LINING MANAGEMENT - RESIDUAL LIFE ASSESSMENT

B. K.Mohanty

VP (Electrical & Instrumentation), Monnet Ispat& Energy Ltd., Raigarh, CG, India.
E-mail: bhabesh.mohanty1970@gmail.com, bhabesh.mohanty@monnetgroup.com

ABSTRACT:

Longer lifetime is the most significant factor in economics of linings. When a furnace burn-through occurs, the resulting loss of production has adverse effect on profitability. It is, therefore important for furnace operators to measure and understand the effect of their operating practice on lining wear. Unlike earlier days, when red spot on shell surface or shell bulging was indicative of a lining failure, nowadays submerged arc furnaces are built with 'Lining Management System' to monitor online lining conditions of the furnace. This provides operational staff with a management tool to predict long term lining life and acts as a process optimization tool. It alarms and records upset furnace conditions. Lining Management system provides operators with instant information on lining conditions based on real time data. Its trending facility provides management with a tool to estimate remaining lining life and understand the effect of specific operating practices on lining wear and crucible conditions. However, this lining management system is based on the design of furnaces with dual thermocouple measurements. There are several submerged arc furnaces working nowadays worldwide, having no thermocouple arrangement or having single thermocouples for temperature measurement. Though single thermocouple measurements can indicate lining deterioration, they do not suggest correctly the exact remaining lining thickness. Higher temperatures can also be attributed to loss of protective skull, electrode lengths and breaks, as well as changes in power input.

This paper describes the principle of Lining Management System based on dual thermocouples. An innovative approach has been tried to introduce the lining management system for furnaces having no thermocouples or having only single thermocouples. Test results of 28.5 MVA Ferro Silicon Furnace of Bhutan Ferro Alloys Ltd., supplied by Elkem, Norway, have been demonstrated. The principles can be extended for furnaces having no/ or having single thermocouples.

KEY WORDS: *Lining, Thermocouples, Heat Flux Density, Thermal Conductivity, Thermal Resistance, Temperature Gradient*

1 INTRODUCTION:

In a submerged electric arc furnace the ultimate goal is to operate the furnace longer between major relines, with fewer or no intermediate repairs. Longer lifetime is the most significant factor in the economics of linings. Furnaces are lined with a varying composition of refractory materials depending on the alloy being produced and whether shell cooling is involved. A submerged arc furnace lining is a dynamic thermal system that drives toward an equilibrium heat flux that is determined largely by the boundary conditions (molten bath temperature and convection cooling by air/ water). The system is dynamic because the components may change according to temperature conditions.

For a conventional Lining Management System, dual thermocouple principle is used. The System consists of numerous thermocouples (K type) placed in pairs around the furnace shell as well as in the hearth. The pairs of hearth thermocouples are installed one above the other, the spacing being such as to create an adequate layer of refractory material between the two thermocouples. This ensures a large enough temperature differential for accurate heat flux calculations. The feedback from the thermocouples is used to detect the present lining condition of the running furnace. During the replacement of faulty thermocouples, the insertion depth is measured and updated to ensure accurate heat flux calculations.

2 FUNDAMENTALS OF HEAT TRANSFER:

Heat is a form of ENERGY. The transfer of heat is usually considered to occur by means of three processes.

CONDUCTION: Conduction is the transfer of heat from one part of a body to another part or to another body by short range interaction of molecules or/and electrons.

CONVECTION: Convection is the transfer of heat by the combined mechanisms of fluid mixing and conduction.

RADIATION: Radiation is the emission of energy in the form of electromagnetic waves. All bodies above absolute zero i.e. temperature above (–) 273^0C or above 0^0K radiate.

The S.I. unit of heat is Joule. Rate of heat transfer is ENERGY/TIME; the S.I. unit is Joule/Sec. or Watt.

