

FERROCHROMIUM PRODUCTION: INSULATING OR CONDUCTIVE LINING DESIGNS?

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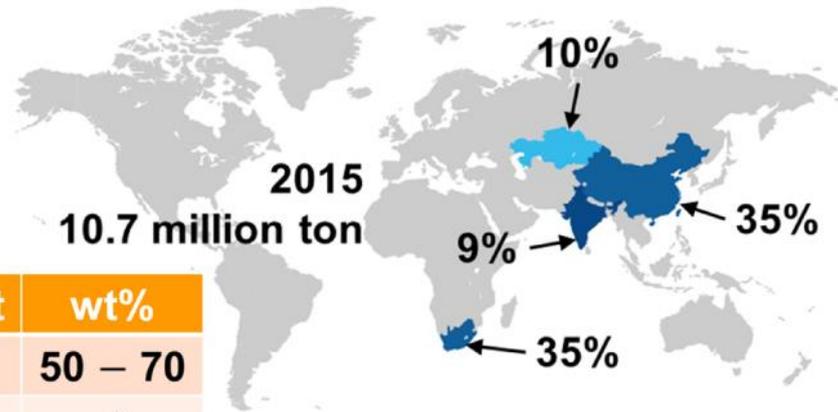
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Thank you, Mr Chairman. Good afternoon, ladies and gentlemen.

In my presentation today, I want to discuss the different refractory design philosophies available in the production of ferrochromium. Although the presentation is aimed specifically at designers of new plants, the information also applies to the understanding and improvement of current operations.

My name is Joalet Steenkamp and I work as chief engineer at MINTEK, a state owned research council in South Africa.

Ferrochrome

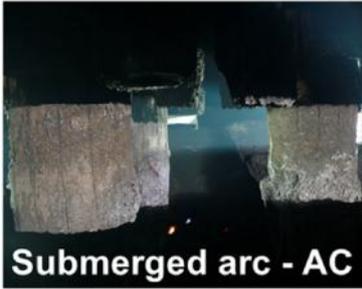


Element	wt%
Cr	50 – 70
C	~8
Si	1 – 1½
Fe	20 – 40

Stainless steel production

Ferrochrome is an essential alloy in the production of stainless steel. The main producers of ferrochromium are South Africa, China, Kazakhstan, and India. In 2015, 10.7 million ton of ferrochromium was produced, with China and South Africa both accounting for 35% of the production, and Kazakhstan and India 10% and 9% respectively. High carbon ferrochrome typically contains 50-70% Cr, 20-40% Fe, 1 – 1.5% Si, and in the order of 8% C.

Choice in operating philosophy

T dependent	 <p>Submerged arc - AC</p> <small>© Joalet Steenkamp</small>	 <p>Lumpy chromite ore</p> <small>© Stefan Swanepoel</small>	+6mm
T independent	 <p>Open arc - DC</p> <small>© Isabel Geldenhuys</small>	 <p>Chromite ore fines</p> <small>© Pranusha Moodley</small>	-6mm




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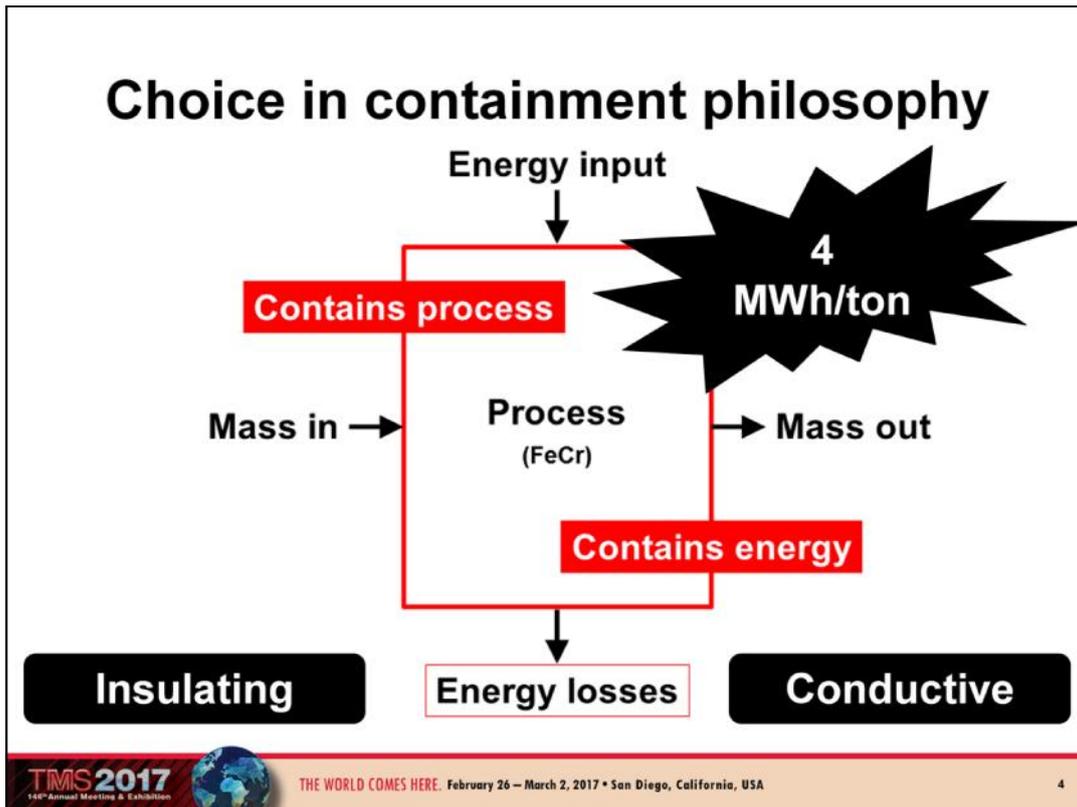
In terms of operating philosophies, ferrochromium is produced both in sub-merged arc furnaces (SAF) and in open-arc furnaces. The electrical systems available, are alternating current (AC) – typically applied in sub-merged arc furnaces – and direct current (DC) – typically applied in open arc furnaces.

