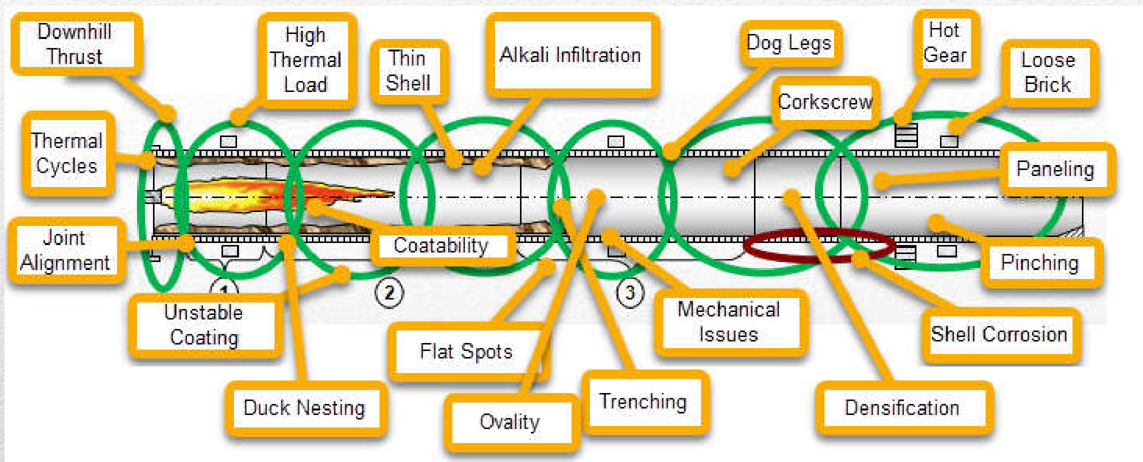
Refractory

Failures and Analysis



October 17, 2025
IEEE Process Training
Lancaster, CA

failure Analysis

AI for Failure Analysis

After exhaustive internet and AI searches to discover the "secrets" of refractory failures, very little useful information was obtained. The information was either very vague, extremely process specific or complicated with calculus formulas and derivatives. Most reported failure mechanisms were related to test procedures which do not even remotely mimic industrial furnace conditions.

failure Analysis

Failure Analysis is critically important to achieve continuous improvement, reliability and "value". "Value" = Reliability.

It is important to remember that the refractory has likely experienced many damaging mechanisms. Unless the failure is pure chemical attack, usually some additional process insight along with recent kiln history is needed to translate the damage seen into usable information about the prevailing cause of the damage.

Refractory Failure

- **“Hey Boss....uh... I think we have a problem!”**

- **Don’t make this call!**

DECEASED PRODUCTION DUE TO REFRACTORY	Repair Costs	Decreased Production Rate	Days at decreased Production	Decreased Production Lost Profit		Days Down	Production Profit Loss	Additional Fuel		Annual Totals
Brick Failure	$180,000.00					5	$500,000.00	$70,000.00		**$750,000.00**
Nose Ring Refractory / Casting Failure	$40,000.00					3	$300,000.00	$55,000.00		**$395,000.00**
Kiln Shell Hot Spot	$120,000.00									New Production Manager

Small Brick Replacement +$1M.

TOday's Agenda

Most Refractory Failure and Post Mortem Analyses are rarely correct or lead to actionable conclusions.

The Goal today is to provide some insights of the various ways to consider failures.

- Part 1 - Material Property Failures
- Part 2 - Brick Failures from Process and Mechanical Issues
- Part 3 - Major Causes of (Monolithic) Failures

Much of this information is just common sense but never properly explained.

Part 1 - Material Properties

#	Topic	Time (hr)	Sponsor
5	**Properties of the Bricks** • Different starndards (ISO, DIN, ASTM) • Mechanical • Thermal • Chemical • Thermo-mechanical • Technical sheet of bricks (how to read) • Test post mortem	1.5	Krosaki
6	**Brick Lab test** • CCS • Bulk density • Porosity • Pyrometric cone • Refractorinss under load • Thermal expansion • Thermal shock resistance • Alkali attack o Heat transfer, Chemistry of the brick	1.5	Krosaki
7	**Brick Installation** • Equipment and tools to use • Importance of good ilumination into the	2	HWI

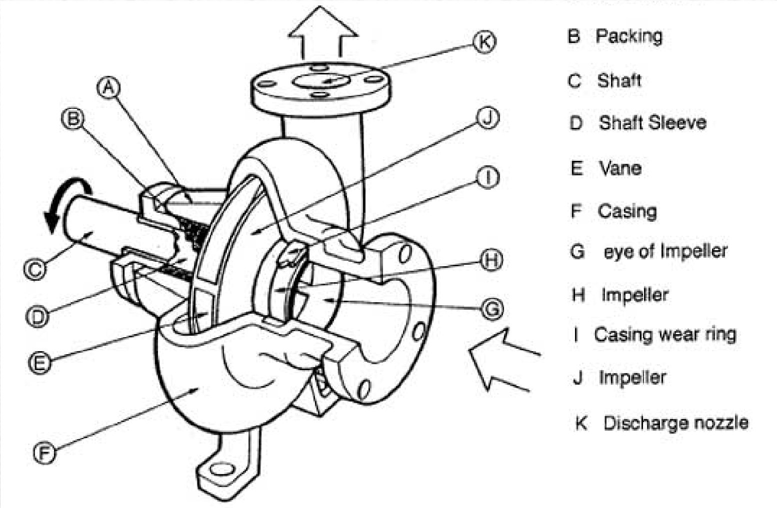
Boring!!

Datasheet considerations

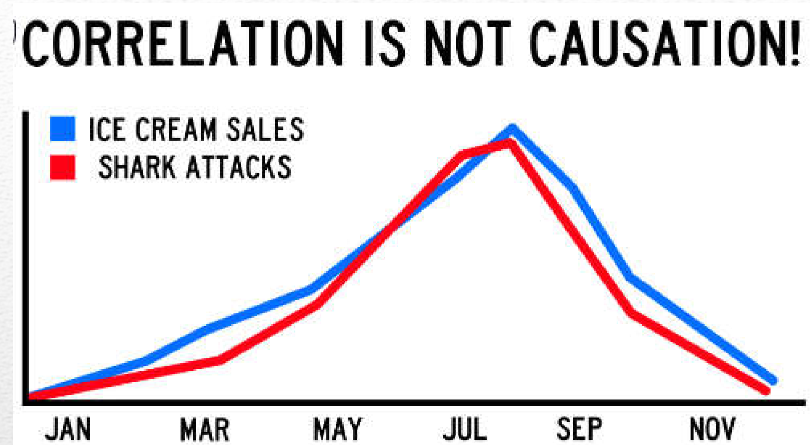
Datasheets, in general, are supposed to help make informed (engineering) decisions about the best fit of a product for a given application.

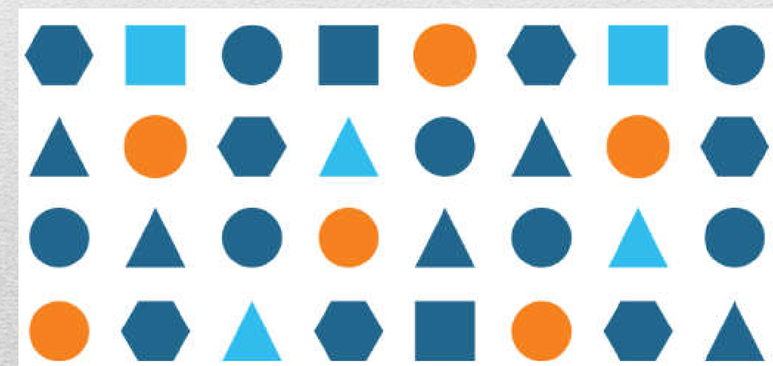
We have all been led to believe that somehow these datasheets are important as they are included in most sales discussions and the topic of many refractory informational seminars and books.

However, refractory datasheets are quite the opposite and only add confusion to the decision-making process and in almost every instance will not offer any clues how it will actually perform in service, how it will compare to similar products or even justify post-mortem poor performance.



Datasheets are not science. Datasheets are only standard lab test results while science is discovering the causation between data and effects. Before causation can be established a correlation (systematic pattern) between two variables must be established, but still a correlation is not science and does not prove causation. Data on a typical refractory datasheet has not been correlated to its performance, except in very specific (easy) applications like "abrasion" for high wear areas in a refinery. So, for most applications there is nothing scientific about datasheets and very little insight that can be derived from them.





Datasheet considerations

Abrasion Resistance

- Dolomite 3.5–4
- Lime (CaO) - 3.5
- Calcite (CaCO3)- 3
- Aragonite (CaCO3) 3.5 - 4
- Clay or shale - 3 - 5.5
- Iron Slag - 5.5
- Alite - 4.5
- Belite - 6
- Quartz (SiO2) - 7
- Clinker - 7

What might appear as "abrasion" to refractory is usually alkali attack and thermal cycles.

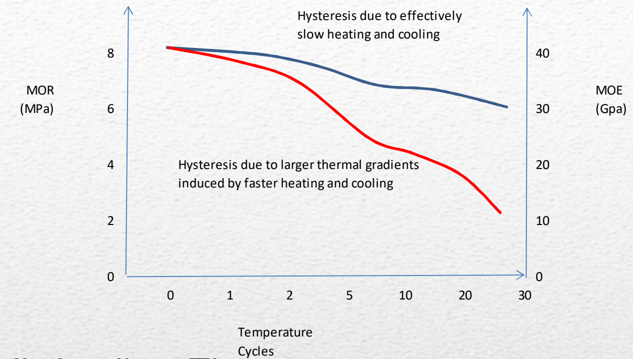
Minerals, Metals and Refractory	Hardness Scale		
	Mohs'	Vickers	Kroop
Diamond	**10**	**10000**	**7000**
Silicon Carbide	9.5		
Tungsten Carbide	9.3		
Titanium Carbide	9.3		
Corundum 99.5 Al2O3	**9**	**2500**	**1800**
Fused Alumina	9		
Boron Carbide	9		
Silicon Nitride	8.5		
Topaz (Al Si F)	**8**	**1500**	**1250**
Cubic Zirconia	8		
Spinel, Zircon	7.7		
Hardened Steel, Tungsten	7.7		
Emerald (Be Al Si)	7.7		
Mullite	7.5		
Alumina-Silicates	7.2		
Quartz Silica	**7**	**1000**	**825**
Forsterite, Cordierite	7		
Cement Clinker	7		
Acid Brick	6.8		
Copper Slag	6.7		
Zircon, Glass, Fused Silica, Silicon	6.5		
Porcelain	6.5		
Titania	6.3		
Apatite (Ca P, Fl), Orthoclase (K Al Si)	**6**	**750**	**700**
Magnesia (MgO) Magnetite (Fe3O4)	6		
Steel Slag	5.5		
Feldspar	**5**	**600**	**500**
Zirconium, Carbon, Cobalt	5		
Tooth Enamel	5		
Iron, Nickel, Steel	4.2		
Fluorite (CaF)	**4**	**250**	**450**
Limestone (CaCO3)	**3**	**90**	**250**
Copper	3		
Silver, Gold, Aluminium	2.7		
Gypsum (CaSO4)	**2**	**17**	**150**
Boron Nitride			
Graphite	2		
Lead, Tin	1.5		
Talc (Mg Si)	**1**	**7**	**20**

Abrasion Resistance

It is important to realize that abrasion loss numbers are meaningless unless abrasion and alkali resistance are evaluated together. Alkali-corrosion products can quickly decrease the physical properties of many refractories and especially the apparent abrasion resistance at the surface. For example, an Alkali-Resistant Firebrick (20 cc loss) will likely hold up better than a high-alumina, cement-based castable (6 cc loss) in high Alkali environments such as a TA Duct due to this corrosion attack.

Hysteresis

Hysteresis refers to a change in the physical property(ies) of a material that has been exposed to any type of stress or work over a period of time. Hysteresis is irreversible and cumulative. Refractories can experience hysteresis when physical load, thermal gradient, thermal shock, or creep are applied as the “stress” and each can “dampen” the strength, strain and/or elasticity of the material upon release of the “stress”.



Fatigue - Refractories are susceptible to premature fatigue failure under cyclic loading. The characteristics of cyclic fatigue in refractory appear to be quite different to metal fatigue. Under cyclic loads, the repetitive opening and closing of the crack results in a decrease in the toughening and strength.

Ratcheting - Refers to a non-reversible process that causes some of the components within the refractory to change dimension. Ratcheting is usually the direct effect of cyclic conditions of temperature, stress or atmosphere (oxidation/reduction) or a combination of these conditions. For example, Iron absorption into MgO. Ratcheting is an additive effect and compounds the effects of hysteresis shown above.

“Redox” reactions that involve the oxidation and reduction of Iron Oxides.

StrengtH - CCS - MOR

Most end-users assume that the Cold Crushing Strength (CCS) implies that all the other refractory strength properties such as Abrasion Loss, MOR, Hot MOR, RUL will also be "better". Although there are good correlations that this exists, we will learn that these "strength" values have no predictive value as to how the refractory will perform.