From the basics of heat conduction, (Fourier's Law for heat conduction through solid bodies) the steady state rate of heat transfer by conduction is directly proportional to the cross sectional area of the medium normal to the direction of heat flow and to the temperature gradient along the conducting path. If

Q = Steady state rate of heat transfer by conduction through a medium [in Watt]
A = Cross sectional area of the medium normal to the direction of heat flow [in Meter^2]
L = Length of the medium along the direction of heat flow [in Meter]
T1 = Temperature at one end of the length 'L' [in ^{0}K] from where heat is flowing
T2 = Temperature at the other end of the length 'L' [in ^{0}K] to where heat is flowing

Temperature gradient along the conducting path = $(T2-T1)/(L)$ in ^{0}K/Meter. The temperature gradient is a negative value as heat flows from higher temperature end to lower temperature end.

$Q \propto A \times (T2-T1)/(L)$ or $Q = -kA \times (T2-T1)/(L)$

The 'k' is proportionality constant, known as Coefficient of thermal conduction or Thermal conductivity; the unit is Watt/ (Meter^{0}K). This is constant for a particular material/medium & particular temperature.

Heat Flux Density is the rate of heat transfer per unit cross sectional area of the medium normal to the direction of heat flow

$q = Q/A = -k \times (T2-T1)/(L)$ in W/M^2 $= k/L \times (T1-T2)$ in W/M^2 (Eq. No. 1)

Or $(T1-T2) = \Delta T =$ Heat Flux Density $\times L/k$ in ^{0}K

Here 'L/k' is called Heat or Thermal Resistance, the unit being M^2 ^{0}K/W. The inverse of Heat Resistance, i.e. 'k/L' is called Thermal Conductance, the unit being W/ (M^2 ^{0}K).

ΔT = Temperature difference across the thermal system, or between two points in ^{0}K,

It is easier to understand one dimensional heat transfer by considering its analogy with simple electrical resistive circuit.

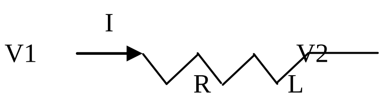


Figure 6: Electrical Analogy

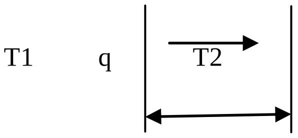


Figure 7: Heat Transfer

In Fig. 1, the Electric Current 'I' (or rate of charge flow) flows from 'V1' (Higher potential) to 'V2' (Lower potential) in a closed path and the magnitude is determined by Ohm's law.

$I = (V1-V2)/R$ (Eq. No. 2)

Here (V1 – V2) = The difference of energy level in a closed path. = Δ V
R = The Electrical resistance of the path from V1 to V2

Similarly, in Fig. 2, in the equivalent thermal system, 'q', is the rate of energy transfer per unit cross sectional area or heat flux density, '(T1-T2) = ΔT' is the difference of energy level, i.e. difference of temperature.

Considering Eq. No. 2 in analogy with Eq. No. 1, it is clear that $q \equiv I, \Delta T \equiv \Delta V, L/k \equiv R$

This 'L/k' is known as thermal resistance and is expressed as ratio of Length & Thermal conductivity. Thermal resistance is inversely related to thermal conductivity.

Thermal resistance $r = L/k$ (Eq. No.3)

In the case of a lining system, the molten liquid acts as high temperature body (T1) and the wall surface in contact with water/air acts as low temperature body (T2).

In an electrical circuit, each component is added as a series of resistors. Net $R = R1 + R2 + R3 + ... + Rn$

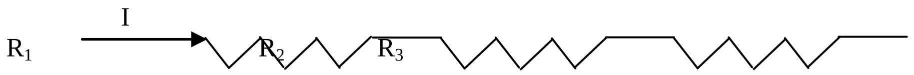


Figure 8: Resistors in Series

Using the process high temperature and cooling temperature (air/water) as the boundary conditions, the equivalent thermal resistance of complete lining at any particular point of furnace hearth can be determined as

Net $r = r_1 + r_2 + r_3 + - - - + r_n = L_1/k_1 + L_2/k_2 + L_3/k_3 + - - - + L_n/k_n$ (Eq. No.4)

L_1 = Thickness of lining adjacent to molten liquid
k_1 = Thermal conductivity of the layer '1' and so on.