The choice in operating philosophy is primarily driven by ore type:

1. In sub-merged arc furnace operation lumpy raw materials with particle size typically in excess of 6mm are required
2. On the other hand, DC open arc furnace operation was specifically developed for the reduction of fine raw materials, in the order of 6mm or even less

One of the advantages of DC open arc furnace technology, is the reduced dependency of process temperature on the electrical resistivity of the process material. Therefore, slag chemistry and process temperature are controlled independently in order to:

- 1) Optimize activity of slag components participating in reduction reactions which will improve the recovery of Cr, and result in low levels of S and P
- 2) Manage viscosity of the slag for tappareability
- 3) Manage activity of refractory components in slag to minimize potential for refractory dissolution or chemical reaction between slag and refractory.



Ferrochrome production is energy intensive with energy consumption typically in the order of 4 MWh/ton for non-preheated or prereduced ore. The purpose of the furnace containment philosophy therefore is not only to contain the process but also to contain the energy supplied to the process. Potential furnace operators have two choices available when selecting a containment philosophy: they can choose between an insulating or conductive lining design.

Containment philosophy principle

Insulating



Conductive



I will now illustrate the difference in the two philosophies using a series of cartoons, starting with the furnace steel shell.

Containment philosophy principle

Insulating

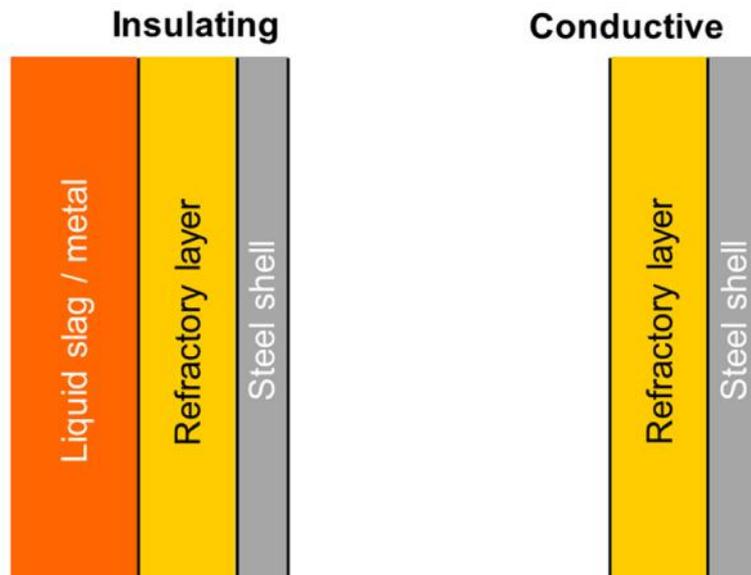


Conductive



In both design philosophies, a refractory lining is added to the steel shell.

Containment philosophy principle



In an insulating lining design, the hot face of the refractory lining is directly in contact with the liquid process material in other words alloy or slag.

