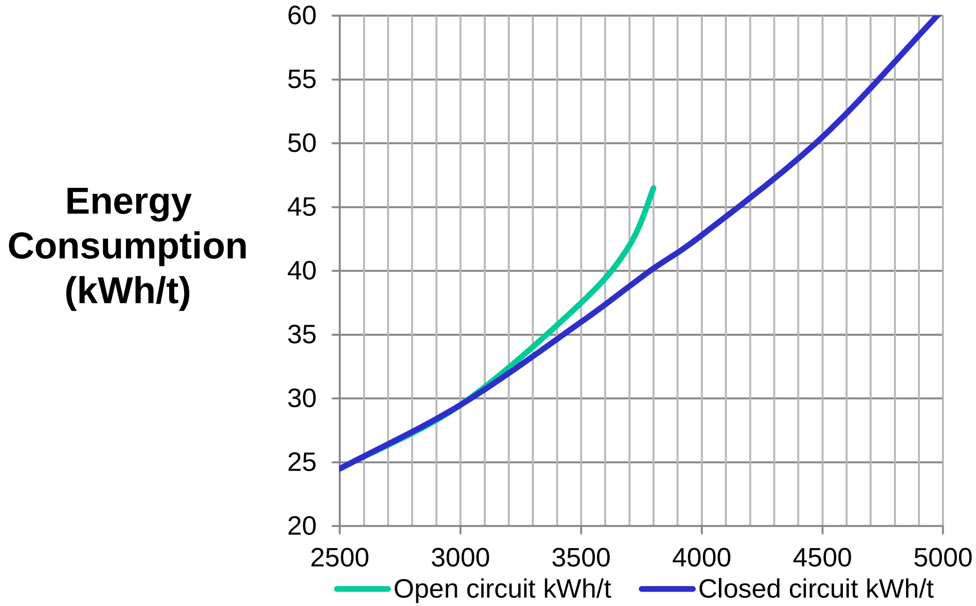
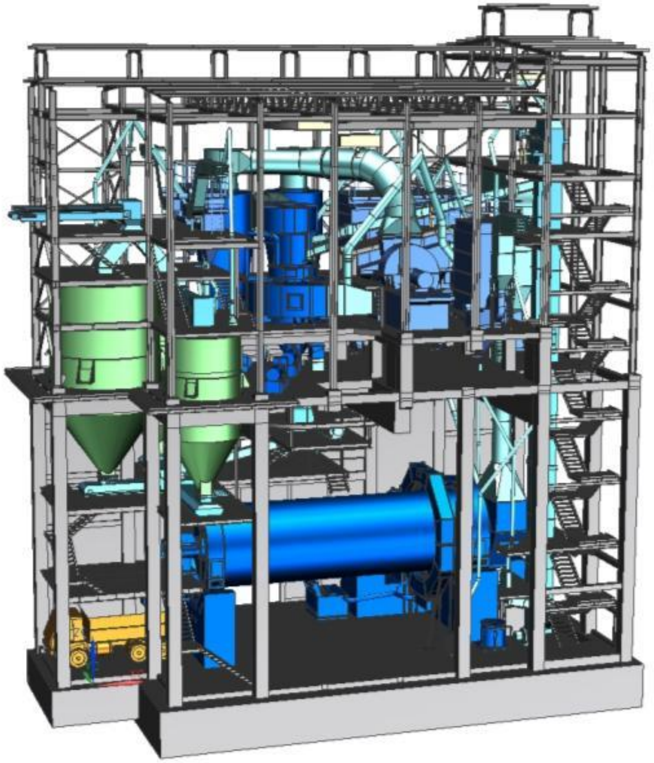
Product fineness



- **Grindability of a 95/5 OPC at various Blaine fineness:**
- 27-32 kWh/t at 3,000 cm²/g
- 39-47 kWh/t at 4,000 cm²/g
- 58-69 kWh/t at 5,000 cm²/g