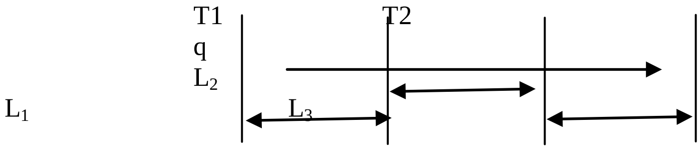


Figure 9: Thermal Resistances in Series

As the current is same in the series resistors in case of an Electrical circuit, Heat flux density is the same in each component of the lining. Therefore, the heat flux density can be used to calculate temperature drop in each component, beginning with either boundary and working through the entire lining.

So, the heat flux density q = (Molten Metal Temperature – End Steel Temperature)/ Net r (Eq. No. 5)

And the layer drop temperature is $dTn = q \times m$ (Eq. No. 6)

'm' being the thermal resistance of that layer.

3 PRINCIPLE OF LINING MANAGEMENT WITH DUAL THERMOCOUPLE:

For explanation, the 28.5MVA Submerged Electric Arc Furnace of Bhutan Ferro Alloys Limited, in Bhutan, supplied by Elkem is considered. The furnace has been provided with single thermocouples at bottom. However, a theoretical analysis has been made how the dual thermocouple Lining Management System works. Based on this understanding, the furnace Lining Management shall be explained without any base on thermocouple.

Let us assume that dual thermocouples are inserted into this furnace at inception stage. The furnace bottom lining has been considered and the similar inference can be extended for side wall and tap hole zone lining. The bottom lining consists of different layers as stated in Table 1. Total design thickness of furnace bottom is 1531 mm, including shell steel.

Table 4: Layer details of Bottom Lining

S.N.	LAYER MATERIAL (FROM INSIDE)	LAYER THICKNESS (mm)
1	Carbon Masse	773
2	Silicon Carbide (SiC)	225
3	60% Al2O3 Brick	150
4	45% Al2O3 Brick	225
5	Ferro Silicon Fine (FeSi)	140
6	Steel	18

The molten metal temperature is 1800 deg. Celsius in the hearth, design heat flux density is 4270 Watts/M^2 and design end steel temperature is 151 deg. Celsius. The dual thermocouples are assumed to measure temperature at the junction of layers (a) SiC and 60% Al2O3 Brick (b) 45% Al2O3 Brick & FeSi Fines. From the coefficient of conduction (design parameter of lining material) and layer thickness the heat resistance of each layer can be calculated (Eq. No. 3). Layer drop temperature is equal to this thermal resistance multiplied by heat flux density (Eq. No. 6). The difference of two thermocouple measured temperatures will provide sum of the layer drop temperatures in 60% Al2O3 Brick & 45% Al2O3 Brick. As thermal resistances are known, it is easy to calculate back the present heat flux density. From this heat flux density & temperature of molten metal, the present lining condition can be inferred (Table No. 4).

In the given example it is clear that the Carbon Masse lining has been eroded by 327 mm at the point of measurement. The similar inference can be made for any deposit inside the furnace. For a Ferro Silicon furnace this deposit shall be Silicon Carbide with conduction coefficient of 3 W/m^{0}K. In this case the thermocouples will read temperatures below the designed ones, which will result in less heat flux density than the designed one.

4 PRINCIPLE OF LINING MANAGEMENT WITHOUT THERMOCOUPLE / SINGLE THERMOCOUPLES:

Again the 28.5 MVA furnace of Bhutan is taken into consideration. In this Lining Management System, all linings i.e. Bottom Lining, Side Wall Lining & Tap Hole Zone lining shall be discussed. The bottom lining layers are described in Table No. 1. The Tap hole zone lining layers are described in Table No. 2 and side wall lining layers are described in Table No. 3. Total design thickness of furnace side wall is 1076mm, including shell steel. Total design thickness of furnace tap hole zone is 1166 mm, including shell steel.