Containment philosophy principle

Insulating

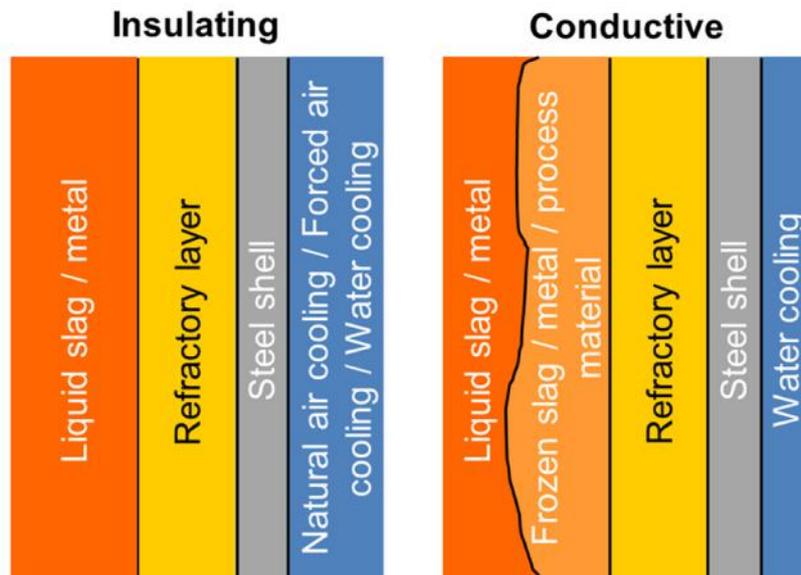


Conductive



In a conductive lining design, the hot face of the refractory material is protected from the liquid process material through the formation of a frozen layer of alloy, slag, raw materials or a combination of these materials.

Containment philosophy principle



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In both design philosophies, the steel shell can be water cooled either through forced cooling or through thin-film cooling. The steel shell is not necessarily water-cooled in the case of an insulating design, and can also be air-cooled through forced air cooling or through natural air cooling.

Doesn't an insulating design also conduct heat?

It does, the difference lies in the primary focus of each philosophy:

Insulating: minimize energy losses from the furnace

Conductive: protect hot face of refractory from chemical wear by freezing a layer of process material onto the hot face of the lining

What are you after?



The question arises then: doesn't an insulating lining design conduct heat too?

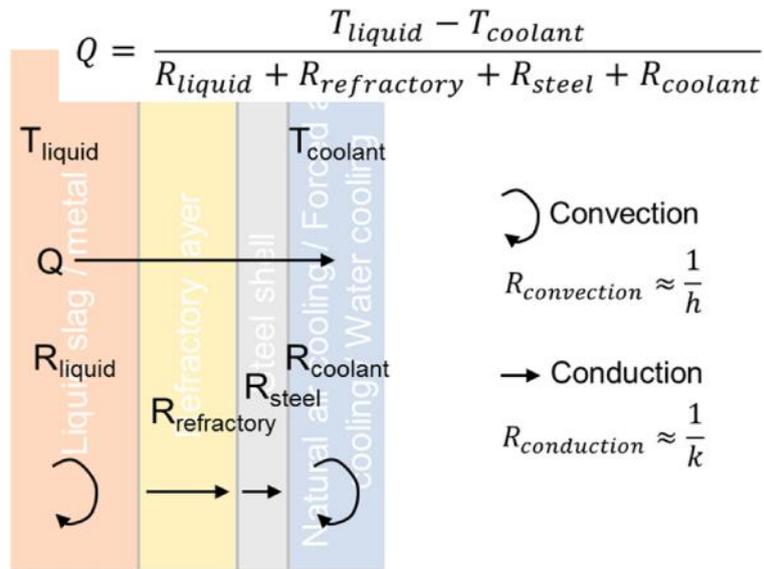
It does, the difference lies in the primary focus of each philosophy:

In an insulating lining design the primary focus is to minimize energy losses from the furnace

In a conductive lining design the main focus is to protect the hot face of refractory from chemical wear by freezing a layer of process material onto the hot face of the lining

The next question then is: does one want to minimize energy losses from the furnace or does one want to protect the hot face of the refractory from chemical wear? Again the answer is probably both but the focus is dependent on the process conditions such as slag chemistry and process temperature. These process conditions are driven by the chemistry of the ore available but first let's look at the heat transfer mechanisms applicable in more detail.

Heat transfer: insulating



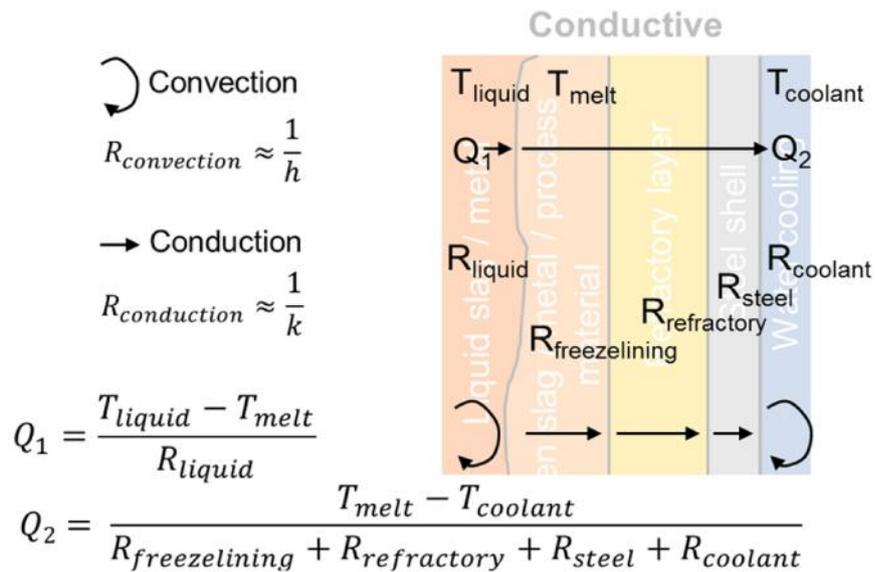
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From a heat transfer perspective, two mechanisms apply: heat transferred through convection and heat transferred through conduction.