It is a fallacy (for most applications) **that higher refractory strengths lead to longer service life.**

In fact, the opposite may be true because as the strength related properties generally increase, the Modulus of Elasticity also increases making the refractory more susceptible to brittle failure mechanisms and a main cause of refractory wear…hysteresis.

Strength / MOE		Low Strength High MOE	High Strength High MOE	Low Strength Low MOE	High Strength Low MOE
Cold Crush Strength	MPa	50	100	50	100
Young's Modulus	MPa	20000	20000	8000	8000
		2.5	**5**	**6.25**	**12.5**
		WORST			BEST

StrengtH - CCS

Rhetoric - It is a fallacy (for most applications) that higher refractory strengths lead to longer service life. Cold Crushing Strength is the most misleading refractory property and (beyond a certain minimum threshold) cannot be used as any indication of a refractory performance.

95% of uninformed end users will make product (brand) selection based on Strength. Vendors know this and may tend to skew the published data.

In fact the opposite may be true because as the strength related properties increase the Modulus of Elasticity also increases making the refractory more susceptible to brittle failure mechanisms.

Strength/MOE Ratio is Important!

Electrocast	CCS	100	MPa	14500	psi
Estimated	MOE	90	GPa	13050000	psi
Strength / MOE Ratio		**1.11**			
Fused Silica Castable	CCS	50	MPa	7250	psi
Estimated MOE	MOE	30	GPa	4350000	psi
Strength / MOE Ratio		**1.67**			

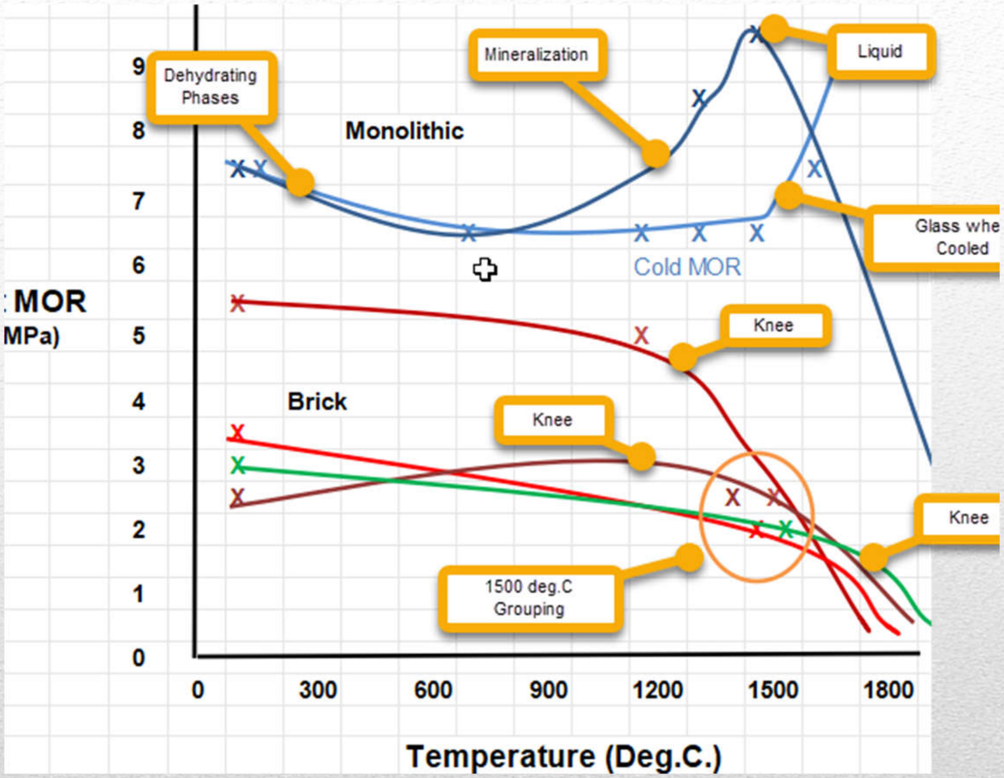
Super-Dupper High-Strength Castable. Sucked after 2 months!!!

MOR

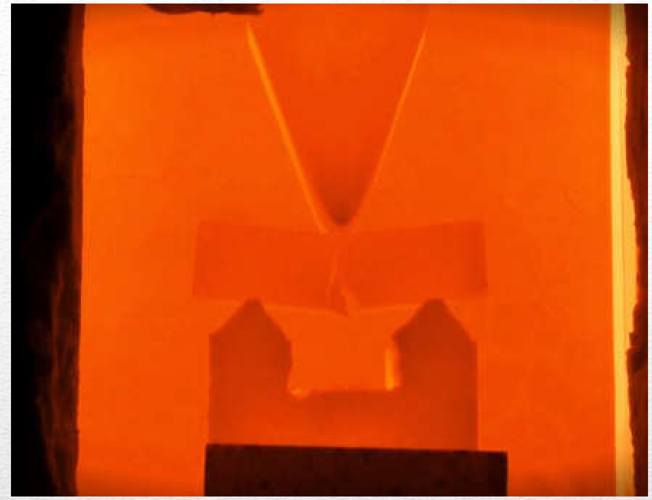
The Modulus of Rupture (MOR) is thought to be a better strength indicator of performance since refractories are extremely strong in compression and weak in tension and therefore more likely to fail in this mode. Many think the MOR mimic the actual failure mechanisms better than CCS, as it is related to fracture mechanics and crack propagation. This might be true for a few limited mechanical interference examples such as anchors, support shelves or other macro thermo-mechanical issues but these are not generally a main refractory failure mechanism.

Most refractory damage and hysteresis results from shear and tensile stresses created from forces internal to the refractory. These internal stresses are likely huge in comparison to the tested strength values of the refractory. Listed below are the actual damage mechanisms with the more common general analysis terms.

- Shear from process infiltration (Infiltration)
- Shear from corrosion mechanisms (Alkali Attack)
- Shear from changes in the thermal gradient (Thermal Cycles)
- Shear from un-restrained expansion (Lack of Compression)
- Shear from differential expansion between grain and aggregate (Mix Design)
- Shear from aggregate debonding (Compression Related)
- Shear from thermal gradients (Temperature Differential)
- Tensile induced behind hot face compression (Fast Heat Up, Lack of Expansion)
- Tensile from rapid cooling of hot face (Fast Cool Down)

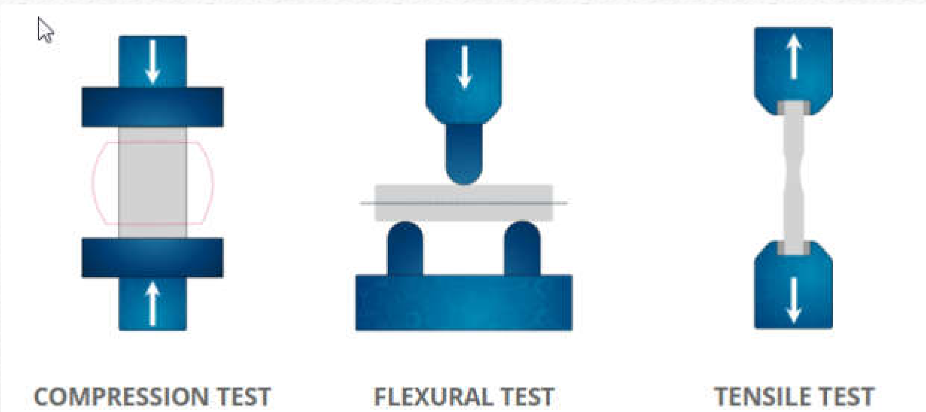


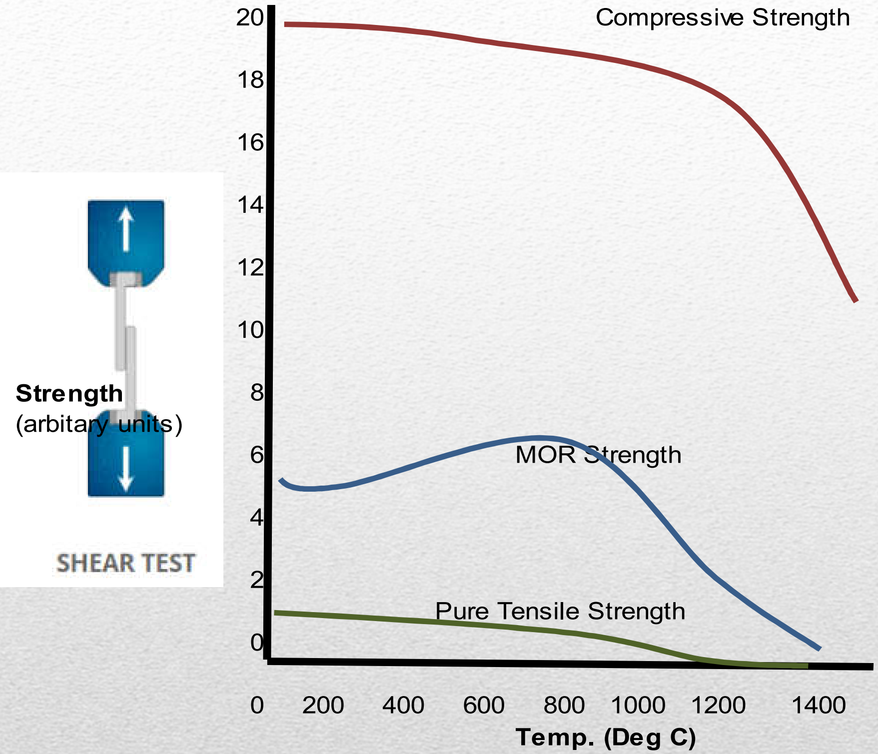
MOR
MPa)
9
8
7
6
5
4
3
2
1
0
Dehydrating Phases
Mineralization
Liquid
Monolithic
Glass whe Cooled
Cold MOR
Knee
Brick
Knee
Knee
1500 deg.C Grouping
0
300
600
900
1200
1500
1800
Temperature (Deg.C.)



Strength vs. Temperature

MOR





Porosity

Porosity is thought to be a "necessary evil" in refractory products as it is well documented that as porosity increases, strength decreases and it increases the refractory surface area that is exposed to the process. Porosity also allows the brick to become penetrated by process liquids and gases. This in effect reduces the "apparent" porosity (densification) and has complex implications in corrosive environments.

However, porosity also plays an important role of stopping the propagation of cracks and thus reducing stress induced damage to the refractory. This means brick with too low of porosity would shatter within a few thermal cycles.

Good Mean Pore Size obtained with optimum manufacturing

Density (Gr / cm3)	3,25
porosity (%)	4.3
CCS (N / mm2)	169.7

Mean Pore Size / Permeability

The mean pore size of of brick is strongly associated with permeability. With the decrease of the mean pore size, the permeability is reduced. The alkali attack test also verified that refractories with lower permeability had better alkali corrosion resistance, because the penetration of K vapor into the materials could be restricted effectively.

Most important is **Mean Pore Size** - Optimum should be < 12 microns. Conventional basis brick where >25 microns is common.

Mortar can have 2-3 time more porosity and 20 times the permeability of Brick. Careful selection is needed if attempting to combating corrosion.