Table 5: Layer details of Tap Hole Zone Lining

S.N.	LAYER MATERIAL (FROM INSIDE)	LAYER THICKNESS (mm)
1	Carbon Masse	700

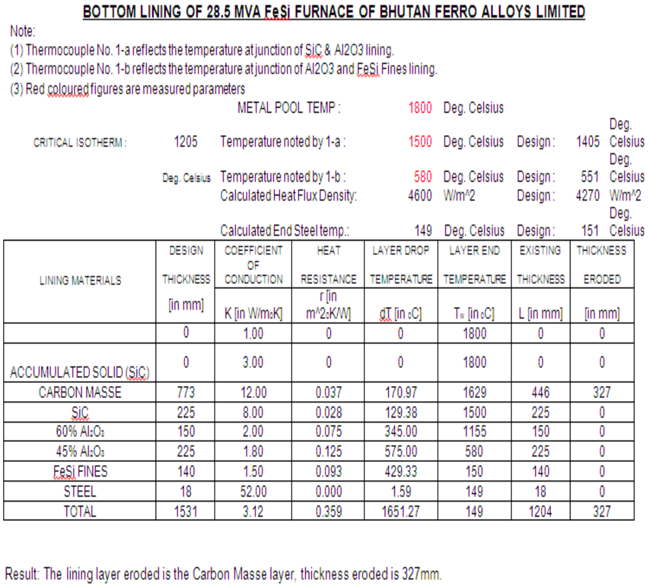
2	Silicon Carbide	450
3	Steel	16

Table 6: Layer details of Side Wall Lining

S.N.	LAYER MATERIAL (FROM INSIDE)	LAYER THICKNESS (mm)
1	Carbon Masse	700
2	Unicast Refractory	30
3	45% Al2O3 Brick	300
4	Mineral Wool	30
5	Steel	16

The molten metal temperature is 1800 deg. Celsius in the hearth for bottom lining, design heat flux density is 4270 Watts/M^2 and design end steel temperature is 151 deg. Celsius. Metal pool temperature is 1400 deg. Celsius for side wall lining, design heat flux density is 4120 Watts/M^2 and design end steel temperature is 163 deg. Celsius. Metal pool temperature is 1400 deg. Celsius for tap hole zone lining, design heat flux density is 10000 Watts/M^2 and design end steel temperature is 400 deg. Celsius.

Further, the instrument measures the heat flux density & temperature on the surface of the furnace side wall, bottom & near tap holes (T.H.) at different points. The instrument readings are noted for these areas in Table No. 8, 9 & 10. From this heat flux density & temperature of molten metal, the present lining condition can be inferred (Table No. 5, 6 & 7).



BOTTOM LINING OF 28.5 MVA FeSi FURNACE OF BHUTAN FERRO ALLOYS LIMITED

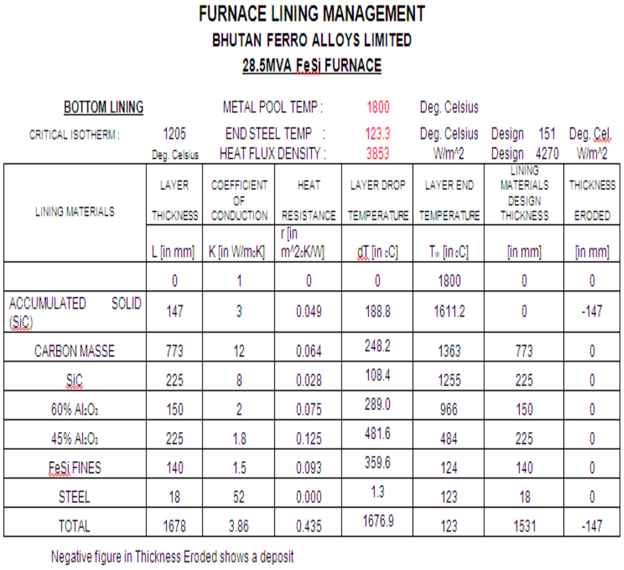
Note:
(1) Thermocouple No. 1-a reflects the temperature at junction of SiC & Al2O3 lining.
(2) Thermocouple No. 1-b reflects the temperature at junction of Al2O3 and FeSi Fines lining.
(3) Red coloured figures are measured parameters