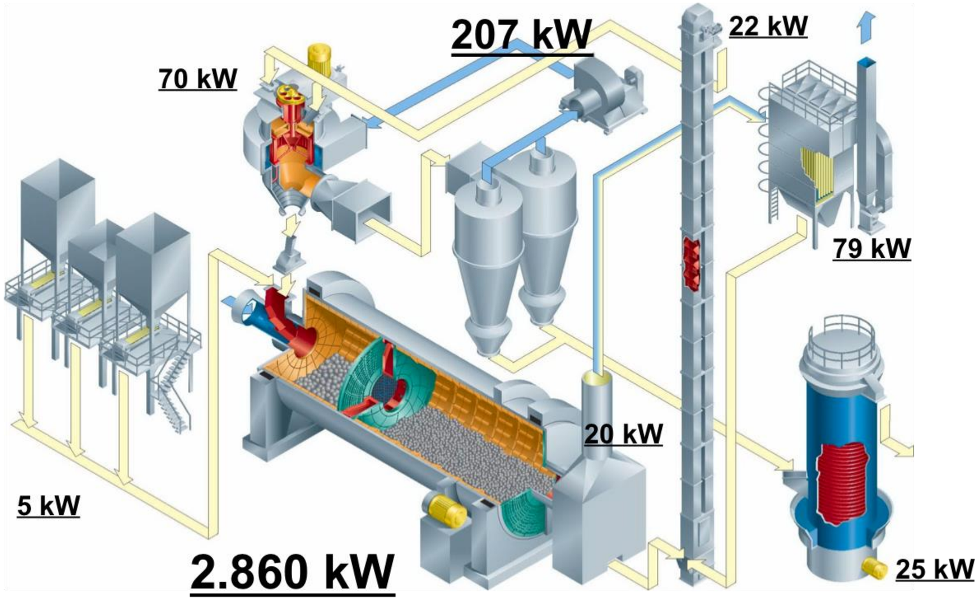
> ➢ The specific power consumption of open and closed circuit mill typically increases by 2-3 kWh/t for or 1-2 kWh/t respectively for every 100 cm²/g increase in the Blaine fineness

Plant engineering & design



- Mill performance is affected by the equipment design such as mill L/D ratio, speed, mill internals, separator, as well as ancillary equipment;
- Plant engineering and configuration, such as transport and control systems, safety protection, also play a role;
- “Minimum Design Approach” and standardization can reduce plant complexity for easier operation and maintenance as well as the TCO.

Reliability & efficiency of the mill is paramount



Example: a closed-circuit mill producing 104 t/h cement:

- Plant power consumption = 3,333 kW = 32.0 kWh/t
- Mill absorbed power = 27.5 kWh/t, or **85.8 %** of the total power consumed

Power absorbed by ball mills

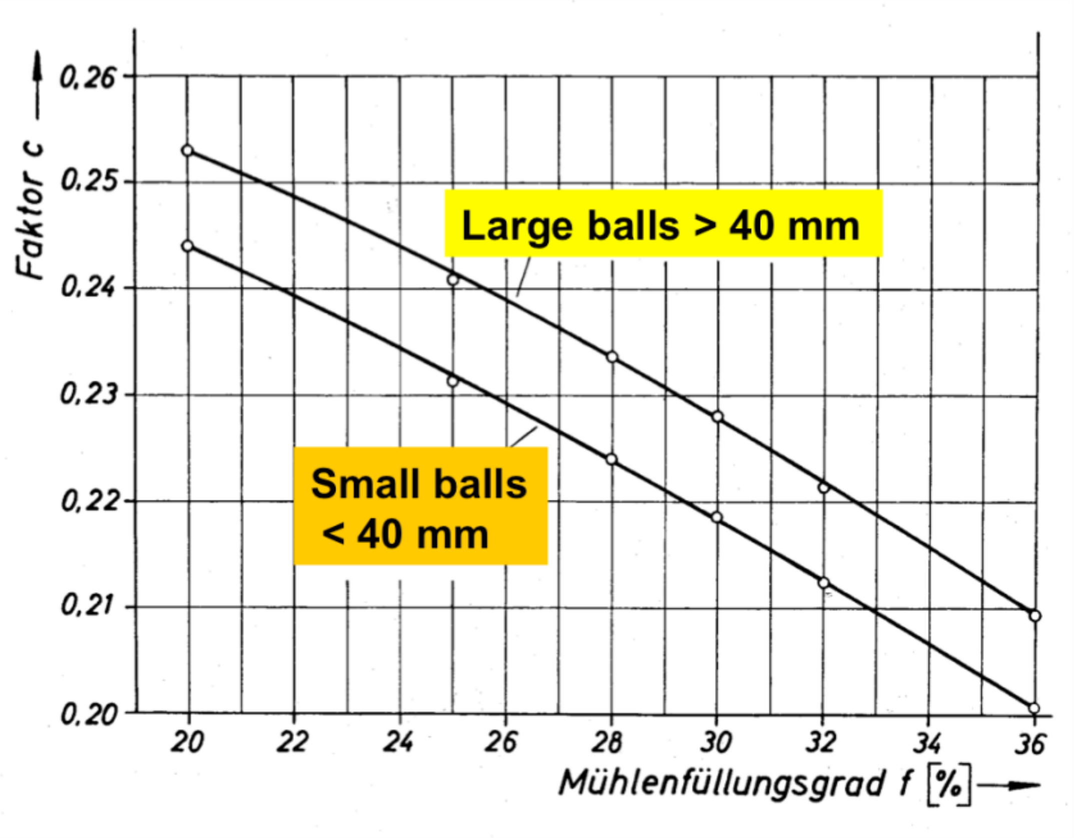
The power absorbed ($\mathbf{P_{ab}}$) by a ball mill depends solely on the physical parameters of the mill & is *independent of the mill throughput* or *material characteristics*, ie:

	$\mathbf{P_{ab}} = D_i \times A \times W \times n$	[kW]
Where	D_i = mill inside diameter	[m]
	A = power factor relating to the media size	[see next slide]
	W = mass grinding media	[t]
	n = mill rotation speed	[min^{-1}]

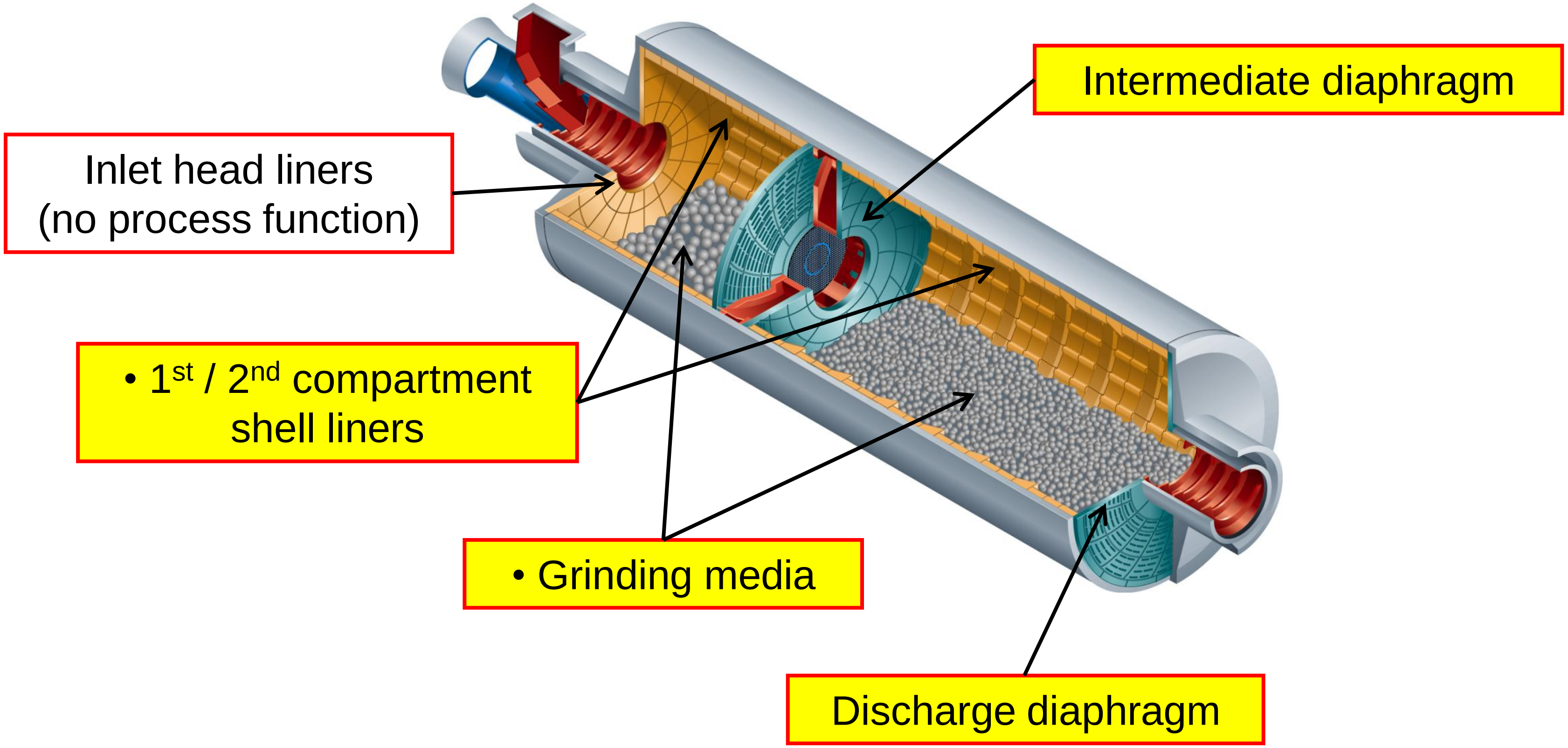
N.B. n usually lies in the range of 72-75% of the mill critical speed, which is related solely to the mill diameter, ie:

$$n_{crit} = \frac{42.305}{\sqrt{D_i}}$$

Power factor A depends on media size and filling %



Mill efficiency is determined by the internals



Efficiency of separator: comparison of 1st, 2nd & 3rd generation separators

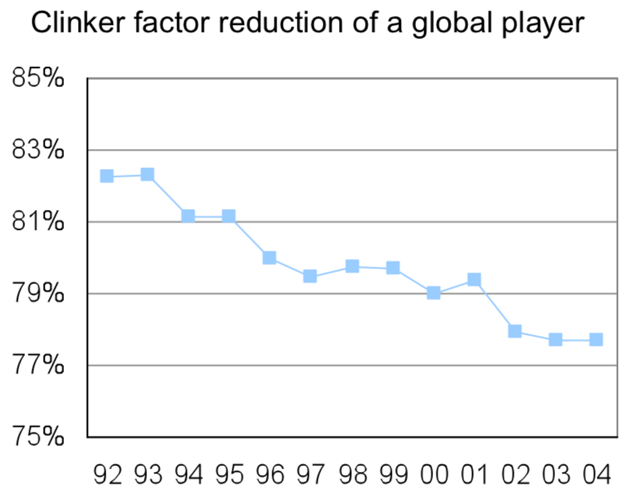
Generation	1st	2nd	3rd	QDK - Latest Design*
Bypass [%]	**30 - 60**	**10 - 35**	**8 - 20**	**4 - 10**
Min. Cut size [µm]	> 20	15 - 20	< 15	< 15
Imperfection [-]	> 0.50	0.35 - 0.50	< 0.4	< 0.35
Sharpness of cut	-	< 0.5	> 0.45	> 0.5
Max. Blaine [cm²/g]	3,800	4,500	≈ 5,500	≈ 6,000

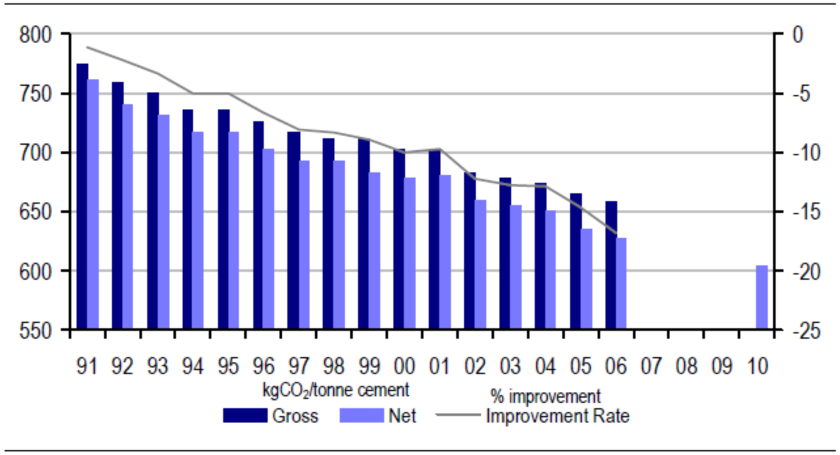
* Actual bypass depends on cement fineness

Note: **Imperfection:** $I = \frac{(x_{75} - x_{25})}{2 \cdot x_{50}}$ (< 0.35 for QDK latest)

Sharpness of cut: $x = \frac{x_{25}}{x_{75}}$ (> 0.5 for QDK latest)

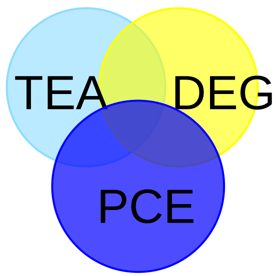
Use of additives (clinker extenders)