Chemical Analysis - Alumina

Rhetroic - Higher Alumina = Better Performance

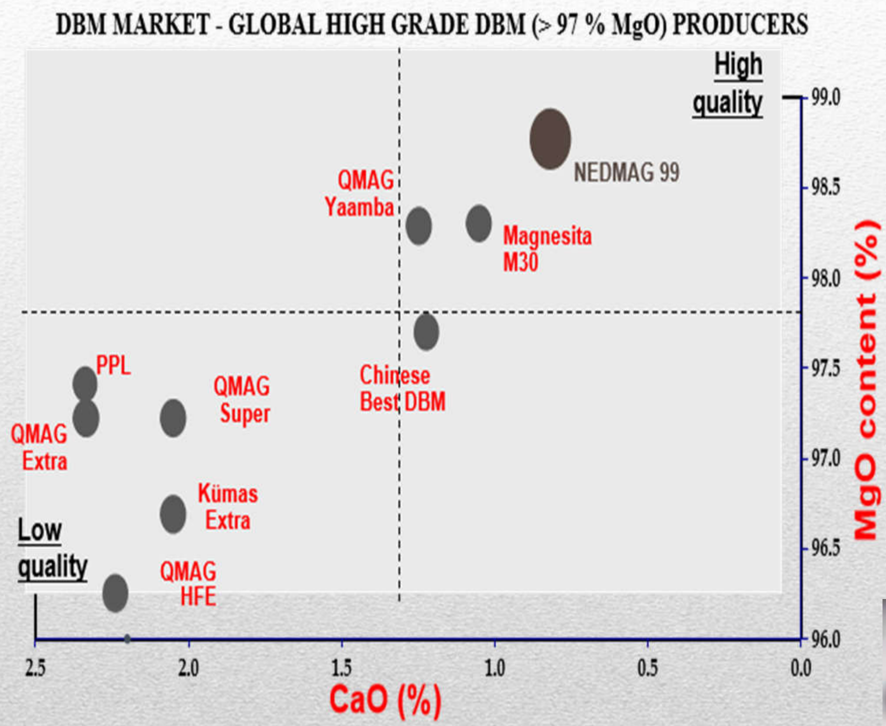
Quality of Alumina Brick

- Mineralogy not Chemical Content
- Quality of Raw Materials
- Quality of Manufacturing

Value Calculations - Unit Prices vs. Expected Service Life - Annualized Cost How to Justify to Purchasing

Mineralogy	Alumina Content	Relative Grain Cost	Expansion Coefficient	Relative Performance	Relative Alkali Resistance	Relative Shock Resistance	Infiltration/ Buildup Resistance
Tabular / Fused Alumina	99	2.30	4.6	Very Good	Good	Good	OK
Guyana Bauxite	89	1.50	3.8	Very Good	Good	Poor	OK
China Bauxite	88	0.90	3.8	OK	Poor	Poor	Poor
Pure Mullite	72	3.00	2.6	Excellent	Excellent	Excellent	OK
Mullite "Calcines"	70	1.05	2.8	Good	OK	Very Good	OK
Andalusite	61	1.15	2.6	Very Good	Very Good	Very Good	OK
Mullite "Calcines"	60	0.80	2.9	Good	OK	Good	OK
Mullite "Calcines"	47	0.70	3.0	Good	Fair	Good	OK
Calcined Fire Clay (Chamotte)	42	0.40	3.2	Fair	Fair	Fair	Poor
Flint Clay	30	0.30	3.0	Fair	Good	Poor	Poor
Fused Silica	0	1.25	0.2	Very Good	Excellent	Excellent	Good
Zircon Additives	0	2.80	3.0	Excellent	Excellent	Excellent	Excellent
Silicon Carbide Additives	0	2.40	2.4	Excellent	Excellent	Excellent	Excellent

Chemical Analysis - Basic



Sintered Tabular Spinel - Best for Bonding to Matrix, Lower MoE, Better Shock Resistance, Coating Adhearence,
Best Purity. Nice white grains in brick structure.

Fused Spinel - Slightly Better Liquid Phase Corrosion Resistance at about 7-9% increased brick price.

Bauxite (Sintered or Fused) Spinel - Lower cost, low Purity. Darker Gray/Brown Grains in brick structure.

High Iron Spinels (Hercynite / Pleonastic Spinel) - Cheap so more profit (beware "CF" and "Q" series designations). Black Grains in brick structure.

	1	2	3	4	5	6	7	8	9	10
Abrasion Resistance			▲							
Cold Crushing Strength		▲								
Modulus of Rupture		▲								
Hot MOR		▲								
Refractory Under Load			▲							
Creep		▲								
Erosion Resistance	▲									
Impact Resistance	▲									
Stainless Needle Effects		▲								
Thermal Conductivity			▲							
Density		▲								
Porosity					▲					
Permeability / Mean Pore Size								▲		
Thermal Expansion				▲						
Permanent Linear Change	▲									
Thermal Shock							▲			
Chemical Analysis		▲								
Mineralogy Analysis										▲
Alkali/Slag Resistance								▲		
Refractoriness (Orton Cone)	▲									
Modulus of Elasticity									▲	
Brand Name / Description									▲	

Not usually available or confidential (Permeability / Mean Pore Size)

There is a huge need for a standardize test (Alkali/Slag Resistance)

Can be obtained (Mineralogy Analysis)

Never available. Too many testing variables (Modulus of Elasticity)

Might be the most useful thing on the entire datasheet (Brand Name / Description)

Datasheet considerations

What is Important??

Data Sheet Comparison

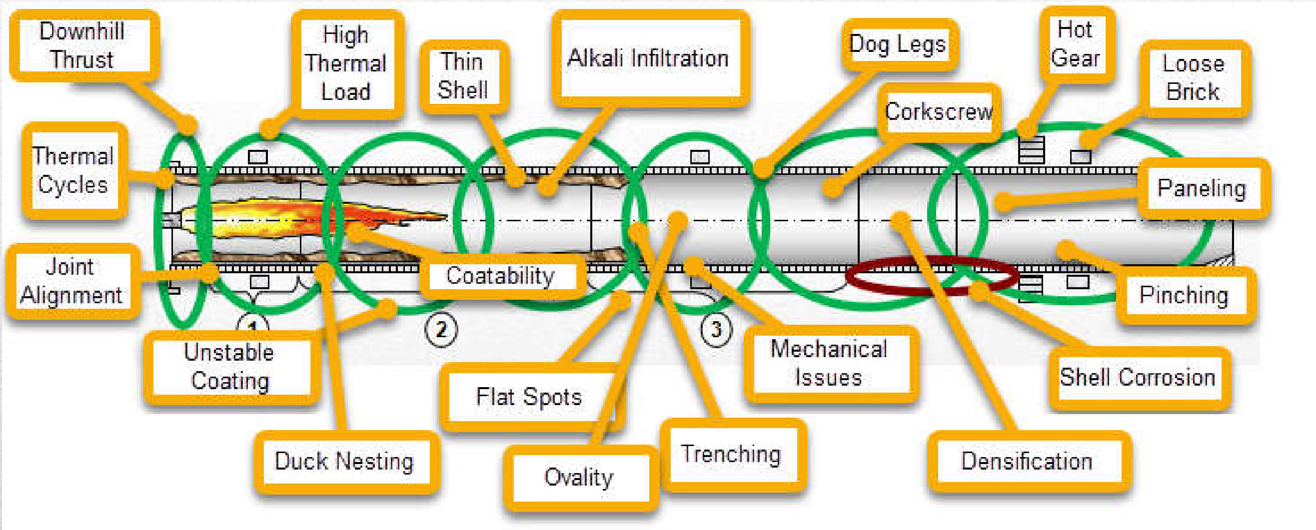
Engineers want to be able make conclusions or patterns from data...however.....

Only Useful (available) Data

Density (for material takeoff)
Water Requirements (for installation)
Brand Name / Description
Justify to Management

Use extreme care using datasheets for product selection or upgrades, failure analysis or any type of engineering data (for modeling)

Process / Mechanical Failures - Part 2



Installation Failures ?

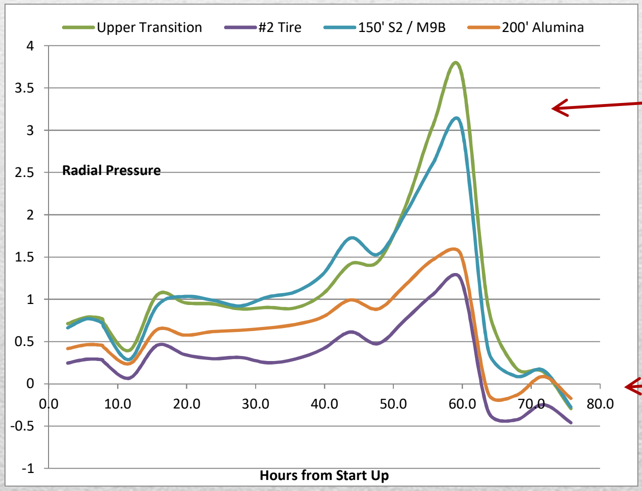
Slack Linings

Shell Expansion is greater than the Brick Expansion

Aligned Joints, Twisting, Spiraling, Out-of-Square, Walking out brick, Loose Rings, Open Joints

Always during Cool Down Periods

Rhetoric -
Poor Installation / Shimming

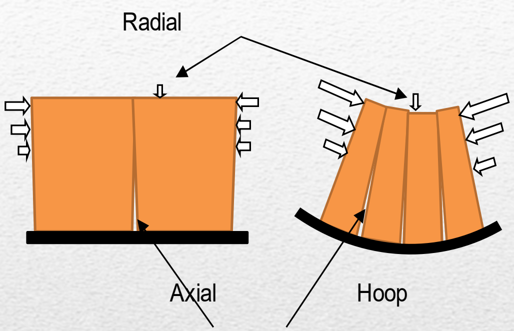


Actual Cool-Down after Cooler Steam Spall. 350 C/Hour!

Negative Radial Pressure - Slack
1mm / meter
4m diameter kiln = 12.5mm slack (10 shims)

SLACK LININGS

These issues can be related to the thermo-mechanical conditions that exist during cool-down periods and low temperature holds (hotface in the 550-850°F. range). As the brick begins cool, the compressive forces that hold the brick together and exerts radial pressure to the shell begins to decrease.



The shell expands more than the cold face of the refractory causing gaps between brick. The location and size of the arrows attempts to show the location and magnitude of typical stresses.

English $x10^{-6}$ F°	Metric $x10^{-6}$ C°	% @1000 C°	in/ft @1832 F°	Composition
0.3	0.4	0.039	1/64	Fused Silica
1.3	2.3	0.229	1/32	Cordierite
2.2	4.0	0.388		Wood / Nitride Bonded SiC
2.4	4.3	0.423		Self-Bonded SiC
2.6	4.7	0.459	1/16	2600 IFB
2.8	5.0	0.494		Mullite / 2000 and 2300 IFB
2.9	5.2	0.512		Super Duty
3.0	5.4	0.529		Zircon Andalucite
3.2	5.8	0.564	5/64	60% alumina / 2800 IFB
3.4	6.1	0.600		70% alumina / 3000 IFB
3.6	6.5	0.635		80% alumina / Concrete
3.8	6.8	0.670		85% alumina
4.0	7.2	0.706	3/32	
4.2	7.6	0.741		90% alumina / 3300 IFB
4.4	7.9	0.776		
4.6	8.3	0.811	7/64	99% alumina
4.8	8.6	0.847		Chrome Ore / Chrome
5.0	9.0	0.882		Mag-Al Spinel Brick
5.3	9.5	0.935	1/8	Stab. Zirconia
6.0	10.8	1.058		Chrome Mag
6.3	11.3	1.111		Mag Chrome
6.5	11.7	1.147	5/32	Silica / Carbon Steel
7.0	12.6	1.235		Insulating Silica
7.7	13.9	1.358	3/16	92% MgO / Forestite Bonded MgO
8.3	14.9	1.464		Periclase / Fused MgO
9.0	16.2	1.588	7/32	
9.5	17.1	1.676		Stainless Steel

About 5-8 shims required after cold turning for a new lining

Slack Linings

THRESHOLD TEMPERATURES

The calculation of the actual temperature that the brick become loose (slack) is difficult and based on many perimeters including:

- Hot face Temperature
- Ambient/Shell Temperatures
- Lining Thickness
- Brick Heat Capacity and Thermal Conductivity
- Amount of Coating/Buildup
- Cooling Air Temperatures
- Localized Cooling Rate and Air Velocity (Draft related)
- Feed/Clinker Retained
- Turning and Indexing Procedure

Based on the expansion of the brick and steel shell, "slack" will occur when the shell temperature is about 50% (alumina) / 75% (basic) of hot face temperature. Alumina much more susceptible.

"Negative" radial pressure is not developed in the lining however once the radial pressure drops below zero, the amount of "slack" in the brick lining begins to increase. (The hot face temperature is not the thermonuclear reading at the Feed End but rather the localized temperature at the Lower Transition brick face).

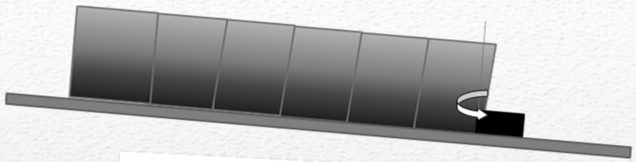
Slack Linings

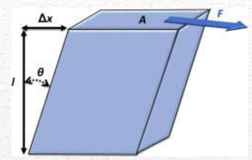
The following conditions make brick more prone to indexing failures:

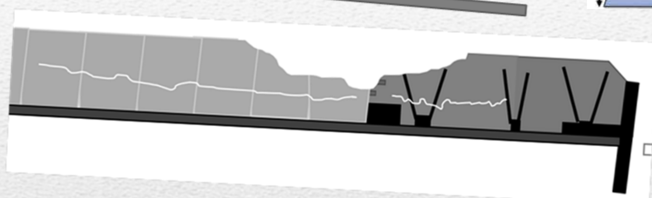
- Brick in the areas of high ovality or mechanical damage (dog-leg or flat spots) Alumina brick will be more susceptible to cooling indexing damage due to lower expansion coefficient. (Basic brick will suffer more damage from heating effects).
- Fairly new (thicker) linings are <u>much more susceptible</u> to Indexing failures than worn linings. Once the kiln has reached full operating temperature for a reasonable amount of time the brick tend to become more thermo-mechanically stable.
- Extremely thin lining will lose Radial Pressure at a quick rate and are also prone to failure.
- Densified brick resulting in higher shell temperature
- Brick rings with a few newly spalled faces
- Non-smooth surfaces within the Kiln such as muck out door, metal underlayments, rough weld seams, retaining rings, etc. Will further aggravate the effects of "slack" conditions.