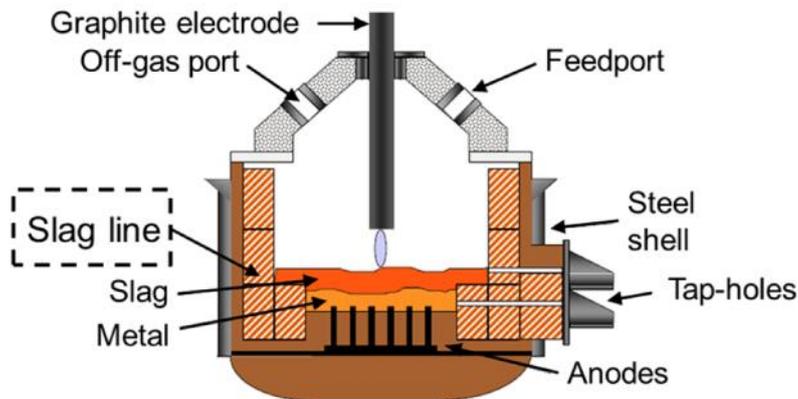
In an insulating design, heat is transferred to the hot face of the refractory through convection, through the refractory and steel shell through conduction, and into the cooling medium through convection. Using an electrical analogy, the heat flux (Q) is proportional to the differences in temperature of the process material inside the furnace and the cooling medium, and inversely proportional to the thermal resistances of the different components in the containment system.

Heat transfer: conductive



In a conductive design, a 5th component is added: the freezelining through which energy is conducted. The freezelining forms a boundary condition: the melting point of the layer of frozen material. Energy transferred from the liquid process material to the freezelining through conduction, will melt the freeze lining at the melting point of the layer of frozen material. The temperature at the interface between the liquid process material and the freezelining therefore remains constant, only the thickness of the freezelining varies. If the lining design is done correctly, with the thermal conductivity of the refractory being higher than that of the freezelining, the energy transferred from the liquid process material to the frozen process material, through convection, determines the heat flux through the system.

Desktop study example



Operating philosophy: open-arc DC
Containment philosophy: ???

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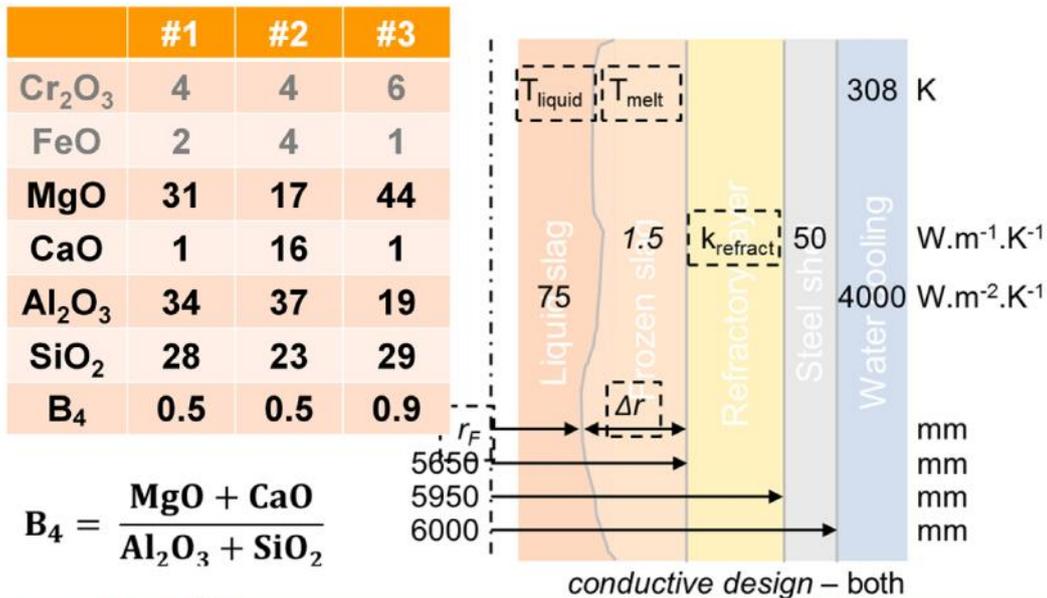
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During the desktop study phase of a project, very little resources are available and decisions are made on models that are easy to develop i.e. spreadsheet-based mass and energy balance calculations and one-dimensional, steady state heat transfer calculations. I will now illustrate the application of these tools in a case study whereas operating philosophy open-arc DC technology was selected.