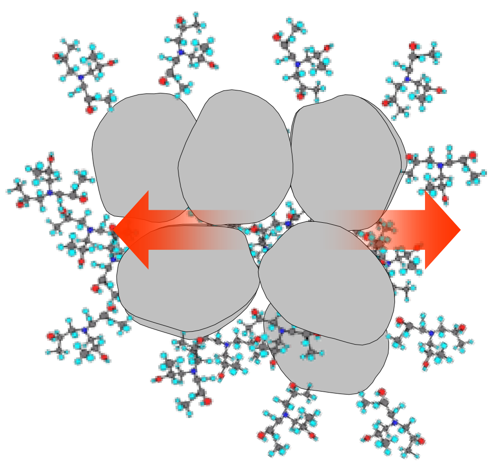




- Reducing clinker factor and use of additives such as limestone, slag, fly-ash & pozzolana can reduce energy consumption, CO_2 emission and production cost by as much as 50% or more.

Use of additives (clinker extenders)





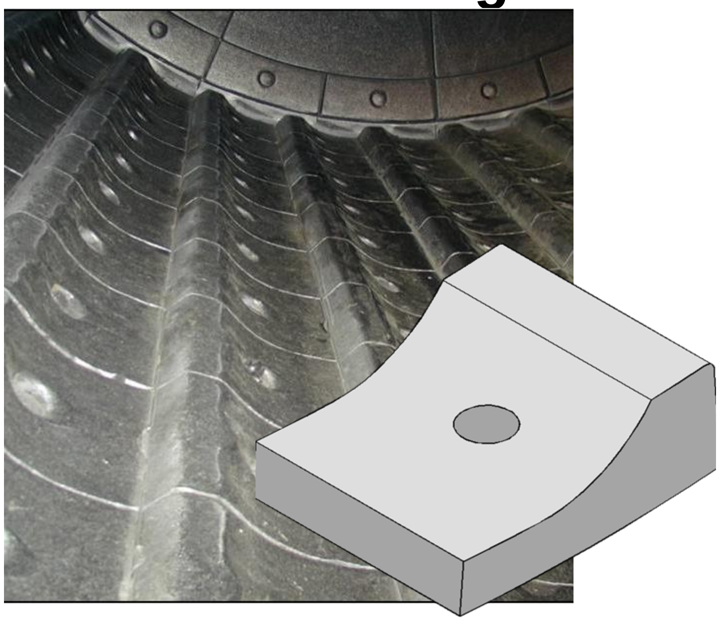
- Amine, glycol and polycarboxylate polymer (PCE) based grinding aids can reduce agglomeration / coating formation on media and liners by neutralizing the electrical charges formed on surfaces and cracks of the particles to improve grinding efficiency by 5-10%, or more esp for finer grinding, even at a low dosage rate of 0.02 – 0.05%.
- (N.B. early strength may be affected at higher dosage (> 0.2%)

Operations & maintenance

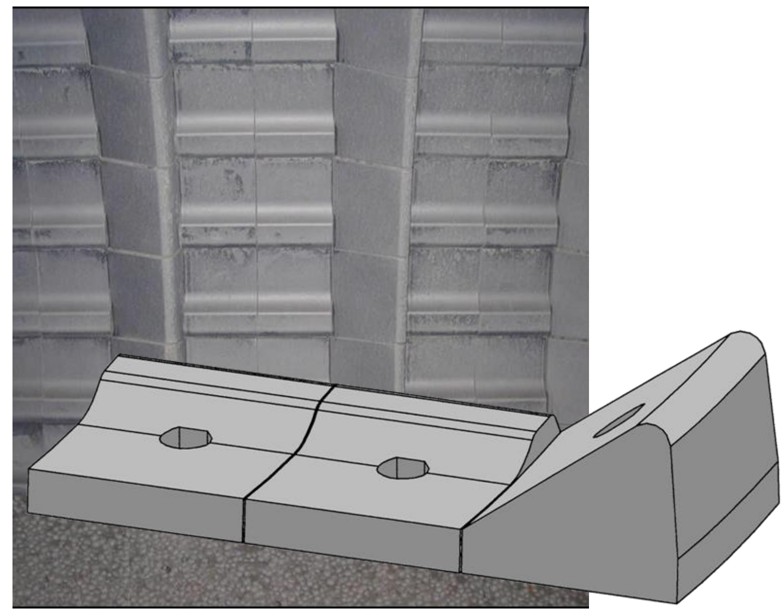
- **Skills & supervision**: operators' skills need refreshing / upgrading periodically and an daily monitoring & control system must be designed to motivate performance and not just for recording purpose;
- **Maintenance:** conditioning monitoring and planned maintenance are essential to ensure reliability / maximum plant availability;
- **Technical audit:** mill inspection and circuit analysis should be carried out periodically to provide early warning of changes in material characteristics or process condition for root-cause analysis and necessary corrective actions;
- **Bench-marking**: plant visits, cement periodicals, cement seminars and conferences can all provide opportunity for performance check and ideas for improvement**.**