Use Shell Cooling Fans Wisely!!

Downhill Thrust







$$G \stackrel{\text{def}}{=} \frac{\tau_{xy}}{\gamma_{xy}} = \frac{F/A}{\Delta x / l} = \frac{Fl}{A \Delta x}$$

Mechanics of Downhill Thrust

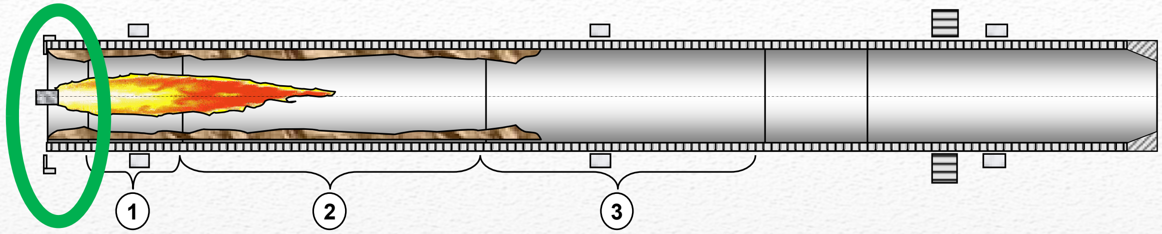
The kiln discharge end is extremely critical because the internal kiln temperatures can be difficult to control and can change extremely fast during an upset or shutdown condition due to cold air influx. This presents conditions when the brick are loose (slack) within the kiln shell and if the kiln is rotated, this allows the brick to slide down the angle of inclination. The displaced brick combined with the effects of Themal Expansion cause “Downhill Thrust”.

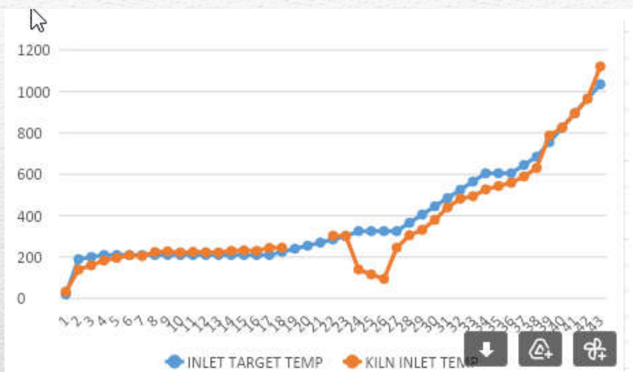
Rhetoric -
Its a “Crushing” Problem
Use Higher Strength Brick
Use Mortar
Use Different Shaped Brick
Use Different Shaped Retainer
Use More Expansion

Other “Solutions” Blah Blah Blah.

Downhill Thrust

Cyclic Conditions





Clicker Temp = 2500°F - Secondary Air Temp = 1800°F= 700°F Cycle

4 revs/min x 60 min/hour x 24 hour/day x 320 days =

1,800,000 Revolutions/Campaign x 700°F Shock / Cycle

Thermal (Mechanical) Load

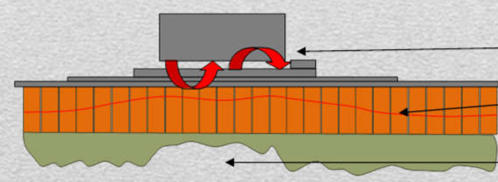
Hotter Burning to Lower Free Lime and Increase Clinker Quality
Hotter Burning due to new Burner Technologies
Low Radiance / Mixed Fuels - Natural Gas
Thin / No / Unstable Coating
No Tower = More Heat Input into Kiln

Hottest Area for Brick Exposure - Minimal Coating Protection

High Thermal Load

Brick
Liquid Phase Penetration into Brick
Brick Properties Change - Above typical property "knee" temperature
Higher Thermo-Mechanical Stresses - **Creep**

Process Issues
Glassy Coating / Fire Polishing
Higher Shell Temperatures
Shell Trumpeting
Heat Effecting #1 Tire
Downhill Thrust / Axial Expansion



Thermal (Mechanical) Load

Issues with Natural Gas

- A Natural Gas flame ignites earlier, releases intense heat and sharper burning characteristics but also has a lower radiant intensity and poor transfer of heat that may affect the clinker quality.
- Natural Gas is a colder flame and normally burns further down the kiln. The refractory zoning may need to be moved uphill (approximately 10 feet) to compensate.
- Burner Pipe alignment is critical. Because of the different shaped flame the Burner Pipe may get aligned too close to the load. Sometime the refractory protective re-circulation zone may not be existent and increases refractory wear.
- Consistent Gas Pressure may be difficult.
- The lack of sulfur in Natural Gas is generally assumed to be a benefit and can result in a decrease in Kiln rings. However the Sulfur/Alkali ratio must still be optimized to avoid alkali related refractory issues.
- Coal that can have around 14-20% ash. This ash generally becomes incorporated into the feed and represents a loss of about 2-3% clinker production.
- When the ash is removed with the use of Natural Gas it necessitates a change in the kiln feed composition changes to optimize the burning characteristics of the mix. Typically the C3S must be adjusted or raw material additions are required to optimize clinker chemistry.
- Natural Gas does not burn well with the Burner Pipes designed for Low NOx burning of solid (Coal/Coke) fuels. For example, limited swirl and limited primary air may tend to burn better. If it is to be utilized exclusively for an extended period of time, it may be viable to invest in a specialized Gas Burner.
- Due to the combustion efficiency of Natural Gas the expected clinker production will likely decrease by around 5% when the BTU input and other factors are consistent. Sometimes this results in an attempt to increase production and further increase the thermal load.
- Water is a product of combustion for Natural Gas but not Coal. The formation of moisture accounts for some of the combustion efficiency and the increased Water Vapor in the system can also have a negative effect on some of the monolithic containing refractories.

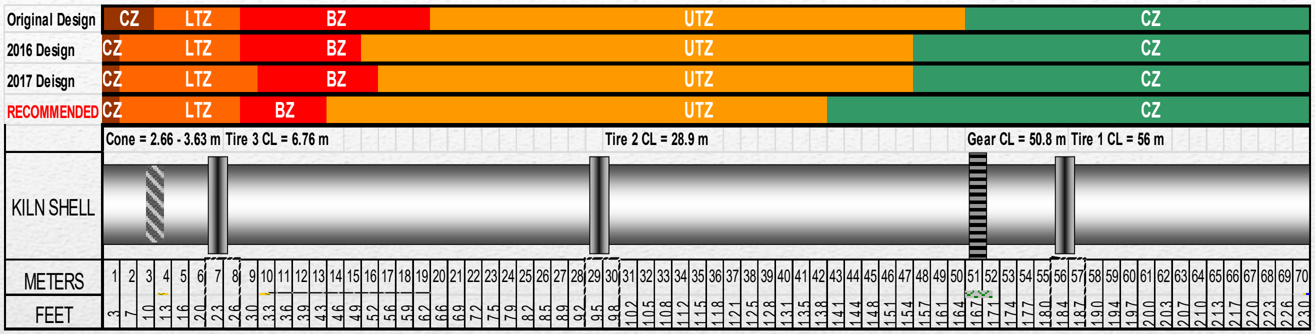
Thermo Chemical Attack

Residual thickness (mm)	±101 coating	101-90 ss_{hf}	90-75	75-30	30-5	5-0 c.f.	material c.f.
periclase (M)	++ (brick)	++++	++++	++++	++++	++++	+ (brick)
spinel (MA)	-	++	++	++	++	++	-
belite (C_2S)	++++	-	-	-	±	±	-
merwinite (C_3MS_2)	-	-	-	±	±	±	-
monticellite (CMS)	-	±	±	±	-	-	-
forsterite (M_2S)	-	±	±	-	-	-	-
alite (C_3S)	+++	-	-	-	-	-	-
brownmillerite (C_4AF)	+	-	-	-	-	-	-
C_3A	+	-	-	-	-	-	-
mayenite ($C_{12}A_7$)	+	-	-	-	-	-	-
sylvine (KCl)	~1 %	~1 %	~1 %	2-4 %	~1 %	1-3 %	-
anhydrite ($CaSO_4$)	-	~1 %	~1 %	1-3 %	~1 %	1-3 %	10-15 %
langbeinite[1)]	-	-	-	2-4 %	?	-	-
magnetite (Fe_3O_4)	-	-	-	-	-	+	++++
pyrite (FeS_2)	-	-	-	-	-	+	++
$CaMg0_{12}S_3$	-	-	-	-	-	+	-

Chlorides (Cl)
Alkali (Na and K)
Sulfur (S)
FUELS / FUEL CHANGES

Thermo-Chemical Attack increases exponentially with temperature

Zoning

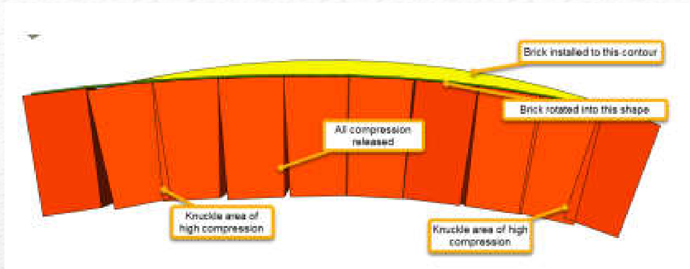


Must Optimize Burning Zone with Changes in Process

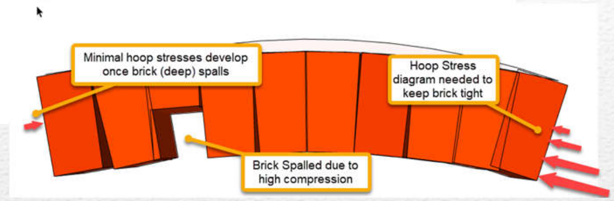
Dolomite - Good Coatability but Poor Corrosion/Shock Resistance and Logistic / Installation Issues

Iron Rich - Deep Liquid Phase Penetration - Deep Capping

Consider Straight run of High-Quality Spinel



"knuckle" refers to areas of change of slope in the kiln shell.



BRICK OVER TIRE

622			622	
622	622	622	622	322
322	622	622	622	622
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TYPICAL

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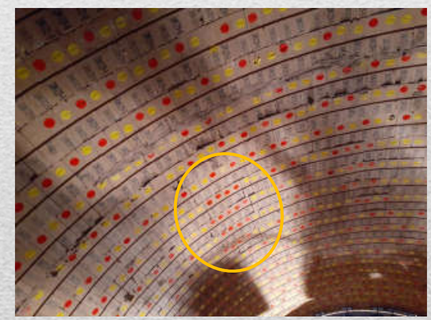
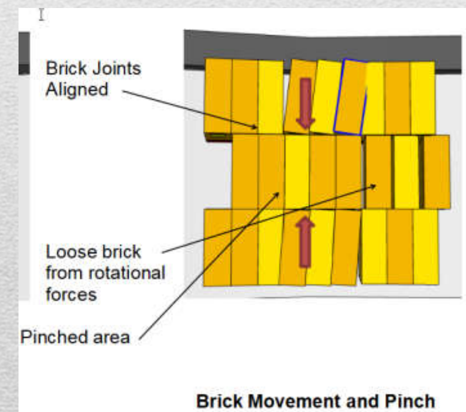


Flat Spots / Slack

Pinching/ Slack

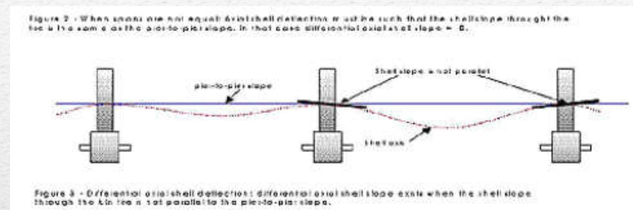
The “pinched” brick stopped movement of the loose brick and they consolidated in the clockwise direction that the kiln turns. This caused the slack area to occur just uphill of the pinched / damaged area and resulted in enough gap for the brick to slide when indexed in a slack condition. It was noted that all the walked out brick were random and not associated with the key-up section.