The schematic presented here typically illustrates the components of a pilot-scale DC-arc furnace: the containment system consists of a refractory-lined steel shell. The roof is sealed with ports for the single graphite electrode, feed, and off-gas. The power is supplied to the process through a graphite electrode forming the cathode and a conductive furnace hearth – in this instance steel pins – forming the anode. As slag and metal separation in the furnace is good, dual-level tap-holes are installed. From a refractory perspective, the slag-line is typically one of the high wear areas.

To answer the question, ‘What should the containment philosophy be?’ a series of calculations can be made.

Assumptions and calculations



In the case study, I assumed that the freezeline consists of slag only. I selected three different slag compositions from a paper presented by one of my colleagues, Isabel Geldenhuys, at INFACON in 2013. These compositions are presented here in the table. The slag compositions typically vary because of the differences in ore body chemistry. In practice, the slag composition will be calculated in a predictive mass and energy balance and will be significantly influenced by ore chemistry and choice in fluxes.

The furnace variables selected were summarised the cartoon. The numbers in italics are only applicable to the investigation of a conductive lining design, all others are applicable to both. The furnace shell outside diameter, is 12 meters i.e. the radius 6000mm. The steel shell thickness is 50mm and the refractory lining thickness 300mm. The coefficients of convection of liquid slag and water was 75 and 4000 W/m²/K respectively. Thermal conductivity of the frozen slag and steel shell, 1.5 and 50 W/m/K respectively. The water temperature was 25C. Unknown variables were the process and liquidus temperature of the slag, the thermal conductivity of the refractory, and in the case of the conductive lining design the thickness of the freezeline.

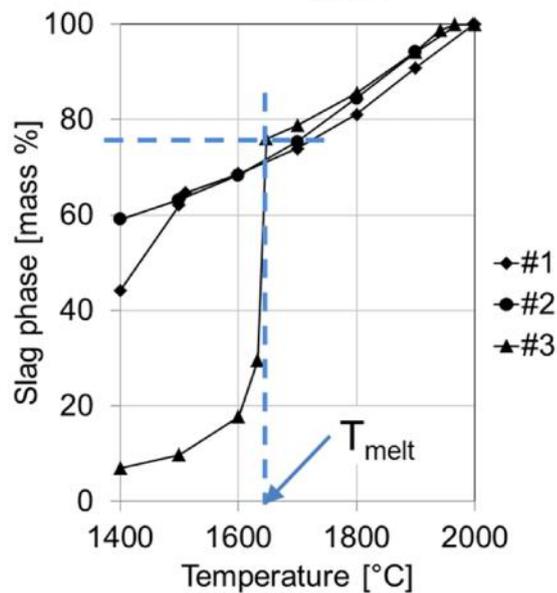
I will now illustrate how to obtain all three unknown variables as part of a desktop study.

Melting point of slag (T_{melt})

	#1	#2	#3
Cr ₂ O ₃	4	4	6
FeO	2	4	1
MgO	31	17	44
CaO	1	16	1
Al ₂ O ₃	34	37	19
SiO ₂	28	23	29