Contents

Improving grinding energy conversion with CPB activator lining

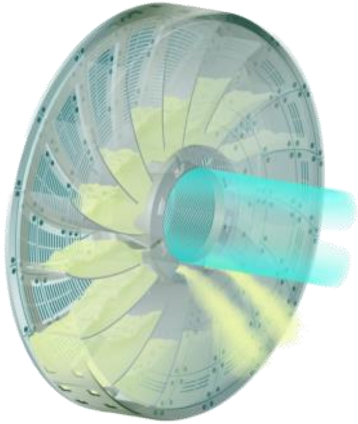


CPB progressive activator liners assures optimum media cataraction in 1st compartment throughout useful life



CPB classifying liners for optimum media cascading & classifying in 2nd compartment

Optimizing material level & particle size control with CPB intermediate diaphragm



- Highly reliable and sturdy CPB welded Monobloc® structure with “floating” fixation assures maintenance-free and long service life;
- The adjustable material flow control enables material level in the 1st compartment to be optimized;
- The rolled-steel slotted plates free from peening assure proper particle size control into the 2nd compartment throughout useful life;
- Large central opening and free slot area assure maximum ventilation;
- Mill performance typically improves by 5-7% and cement quality more consistent.

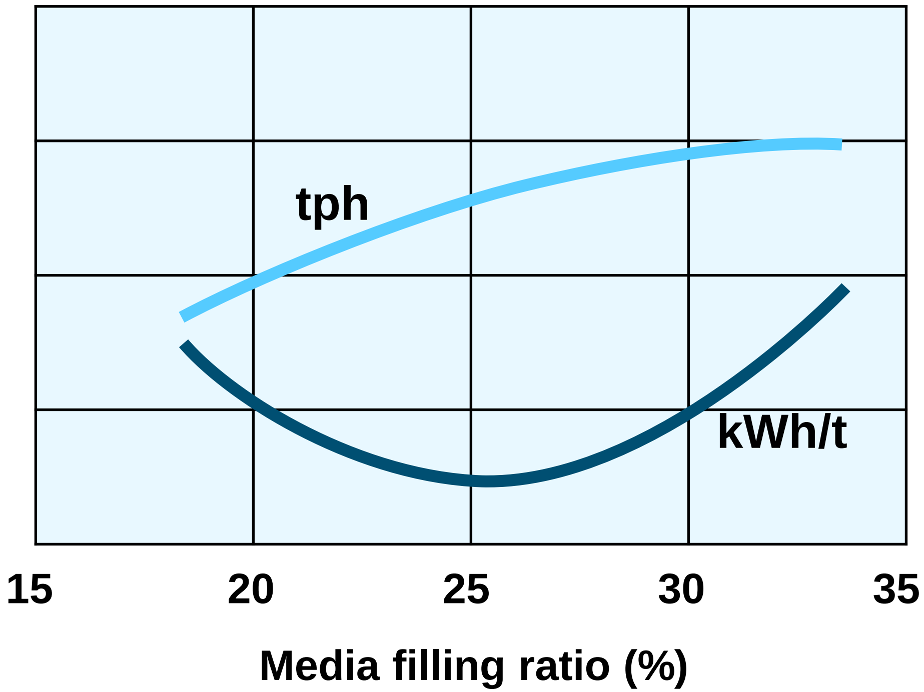
Optimizing media composition

- Bigger media with higher specific weight is required for higher impact and compressive force to grind coarser particles in the 1st compartment;
- Smaller media with higher specific grinding surface is required for shearing and attrition of finer particles in the 2nd compartment.