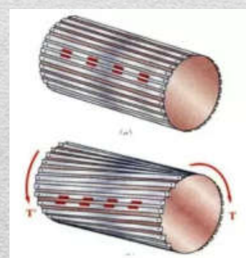


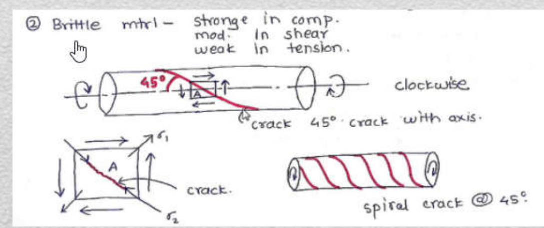
Scale, Manways, Welds, Flat Spots

CORKSCREW / OUT OF OUT-OF-

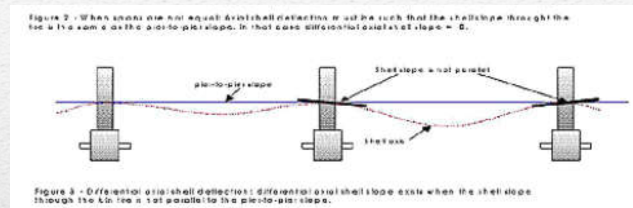
OUT-OF-SQUARE

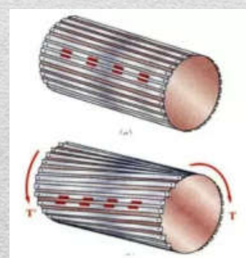


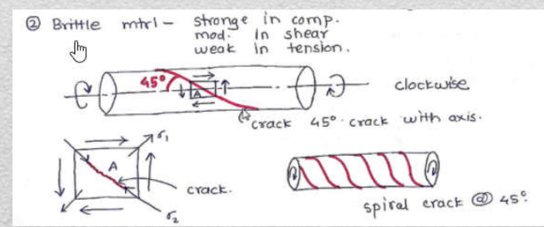


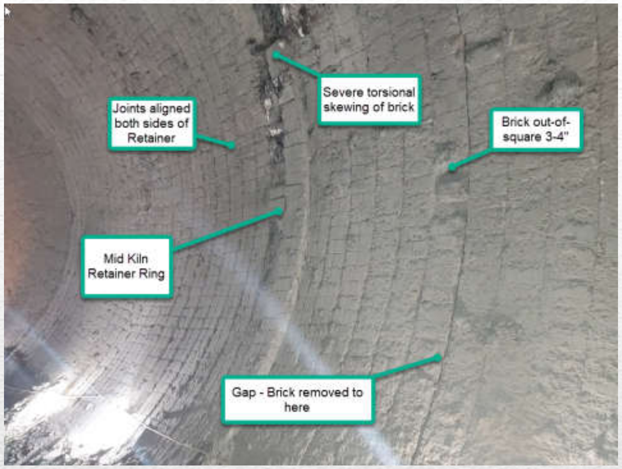


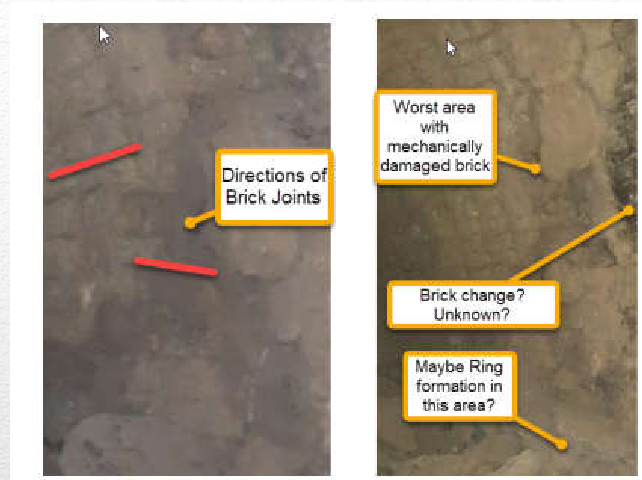
Corkscrew / Out of Square









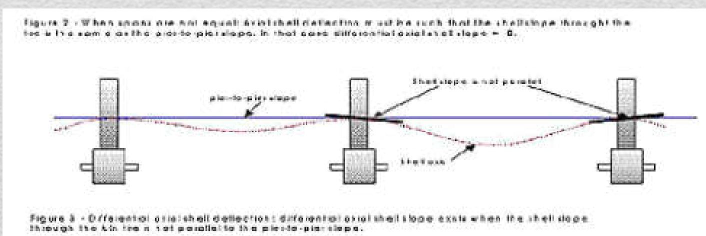


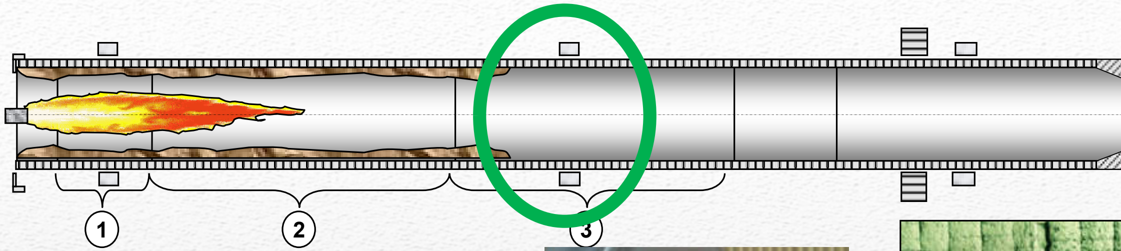
Corkscrew / Out of Square

Trenching

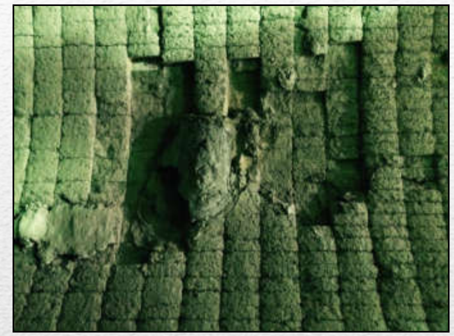
Shimming can add a lot of additional stress to the brick and (if over-shimmed) can result in spalled faces, broken brick and residual stresses that metastasis as "trenching". This is especially true when the key zone has created "open joints" on the brick heel which concentrates even more stress on the face when a shim is installed. A 3rd Key Shape can help resolve this.

Trenching also becomes more pronounced in brick brands with high Modulus of Elasticity (more brittle) which is typical with some specific brands of Burning Zone brick. The procedure to mortar on either side of the key up zone can be used to alleviate this. Of course the shims should be spread out over a large area to help mitigate the residual stresses in the brick.



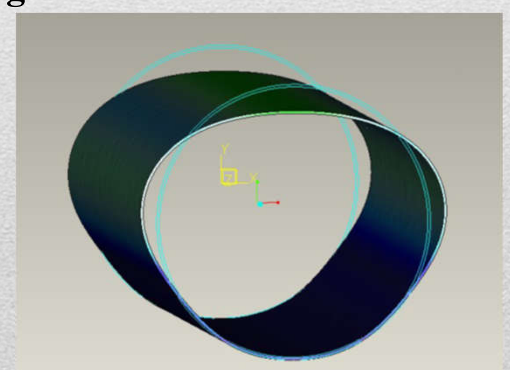


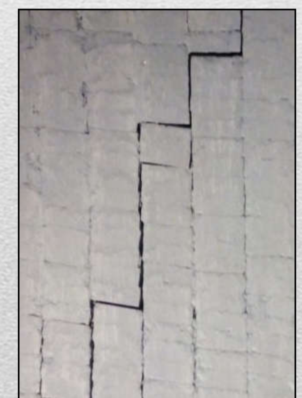
Ovality

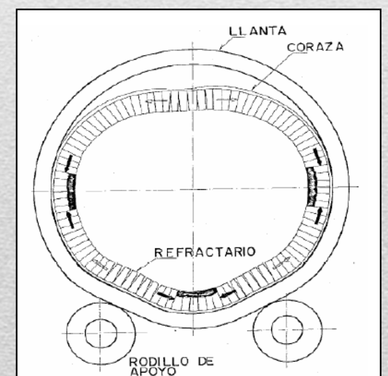


Identify the leading causes of damage

- **Ovality / Slack Conditions**
- **Dog Legs**

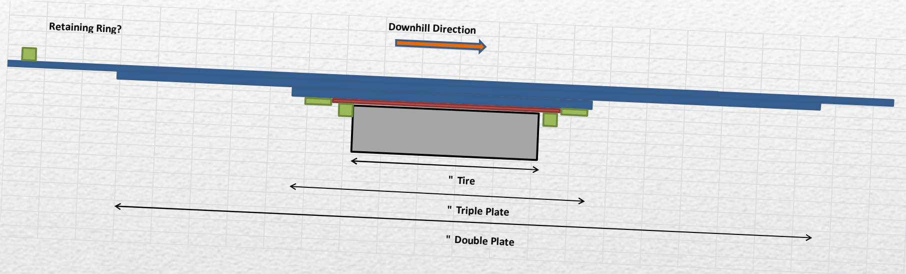


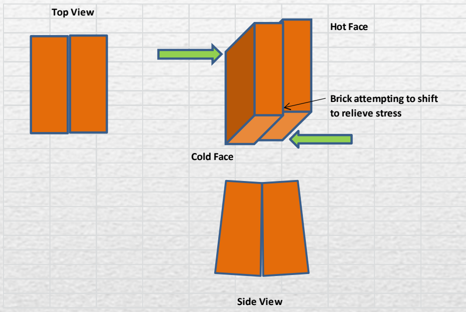




Dog Legs

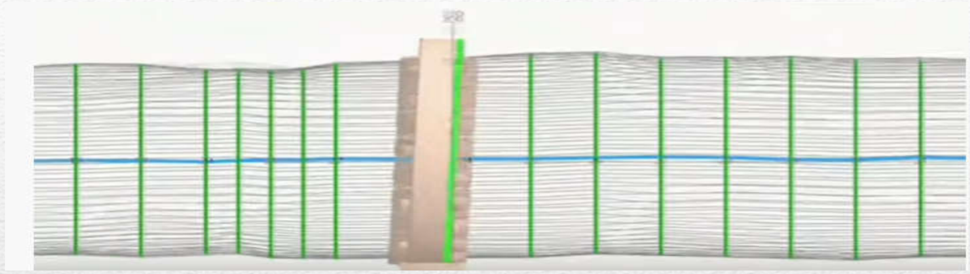
Kiln "Dog-Leg" Crank typically happen near the transition of steel thicknesses.

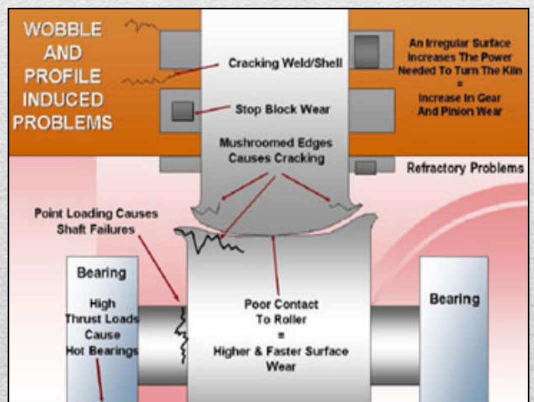




Kiln Cranks cause huge shear stress in the brick during each rotation x 5000 rotation/day. This causes the brick to attempt to shift position (become out-of-square) relative to the Shell. New brick lining are more susceptible as they have yet to fully conform to the shell.

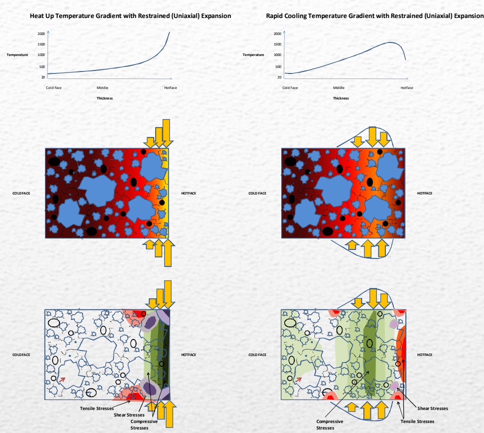
Wobble / Cantilever

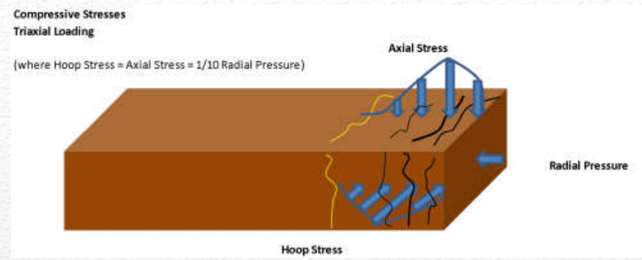


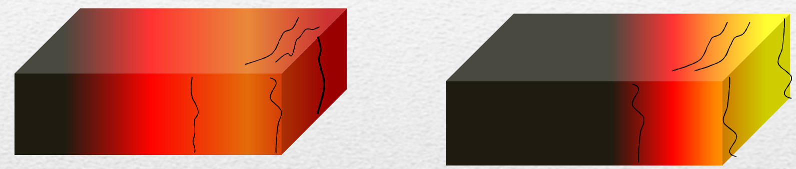


Heel Damage

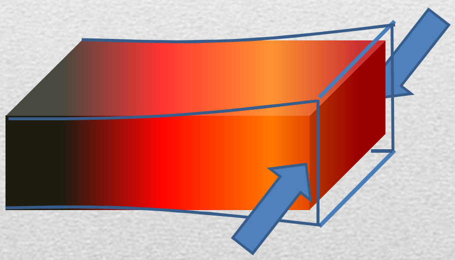
Damage appears on the "heel" of the brick against the shell. Typically the heel in has almost no stress loading due to the thermo-mechanical interaction of the shell and refractory. In an ideal situation the heel will have no axial stresses, no hoop stresses and only a few pounds of radial stress. This brick has clearly been exposed to thousands of pound of pressure (shear) to damage brick. This is typical of Dog Leg failures.