FACTSage
FToxid, FactPS

T_{melt} assumed slag < 80%

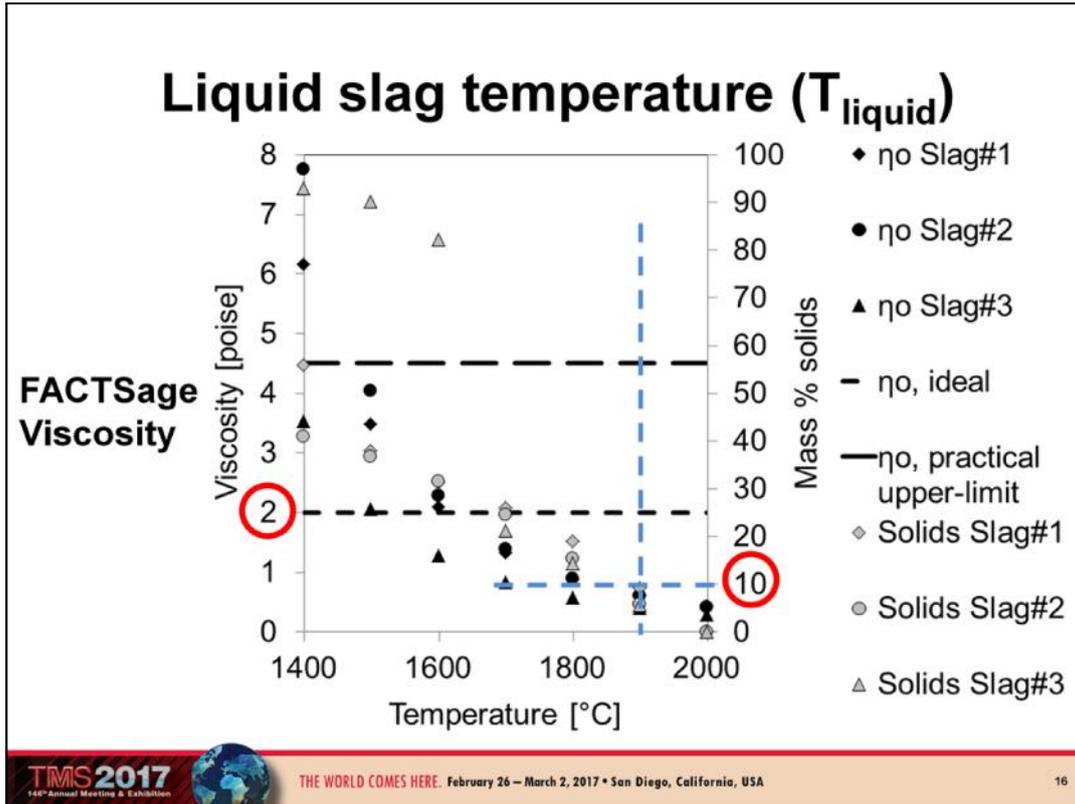


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The melting point of the slag was estimated from the calculated percentage slag phase formed as a function of temperature, under equilibrium conditions. Calculations were done in FACTSage thermodynamic software. The Equilib module was applied, and FToxid and FactPS databases selected. The results were presented in the graph on the righthand side, where the % slag phase formed was plot as a function of temperature for the different slag compositions.

Wettability tests conducted on synthetic and industrial silicomanganese slag demonstrated that balling temperatures (considered to be the melting point of the slag) typically occurred in the temperature range where 80-95% of the slag phase is calculated to form. Therefore, the melting temperature was selected as the temperature where < 80% slag phase formed: 1650°C. Note the sensitivity of slag phase formation for Slag #3, compared to Slag #1 and Slag #2, as the temperature reduces.



Two of my colleagues, Rodney Jones and Markus Erwee, discussed in a paper presented at TMS in 2016, the design of slag compositions for ferrochrome production, specifically focussing on slag/metal separability and tap-ability. They stated that for ferrochrome slag to be tap-able, the liquid viscosity (calculated in the viscosity module of FACTSage), should ideally be 2 poise or less. Slag with a liquid viscosity of more than 4.5 poise was considered not tap-able.

Furthermore, we know from the Roscoe relationship that the apparent viscosity of slag changes exponentially with increase in solids fraction. Assuming that a liquid viscosity of 2 poise and solids mass fraction less than 10% are required for a tap-able slag, the liquid slag temperature was assumed to be 1900°C.

Thermal conductivity ($k_{\text{refractory}}$), thickness of freezeline (Δr), and heat flux (Q)

	Insulating?	$k_{\text{Refractory}}$ @ 1000°C [W.m ⁻¹ .K ⁻¹]	Δr [mm]	Q [kW]
#A	Magnesia	4	18	663
#B	Sintered corundum	2.5	-	505
#C	Fireclay	1.4	-	297
#D	Spinel	2.5	-	505
#E	Carbon	10	85	656
#F	Graphite	80	123	651

The thermal conductivity of the refractory materials were obtained from literature. For an insulating lining design, low thermal conductivity is of interest and for a conductive lining design, high thermal conductivity. Using the one-dimensional, steady-state heat transfer calculation discussed earlier, I then calculated the thickness of the freezeline.

I found that, under the conditions specified, a freezeline will only form for magnesia or carbon-based lining designs, not for the Al_2O_3 -, and SiO_2 - based refractory. Under these conditions, heat losses for the insulating lining designs are significantly less than for the conductive designs i.e. at this stage an argument exists for the selection of an insulating lining design for the case study under investigation.

Chemical compatibility

		C	FeO	MgO	Al ₂ O ₃	SiO ₂	CaO	Total
#A	Magnesia	-	1	98	-	-	1	100
#B	Sintered corundum	-	1	-	95	4	-	100
#C	Fireclay	-	3	-	22	75	-	100
#D	Spinel	-	1	30	68	1	1	100