Guidelines for Closed circuit mill	Fineness (cm^2/g)	1st	2nd
Specific weight (g/pc)	**3,500** **5,000**	1,400 – 1,600 1,200 – 1,400	(50-60)
Sp surface area (m^2/t)	**3,500** **5,000**	(10±0.5)	32 - 36 38 – 40
Particle size at compartment outlet	**2,000-2,400** (separator inlet)	< 1% + 2.4 mm < 5% + 1.2 mm < 20% + 300µm	< 5% + 300µm < 10% + 90µm < 30% + 45µm

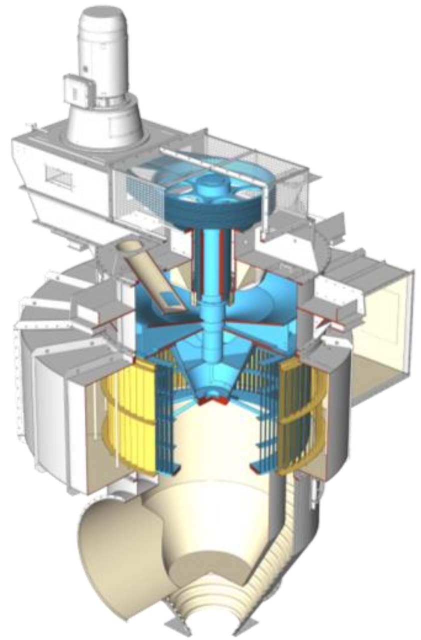
Optimizing media filling ratio

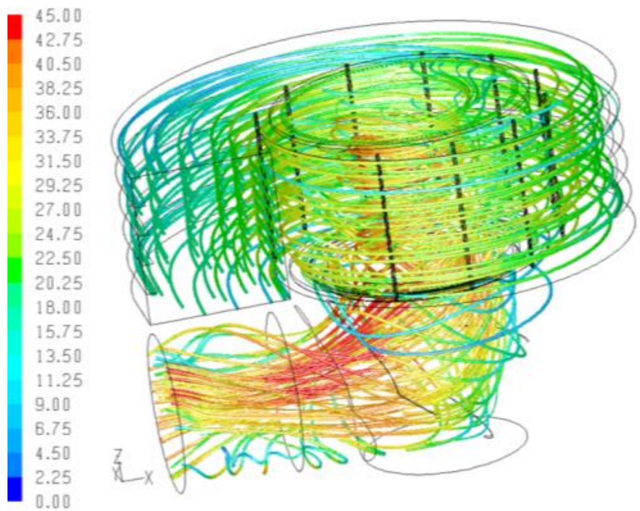
- Minimum mill specific power consumption at 24-26% filling ratio;
- Media should be lowered to this level if higher output is not required.

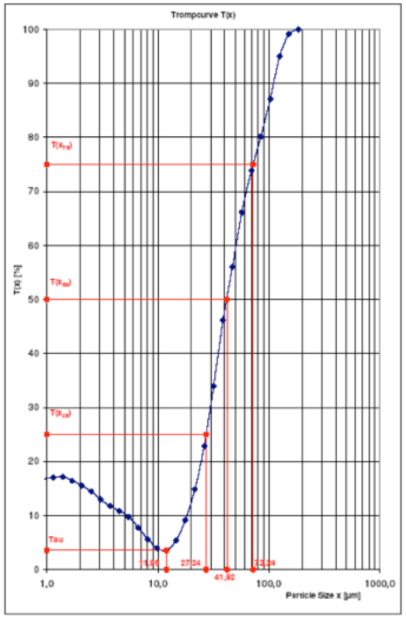


Upgrading separator efficiency with CPB Optitromp high efficiency separtors

- Aided by CFD modelling in the development, the latest CPB separator has an extremely low bypass of only 4-10% depending on the cement fineness.







Case Example 1: Liners replacement (2011)

Plant name (Country)	Leube Cement (Austria)
Cement mill type	2 compartment closed circuit mill, Ø 3,8 x 12,0 m
Scope of modifications	Installation of new 1st comp. Activator lining

Results		Before	After	Difference
Cement type		CEM II AM-SL 42.5N		
Fineness acc Blaine	[cm^2/g]	4,000		
Output	[t/h]	66.2	73.5	**+ 11%**
Power consumption	[kWh/t]	36.7	33.0	**- 10%**
Mill exit temperature	[° C]	95	95	

Case Example 2: Diaphragm replacement (2011)

Plant name (Country) Lafarge (Austria)