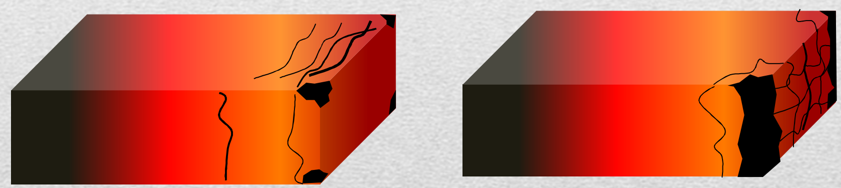


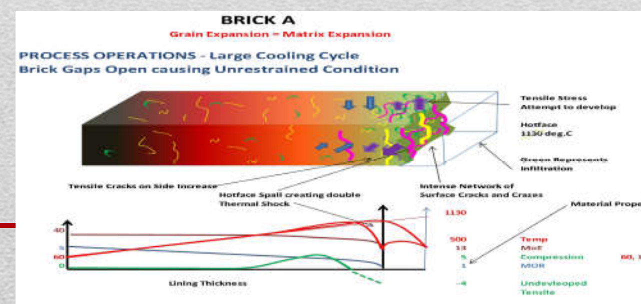


Expansion Effects of Possion's Ratio
Uniaxially Restrained Sample

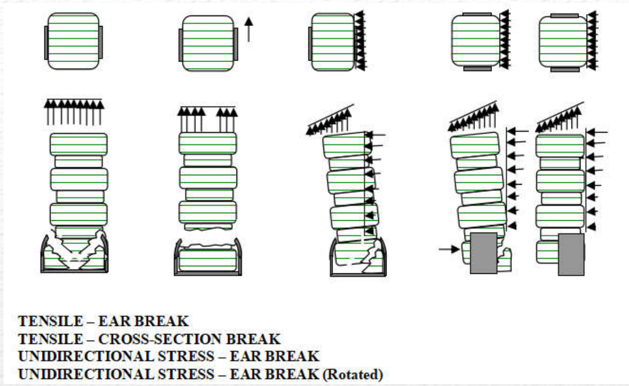


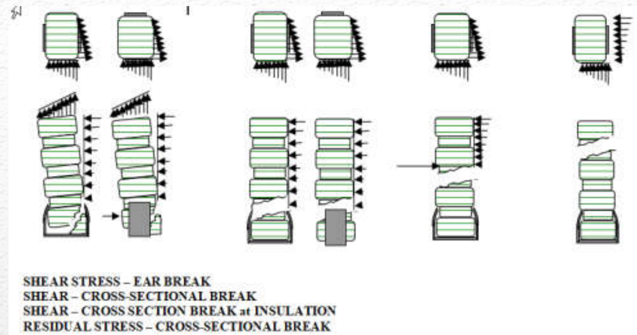
Resulting Damage of
Uniaxial Compressive Forces

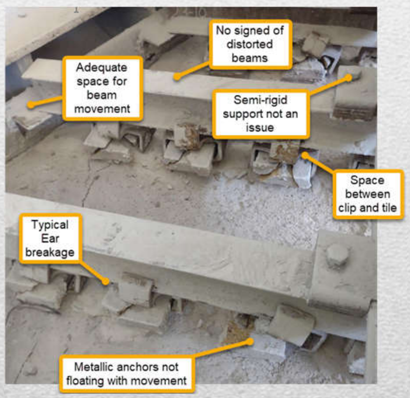


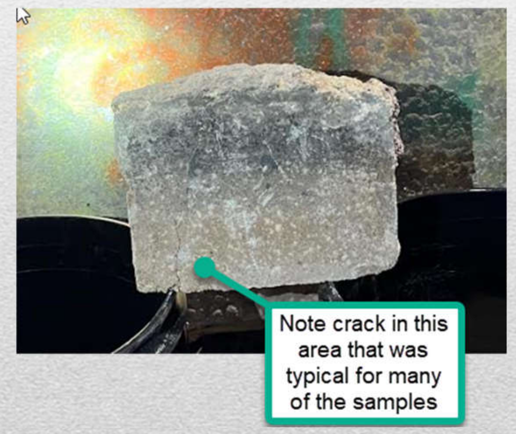


Stress Induced Cracking







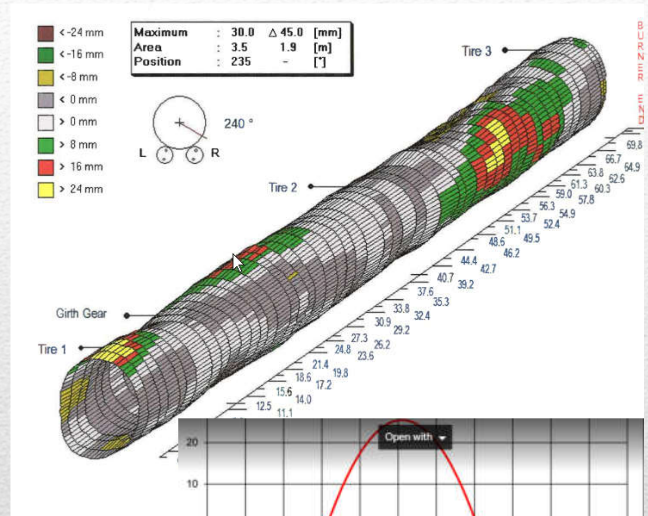


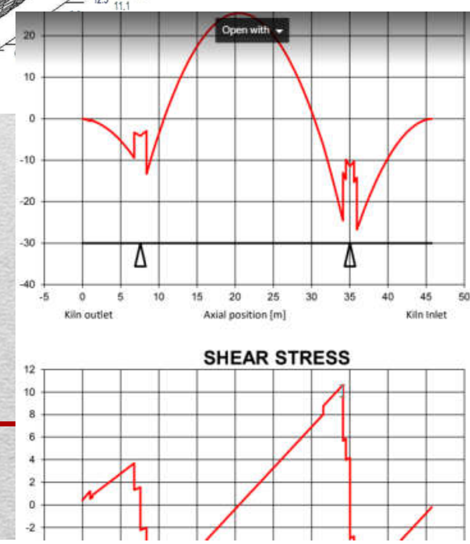
Stress Induced Cracking

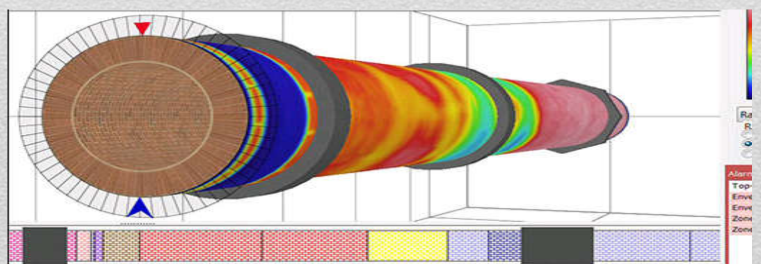
Kiln Mechanics

Fix Mechanical Issues

Perform a Hot Kiln Alignment to fix or moderate Dog Legs.
Inspect Tire Pads, Tire and Support Rolls for non-uniform wear.
Visually Inspect for weld cracks. Perform a MT, PT or UT test if necessary.
Develop a proper “indexing” procedure for all heat up and cool down periods
Analyze Tire Ovality (creep data) to see if the tire creep.
Evaluate tire shimming next outage if required.





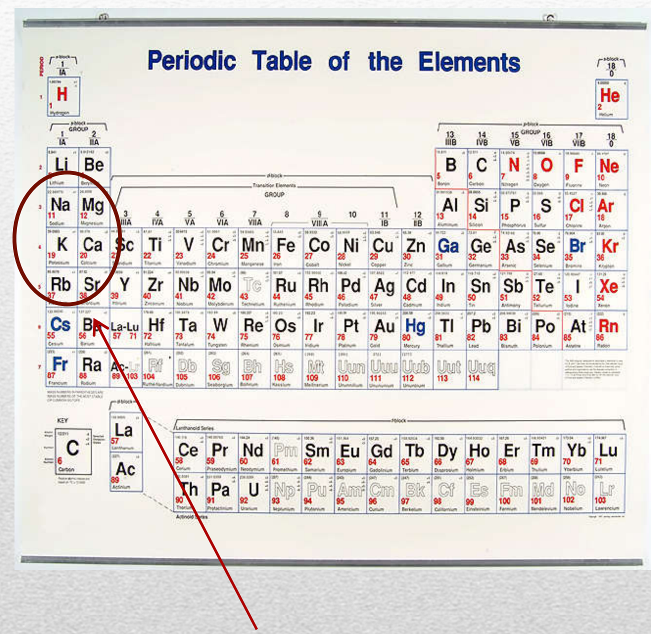


Basic vs. Alumina

Acidic refractories consist of mostly acidic materials like alumina (Al_2O_3) and silica (SiO_2). They are generally not attacked or affected by acidic materials, but easily affected by basic materials. At high temperatures, acidic refractories may also react with limes and basic oxides.

Neutral refractories are chemically stable to both acids and bases. The main raw materials belong to, but are not confined to, the R2O3 group. Common examples of these materials are alumina (Al_2O_3), chromia (Cr_2O_3), Zirconia (ZrO_2) and carbon.

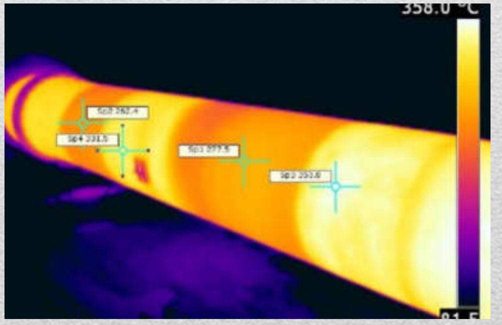
Basic refractories These are used in areas where the process and atmosphere are basic. They are stable to alkaline materials but can react to acids. The main raw materials belong to the RO group, of which magnesia (MgO)



High-Temperature Alkali Attack

Brick with Insulation

You need some very specific process or mechanical reasons to install insulation. The fuel savings does not justify the potential increase in refractory consumption, costs or shell corrosion.



Carbon Reduction

Green Refractory??

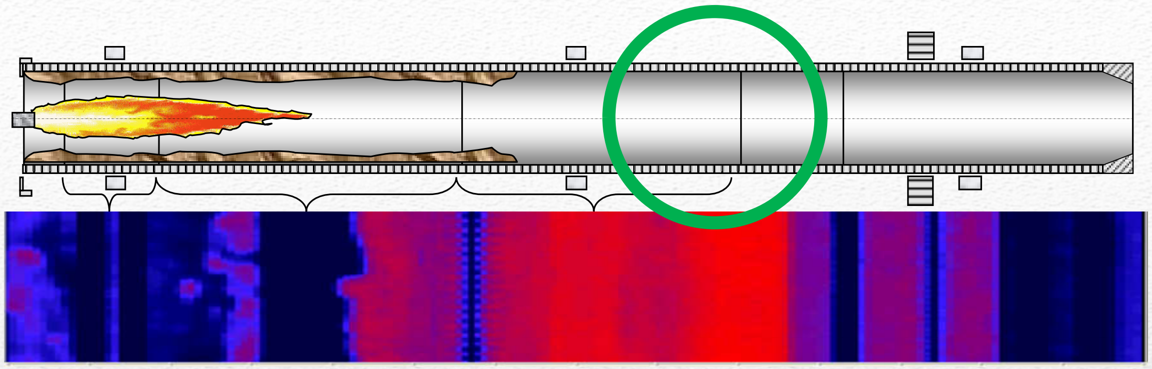
Quick calculations found that every 25oF drop in the kiln shell temperature resulted in ~1.5 tons CO_2 being saved /ton of brick over the course of a year.

It is well known that the thermal conductivity of these more-insulating Spinel brick change over time as the process infiltrates the open porosity and the insulating value can be short-lived. In many cases the actual savings suggested by the datasheet for these insulating brick were never realized, even before the process infiltration.

If these brick fail prematurely then most of the CO_2 savings evaporates due to the footprint of the replacement brick. It is also a huge financial cost to the plant for the cost of the brick, installation, removal, heat up costs and emissions, loss production and stress on the other refractory.

It should also be noted that brick manufactured with Natural (mined) Magnesite have a much larger carbon footprint than synthetic (brine extracted) MgO since CO_2 is released in the decomposition of the naturally occurring $MgCO_3$. This is even worst for Chinese mined Magnesite due to less efficient processing techniques. You need some very specific process or mechanical reasons to install insulation. The fuel savings does not justify the potential increase in refractory consumption, costs or shell corrosion.