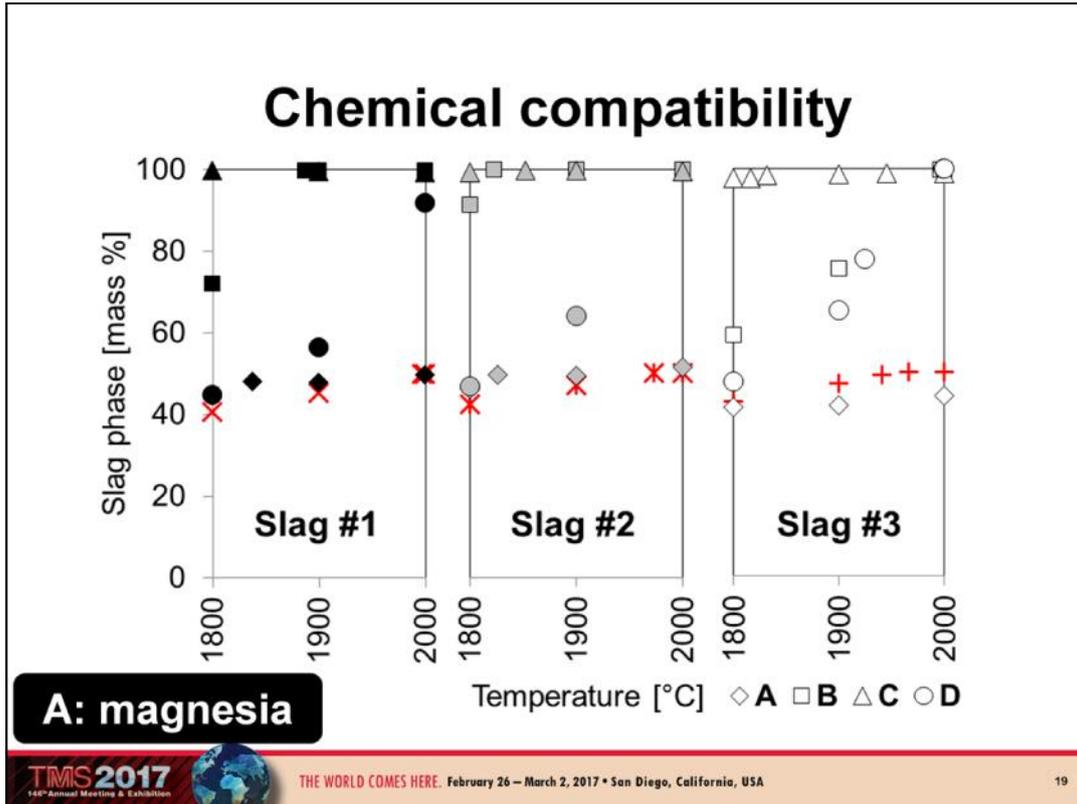
FACTSage
FToxid, FactPS
50g slag + 50g refractory



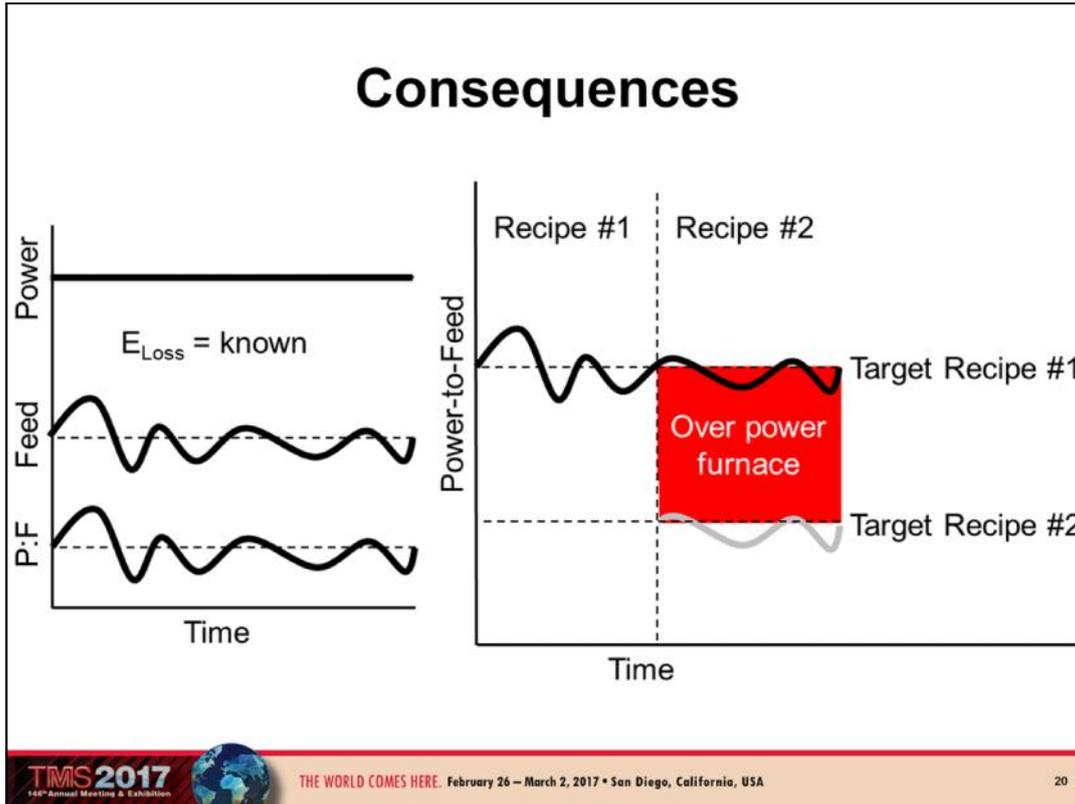
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When considering an insulating lining design, the chemical compatibility between the slag and oxide-based refractory material is important. On desktop level, the potential for chemical wear of a refractory by slag can also be calculated using FACTSage. I calculated the equilibrium liquid phase formation when reacting 50g of slag with 50g of refractory using the Equilib module and FToxid and FactPS databases. Although the calculation only applies to insulating lining designs, magnesia refractory was also included..