Cement mill type 2 compartment closed circuit mill, Ø 4.6 x 14.4 m

Scope of modifications Installation of new Flow Control Intermediate Diaphragm

Results		Before	After	Difference
Cement type		CEM II AM-SL 42,5N		
Fineness acc Blaine	[cm^2/g]	4.000		
Output	[t/h]	122	130	**+ 6.6%**
Power consumption	[kWh/t]	35.1	33.0	**- 6.0%**
Mill exit temperature	[° C]	115	110	**- 5**

Case Example 3: Mill internals upgrade (2012)

Plant name (Country) Heidelberg Cement (Romania)

Cement mill type 2 compartment closed circuit mill, Ø 4.2 x 10.77 m

Scope of modifications 1st & 2nd cpt lining + flow control intermediate diaphragm

Results		Before	After	Difference
Cement type		CEM II A-S 32.5R		
Fineness acc Blaine	[cm²/g]	3,200		
Output	[t/h]	69	81	**+ 17.4%**
Power consumption	[kWh/t]	34.6	29.6	**- 14.4%**

Case Example 4: Separator upgrade (2010)

Plant name (Country)	Phoenix Cement (Germany)
Cement mill type	2 compartment closed circuit mill, Ø 3.8 x 12.08 m
Scope of modifications	Replacement of 1st gen separator by CPB high efficiency QDK 143-Z

Results		Before	After	Difference
Cement type		CEM II A-CC 32,5R		
Fineness acc Blaine	[cm^2/g]	4,100	3,450	
Residue 63 µm	[%]	6.5 – 8.0	2 – 4.5	
Output	[t/h]	68	84	**+ 23.5%**
Power consumption	[kWh/t]	37	30.4	**- 17.8%**
Cement quality – 2 D	[N/mm^2]	24	25	**+ 1**
Cement quality – 28 D	[N/mm^2]	48	49	**+ 1**

Case Example 5: Closed circuit conversion (2012)

Plant name (Country)	Ivano Frankivsk (Ukraine)
Cement mill type	2 compartment mill, Ø 4.2 x 13.0 m
Scope of modifications	Installation of CPB high efficiency separator TGS 143-Z

Results		Before	After	Difference
Cement type		CEM II 32.5R		
Fineness acc Blaine	[cm^2/g]	3,100	3,000	
Residue 80 µm	[%]	7	2	
Output	[t/h]	100	118	**+ 18%**
Power consumption (mill only)	[kWh/t]	33.0	28.0	**- 15%**
Power consumption (whole circuit)	[kWh/t]	34.0	31.5	**- 7.4%**

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Case Example 6: New closed circuit mill (2010)

Plant name (Country) Wotan Cement (Germany)

Cement mill type 2 compartment closed circuit mill, Ø 4.4 x 14.0 m

Scope of modifications Complete grinding plant on EPC basis

Results		High fines cement types	
Cement type		CEM I 42.5 R	CEM III / A 42.5*
Fineness acc Blaine	[cm^2/g]	4,850	4,900
Output	[t/h]	73.5	64.5
Power consumption (mill only)	[kWh/t]	52.5	60.0
Power consumption (whole circuit)	[kWh/t]	61.0	70.0
Early strength (2 days)	[N/mm^2]	35.0	21.5

Case Example 7: Biggest ball mill in Europe (2012)

Plant name (Country)	Heidelberg Cement (Poland)
Cement mill type	2 compartment closed circuit mill, Ø 5.2 x 16.75 m
Scope of modifications	Complete grinding plant on EP basis

Results		For
Cement type		CEM I 42.5R
Fineness acc Blaine	[cm^2/g]	3.400
Output	[t/h]	236
Power consumption (mill only)	[kWh/t]	30.5
Power consumption (whole circuit)	[kWh/t]	34.2

5. Conclusions

➢ There are basically 3 cement mill systems in operation and ball mill is by far the most prevalent due to its reliability, simplicity, flexibility, ease of operations and maintenance, generally more acceptable cement quality, as well as often offering the lowest TCO;

➢ Vertical roller mills is technically more energy efficient but due to its operational sensitivity, lower reliability, higher investment and maintenance costs, actual energy saving is often lower and the TCO less attractive, cement quality can also be an issue in some markets;

➢ For existing ball mill, energy improvement is possible by adopting well-designed mill internals such as the CPB activator liners and Monobloc® flow control diaphragms, and upgrading the separator to the highly efficient CPB Optitromp separators.

Any question or comment?

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