Insulating Alumina brick will likely be much more advantageous to utilize than the Basic Zone due to lower brick cost, lower brick carbon footprint, better reliability, larger conductivity changes and much longer service life.



Densification Zone

Muestra	Probeta	Permeabilidad ($x 10^{-13} m^2$)	Media ($x 10^{-13} m^2$)	Desv. Estándar ($x 10^{-13} m^2$)
MKE	1	3.3	4.0	0.8
	2	3.8		
	3	4.9		
MKS	1	2.8	2.3	0.4
	2	2.0		
	3	2.2		
MLB	1	4.3	4.0	0.2
	2	3.9		
	3	3.9		
MLA	1	3.1	2.9	0.6
	2	3.4		
	3	2.2		
MLC	1	3.6	3.3	0.5
	2	3.5		
	3	2.7		
MLS	1	2.1	2.5	0.3
	2	2.6		
	3	2.8		

MgO	87446
SiO2	0.295
CaO	0.788
Al2O3	10,801
Fe203	0.529
Cr2O3	0.022
TiO2	0.020
MnO	0.096
Na2O	0,001
K2O	0,001
ZrO2	0,001
SO3	0,001
P2O5	0,001

Density (Gr / cm3)	3.02
porosity (%)	13.7
CCS (N / mm2)	62.6

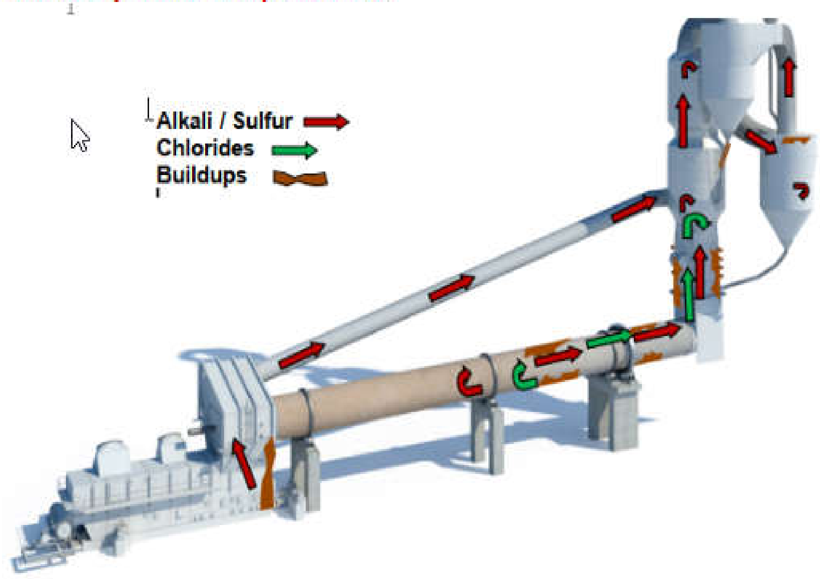
MgO	87446
SiO2	0.284
CaO	0.720
Al2O3	10,334
Fe203	0.478
Cr2O3	0.104
TiO2	0.013
MnO	0.094
Na2O	0,001
K2O	3,858
ZrO2	0.019
SO3	2,648
P2O5	0,001

Density (Gr / cm3)	3,25
porosity (%)	4.3
CCS (N / mm2)	169.7

Densification

Densification

Process Cycles / Buildup Locations



The locations and severity of the Kiln Rings are likely dependent on where the volatilization of these coincide within the Kiln and due to the higher partial pressure they re-condense in the same vicinity. Please refer to Issue #2 regarding Kiln Rings.

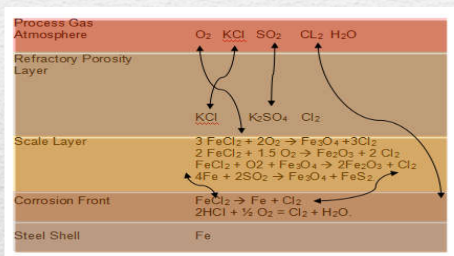
Since Clinker does not have the capacity to absorb much Chloride, tons of reactive Cl^- ions can accumulate in the Kiln in an endless Chloride cycle which increases in concentration as the process continues. Even if Chloride input can be measured in parts per million and even if the plant has an Alkali Bypass the accumulation is large over time and continues until it can be "flushed" out of the system (upset conditions).

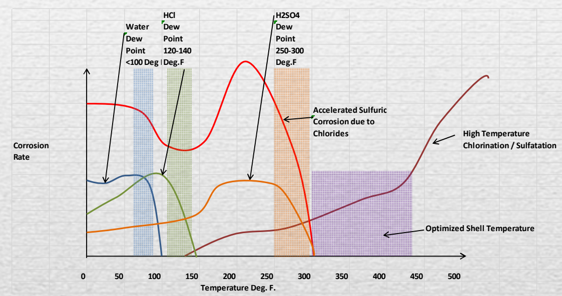
Plant Capacity	3500	tons (raw material basis)
Chloride Input	150	parts per million
Chloride Output	30	varies ave. 20% of input
Circulating Cl	0.42	tons/day Cl accumulation
After 10 days	4.2	tons Cl in circulation
After 30 days	**12.6**	**tons Cl in circulation**

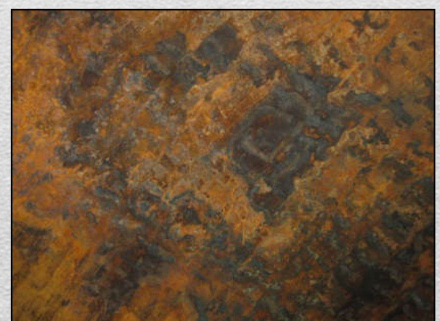
The presence of Chlorides accelerates the brick corrosion reactions and all efforts should be made to limit the amount of Chlorides entering the system. Chlorides can also aggravate the buildups but more importantly they become concentrated in the buildup which allows them to migrate to the shell causing severe shell corrosion. Chlorides are present in small amounts in the feed, coal, tires and in larger amounts in biosolids, waste fuels and wood byproducts.

Shell Corrosion

The release of HCl and particularly Cl_2 likely takes place directly on the metal surface, and therefore plays a critical role in the corrosion mechanism. It is noted that Cl_2 is far more corrosive than HCl. Once Cl_2 is formed, it will react directly with the kiln shell according to the following reactions resulting in the corrosion of the kiln shell: $Fe+Cl_2 = FeCl_2$. The chloridation of Iron by highly corrosive chlorine is self-perpetuating, since fresh Cl_2 continues to be generated by reaction. The presence of a $FeCl_2$ corrosion product layer in contact with the metal is judged to be particularly damaging because it promotes scale disruption or spallation as a result of large volume expansion of the afflicted metal.



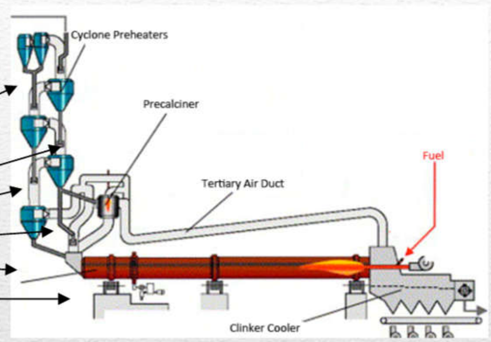




Shell Corrosion

Estimated Temperatures based on Original Refractory Configuration

Shell	Deg.F Temp	Summer Internal Shell Temp	Winter Shell Temp
Stage 1	700	180	115
Stage 2	1110	180	115
Stage 3	1260	190	120
Stage 4	1480	195	125
Stage 5	1600	202	139
Riser	1700	290	250



*Note all Cyclones lined with Skamol
*No Process penetration calculated so
Actual shell temperatures are likely higher

dew point of sulfuric acid = 250-300° F
dew point of hydrochloric acid = 120-140° F
dew point of water vapor = <100°F.

The immediate areas that are in the temperature range where the raw materials decompose and release corrosive volatile agents are more prone to corrosion due to an increase in activity and migration. For example;

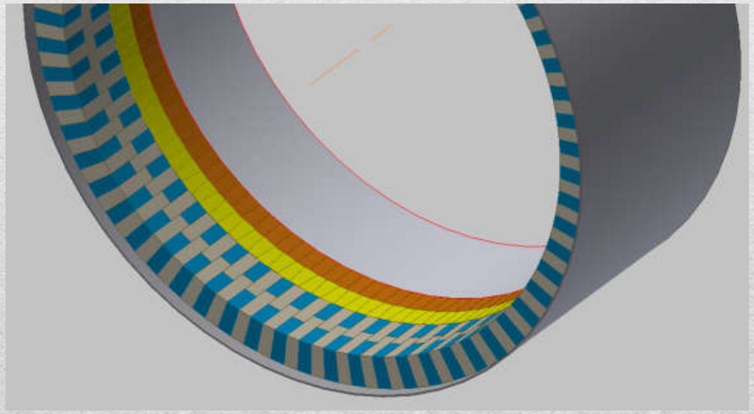
- 1st Stage cyclone - Free water volatilization
- 2nd Stage Cyclone – Release of chemically combined water (clays)
- 4th Stage Cyclone – Volatilization of SOx compounds
- 5th -3rd Stage Cyclones – Condensation of K_2SO_4 and KCl
- Kiln Upper Transition – Further volatilization of SOx compounds

Upper Alumina Brick

Conditions -
Thermo-Chemical / Alkali Attack
Process Cycles
Kiln Mechanics Issues
Slack Brick Conditions
Hot Thermal Conditions (+2000 deg.F.)
Abrasion from tumbling product

Recommendations
- Higher Quality Alumina Brick
- Firebrick

See Data Sheets



System used for Dog Legs and Downhill Thrust

Infiltration Resistant Alumina Brick

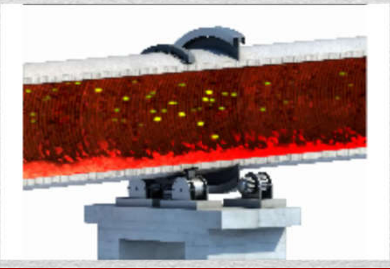
Value Calculations - Unit Prices vs. Expected Service Life - Annualized Cost

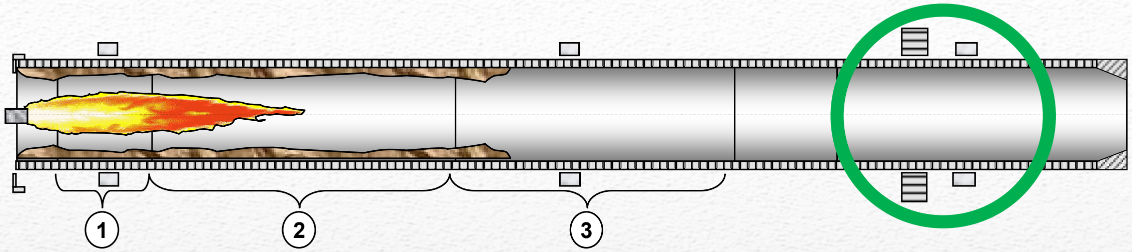
Caused by Infiltration of K_2SO_4, Na_2SO_4, *NaCl, KCl, Boron*

Once K_2SO_4, Na_2SO_4, NaCl and KCl condensate they modify:

- *Increase Lineal Expansion.*
- *Increase Conductivity.*
- *Reduce Porosity.*
- *Increase toughness, but reduce mechanical resistance. Brittle.*
- *Changed chemical composition*

Solution
Brick with Silicon Carbide
Brick with Zirconia
Brick with SiC + ZrO_2





Bull Gear Zone

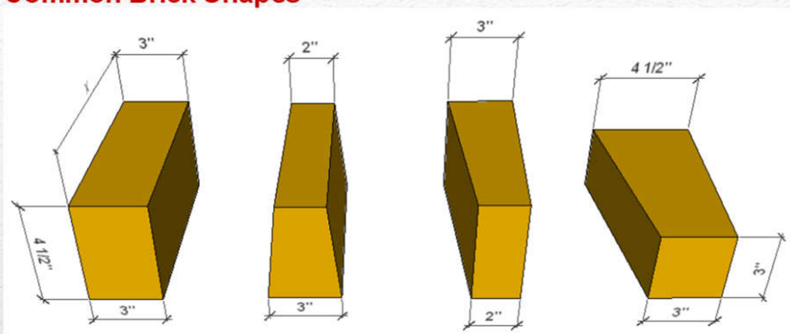
Identify the leading causes of damage

- **Hot Shell - Leads to Gear Lubrication Issues**

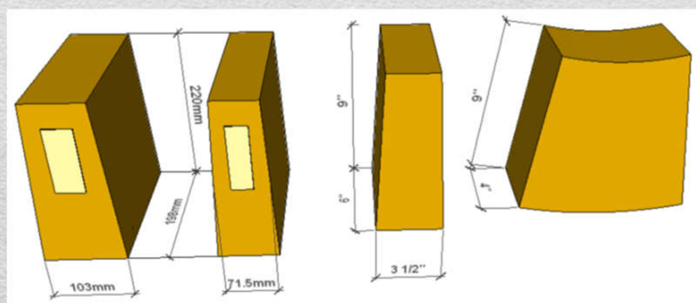
Insulation only for Extreme Problems

Brick Shapes / Mortar

Common Brick Shapes



Straight Arch Wedge Key



ISO VDZ (B-Series) Kiln Wedge (KW) Rotary Kiln Block (RKB)

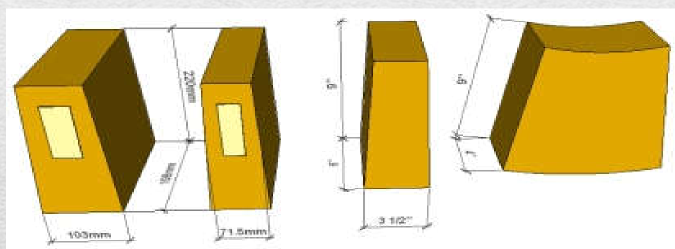
Brick Shape Rhetroic
Failures related to brick shape.