The results were presented in these graphs. Again I plotted the slag phase formed as a function of temperature. Should the slag phase formation be equal to, or less than, the slag phase formation calculated for slag only, the refractory is considered compatible with slag. When more slag is formed it is not compatible with slag. It can be seen here that only slag 3 is compatible with the refractory and that it is compatible only with the magnesia refractory. In other words, under the conditions investigated only slag 3 should be considered for an insulating refractory design and then only when magnesia refractory materials are used.



In the operation of DC open arc furnaces, a typical process control measure applied is the power-to-feed ratio, where power is the electrical energy input to the furnace and feed the total feed. Typically, the furnace operator selects a specific power setting to operate at, and with known energy losses, adjusts the feedrate of the material fed to the furnace, in order to control the power-to-feed ratio for a specific recipe.

At a constant power setting with constant energy losses, the power requirement will change when the recipe changes due to the differences in enthalpies of the input materials. The differences can occur when the ratios of feed materials changes i.e. ore / flux, or when the mineralogy of a specific feed material changes i.e. changes in mineralogy within chromite ore.

If the energy requirement of the process changes, without the awareness of the furnace operator, more or less energy can be added to the furnace than what is required by the process and energy losses – in layman’s terms referred to as ‘over-powering or under-powering the furnace’.

Consequences of over-powering

Open arc furnace

Insulating: increase temperature, influence saturation of slag in refractory components

Conductive: melt away freezelining, then ditto

SAF

**Depending on heat transfer mechanism at play could consume burden at faster rate
OR increase slag temperature (ditto)**



In terms of the refractory containment system, the consequences of over-powering an open-arc furnace are:

- 1) For an insulating design, where liquid slag is in contact with the refractory materials, the temperature of the slag will increase influencing the saturation of the slag in refractory components or influencing the potential for chemical reaction between the slag and refractory.
- 2) For a conductive lining design, the freezelining will melt away and once it is gone, the slag will react with the refractory in a similar fashion as for an insulating lining design.

In a submerged arc furnace, depending on the heat transfer mechanisms at play, either the burden will be consumed at a faster rate or the slag temperature will change with similar consequences as discussed for an open-arc furnace.

Consequences

How?

$$E_{In} = E_{Process} + E_{Losses}$$

$E_{Process}$

Inputs & outputs:

- Mass measurement
- Sampling, sample analysis
- Temperature measurement
- Enthalpy values

E_{Losses}

Water cooled: ΔT_{water} and flow rates

Non-water cooled:

$\Delta T_{refractory}$ and $k_{refractory}$

Accurate, reliable, validated

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Once in operation, managing the specific refractory design philosophy selected is very much dependent on managing the mass and the energy balance for the process. In the case of ferrochrome production, the electrical energy supplied should balance the process energy required as well as the energy losses from the furnace.

Usually furnace operators calculate the process energy requirement in theoretical mass and energy balance calculations. To calculate the process energy requirement, masses, chemical compositions, temperatures, and enthalpies, of all inputs to and outputs from the furnace are required.

Where sections of the furnace containment system is water-cooled, energy losses are calculated from water temperatures and flow rates. For the non-water cooled sections, differences in refractory temperatures – preferably in a single brick – and the thermal conductivity of the refractory material is important.

All of these measurements should be accurated, reliable, and validated.

Consequences – Project life cycle

- How managed during normal operations?
- How validated during cold, hot commissioning?

Project life cycle

Desktop study
Prefeasibility study
Feasibility study
Detailed design
Construction
Commissioning
Operation



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During the life-cycle of the project, future plant owners and furnace designers should not only seek to answer the question 'how will the furnace and process be managed during normal operations?' but also to answer 'how will the information required be validated during cold and hot commissioning?' Often, the procedures, and even equipment required, will differ and validating measurements during the initial commissioning of the furnace is as important as validating the measurements after extended maintenance periods.

Closing remark

Calculations are useful on desktop study level. Should be validated with experimental work on laboratory or pilot-scale, else the industrial-scale furnace becomes the pilot furnace.



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As a closing remark, I want to state that calculations, as the ones illustrated here today, are useful when deciding on a furnace containment philosophy on desktop study level. It is important, though, that the results are validated by experimental work on laboratory or pilot-scale during the prefeasibility or feasibility study stages of the project life-cycle. Failing to do so will result in the industrial-scale furnace becoming the pilot furnace with severe cost implications.

Questions



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