Mortar Rhetoric

- Seal joints so process cannot penetrate
- Bond brick together to provide tensile strength

Refractory Quality

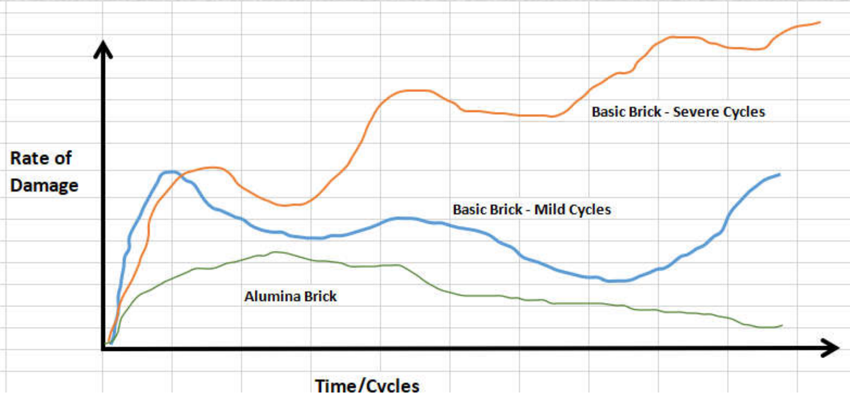
ISO vs. VDZ - ISO Shapes are generally the preferred shape for the alumina brick.   It is thought that the larger amount of taper and a lesser amount of joints will help keep the brick tight but can assist in keeping the brick rings from a catastrophic failure. VDZ brick will have the more joints and a smaller taper and can possibly **fit the shell better and add flexibility**. A VDZ lining will also slightly lower the apparent lining Modulus of Elasticity which might somewhat slightly **reduce the amount of stress** developed in the individual brick. The installation speed and quality should not vary much between the shapes.



ISO   **VDZ (B-Series)**   **Kiln Wedge (KW)**   **Rotary Kiln Block (RKB)**

Non-Linear Properties

- MoE decreases with Damage so the magnitude of stress related damage decreases with time/cycles
- Hysteresis (damage) increases with time/cycles
- Thermal Shock Damage decrease with time/cycles
- Depth of damage from Infiltration decreases with time/cycles
- Thermo-Mechanical Stress Load decrease with time/cycles as shell temperature increase
- Creep damage increase with time/cycles
- Depth of Creep damage decreases as thermo-mechanical load decreases.
- Damage from Initial Heat up decrease with time/cycles
- Damage from Initial Mechanical Issues decrease with time/cycles



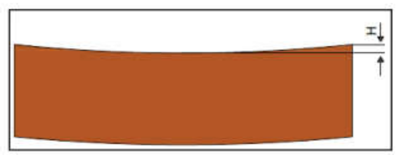
Number and Magnitude of Cycles most important

Refractory Quality

Poor Quality brick are usually quickly identified by Bricklayers

Tapers - Sometimes when the brick are not formed with equal taper on either side of the brick this can lead to potential failures.

2.4. Deformation.		
	Unfired material	Fired material
H	≤0.5mm	≤1mm



Banana Brick - Warped when fired.

Installation

It was most likely **NOT** the Installation

It was most likely **NOT** related to any Physical Properties shown on the datasheet

INSTALLATION CRITICALITY WORKSHEET

Item	Problem Indentification	Probability of leading to premature failure 1 critical 5 non-critical	Information
Brick Quality			
	Warped brick	**1**	**Do Not Install**
	Easily broken from handling	**2**	**Evaluate with Manufacturer**
	Offset Tapers	3	Evaluate with Manufacturer
	Visible defects (see defect list)	3	Evaluate with Manufacturer
	Length Tolerances	4	May effect axial expansion
	Taper Tolerances	5	Watch Mixing Ratio
	Height Tolerances	5	Might appear as hacking
Water Issues			
	Wet / Hydrated Brick	**1**	**Do Not Install**
	Dolomite and Low Quality BZ Cut We	**1**	**Do Not Install**
	Spilled water in Kiln (Dolomite Only)	**1**	**Remove and Replace**
	Condensation "sweat" (Dolomite Only)	3	Judgement Call
	High Quality Spinel Cut Wet	4	Not an issue unless extended downtime
	Alumina Brick cut Wet	5	Never an issue
Mortar			
	Incorrect use of full mortar	**2**	**Separate Report to Follow**
	Use wrong correction mortar (Alumina v:	3	May accelerate thermo-chemical reactions
Alignment			
	Edge Hacking	**2**	**Only allowed against old work / cut rings**
	Square to shell Radial	3	+/- 1/4" unless otherwise determined
	Cut in first ring to square	3	To be determined
	Square to shell Axial	4	+/- 1" unless otherwise determined
	Brick retainer out of alginment	4	+/- 1" unless otherwise determined
	Dead center on axial axis	5	Not an issue
	Lack of Reference Lines and Laser Mar	5	Not an issue
Hacking / Corrections			
	Severe hacking brick to brick	3	Determine cause. Look at shell / turning ratio
	Mild Hacking brick to brick	4	Not an issue
	Lining Corrections (mortar vs. shims)	5	Both have advantages and issues
Jacking Pressure			
	Brick cracked during keyup	**1**	**Remove and Replace. Look for brick warpage**
	Tamp Shoulders brick while jacking	**2**	**This is a requirement to get the brick tight**
	Over Jacking Pressure	3	May cause longer-term trenching issues
	Under Jacking Pressure	3	Not a critical as precieved

Item	Problem Indentification	Probability of leading to premature failure 1 critical 5 non-critical	Information
Misc Installation Items			
	Upside Down Brick (notch / paint)	**1**	**Remove and Replace**
	"Clip" the remaining brick	**2**	**Slipped brick must be tighten or replaced**
	Cut less than 1/2 brick	3	Only critical when small
	Cut less than 2/3 brick	5	Not critical until under 1/2 brick
	Staggered Bonding Pattern	4	Not critical but recommended
	Spacing out cut and double-cut rows	4	Not critical but recommended
	Full brick against old work	4	Better for closure installation
	Direction of Cardboard Tabs	5	Not critical
	Removal of Cardboard Tabs	4	OK in moderation
	Mixing Brick Shapes	4	Generally not critical
	Mixing Brick Heights	4	Generally not critical
	Mixing Brick Qualities / Brands	4	Generally not critical
Shims			
	Shims in Axial Joints	**1**	**This should be never done**
	2 shims together in same joint	**2**	**Never seen this**
	Too many shims >6	**2**	**See Optimize Taper below**
	Over shimming	**2**	**Can cause brick damage and trenching**
	Under shimming	3	Not a critical as precieved
	Spread shims over large area	3	Helps mitigate stresses
	Re-shim if rolled many revolutions cold	3	Many times not possible before startup
	Re-shim - Standard or Rotated	4	Usually just a double check
	Shims quality / thickness	4	Never exceed 12 gauge or easily distorted steel grades
	Use of Double Shims	4	Use properly
	Mortar vs. Shims	4	Both have advantages and disadvantages.
Key Brick			
	Optimize the Taper in the Key Zone	**1**	**Always a compromise with Key brick / shims / othe**
	Large face / corner spalls during keyup	**2**	**Remove and Replace (+5 sq.in)**
	Shape / Dimensions of Key Brick	4	Could help Installation in particular Kilns
	Staggered Keys Brick	4	Not critical
	Install Key brick together	5	Not critical
	Quantity of total Key Brick	5	Not critical
	Shims next to Key Brick	5	Not critical
	Slight face / corner spalling during keyup	5	Point with mortar

Installation blamed ZERO times!

Almost always some underlying (multiple) issues

Next Step

Low Hanging Reliability Improvements

Good Failure Analysis with Actionable Items

Probably need reconsideration if:

- **Installation is blamed**
- **Reference to Installation Guidelines or Specifications**
- **Reference to Physical Properties found on a datasheet**
- **Reference "wrong" Brick Sizes or Shapes**
- **Only 1 contributing cause**
- **Earthquakes**

Immediately implement Cool Down Schedule

Develop a plan to improve refractory design (reevaluation Insulation and anything OEM related)

Major Causes of Failures

Part 3 -

Major Causes of Failures

OEMs - Catastrophic for Monolithics

Design / Insulation - Severely reduces Service Life

Cool Down - Catastrophic for Kiln

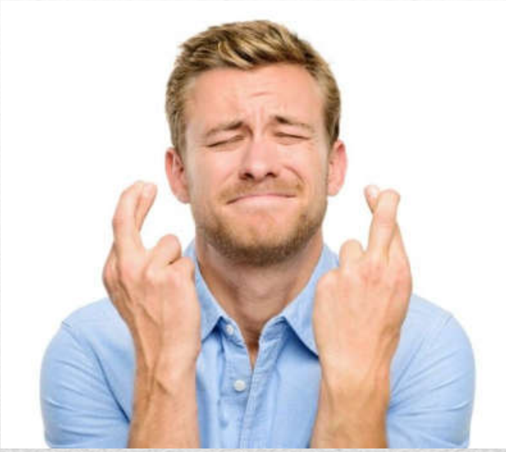
OEMs

Excessive insulation is the leading cause of premature lining wear and failures. If your takeoff is based on the original OEM drawings, you should also be leery as the OEM are notorious for crappy refractory designs (even if subcontracted to a refractory company) only to assure that they reach their thermal efficiency guarantee.

I always advise customers to only use these OEM drawings for dimensions only and assume the material selection, anchoring, insulation and design are WRONG!

Bid Package Example

- **Typical Refractory / Anchor / Expansion Design**
- **Cross your fingers**
- **Status Quo - Upgraded Material**
- **Use Bricklayers**
- **Who should be responsible?**

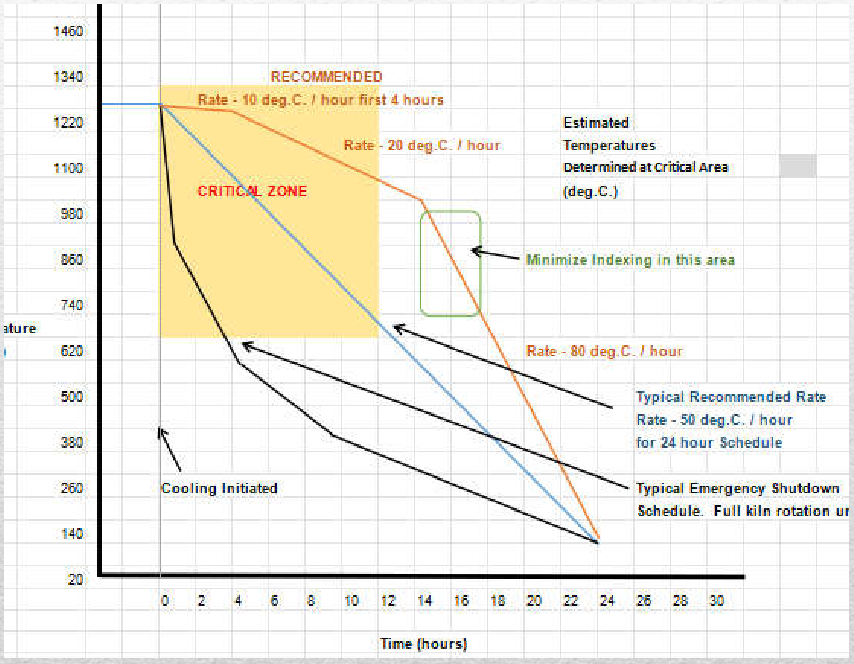


Design / Expansion

Cool Down / Indexing Failures

The majority of brick failures occur during cool-down periods as the brick are allowed to cool and contract while the shell remains in a relatively hot, expanded condition resulting in the compression in the hot face is completely relaxed.

Release of Residual Stress



Cost of Refractory Failures

Largest "Value" Factor (by far) is "Extended Service Life"and/or "Campaign Reliability".

Keep Track of all the times that I mention Installation failures

Thanks for the consideration