METAL POOL TEMP : 1800 Deg. Celsius
CRITICAL ISOTHERM : 1205 Deg. Celsius
Temperature noted by 1-a : 1500 Deg. Celsius Design : 1405 Deg. Celsius
Temperature noted by 1-b : 580 Deg. Celsius Design : 551 Deg. Celsius
Calculated Heat Flux Density: 4600 W/m^2 Design : 4270 W/m^2
Calculated End Steel temp.: 149 Deg. Celsius Design : 151 Deg. Celsius

LINING MATERIALS	DESIGN THICKNESS [in mm]	COEFFICIENT OF CONDUCTION	HEAT RESISTANCE	LAYER DROP TEMPERATURE	LAYER END TEMPERATURE	EXISTING THICKNESS	THICKNESS ERODED
		K [in W/m₀K]	r [in m^2₀K/W]	dT [in ₀C]	Tw [in ₀C]	L [in mm]	[in mm]
	0	1.00	0	0	1800	0	0
ACCUMULATED SOLID (SiC)	0	3.00	0	0	1800	0	0
CARBON MASSE	773	12.00	0.037	170.97	1629	446	327
SiC	225	8.00	0.028	129.38	1500	225	0
60% Al_2O_3	150	2.00	0.075	345.00	1155	150	0
45% Al_2O_3	225	1.80	0.125	575.00	580	225	0
FeSi FINES	140	1.50	0.093	429.33	150	140	0
STEEL	18	52.00	0.000	1.59	149	18	0
TOTAL	1531	3.12	0.359	1651.27	149	1204	327

Result: The lining layer eroded is the Carbon Masse layer, thickness eroded is 327mm.

Table No. 4



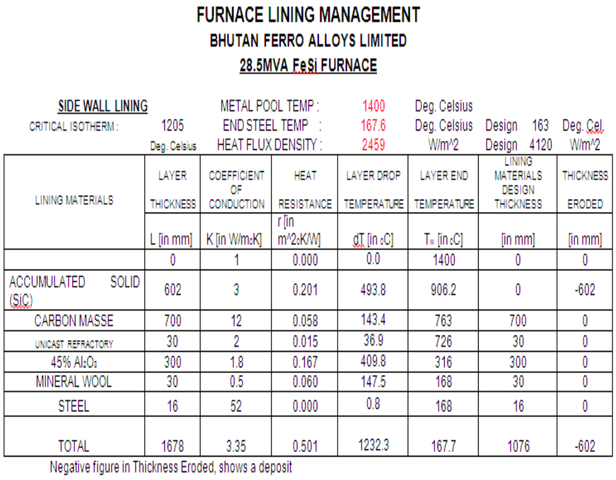
FURNACE LINING MANAGEMENT
BHUTAN FERRO ALLOYS LIMITED
28.5MVA FeSi FURNACE

BOTTOM LINING METAL POOL TEMP : 1800 Deg. Celsius
CRITICAL ISOTHERM : 1205 Deg. Celsius
END STEEL TEMP : 123.3 Deg. Celsius Design 151 Deg. Cel.
HEAT FLUX DENSITY : 3853 W/m^2 Design 4270 W/m^2

LINING MATERIALS	LAYER THICKNESS	COEFFICIENT OF CONDUCTION	HEAT RESISTANCE	LAYER DROP TEMPERATURE	LAYER END TEMPERATURE	LINING MATERIALS DESIGN THICKNESS	THICKNESS ERODED
	L [in mm]	K [in W/m₀K]	r [in m^2₀K/W]	dT [in ₀C]	Tw [in ₀C]	[in mm]	[in mm]
	0	1	0	0	1800	0	0
ACCUMULATED SOLID (SiC)	147	3	0.049	188.8	1611.2	0	-147
CARBON MASSE	773	12	0.064	248.2	1363	773	0
SiC	225	8	0.028	108.4	1255	225	0
60% Al_2O_3	150	2	0.075	289.0	966	150	0
45% Al_2O_3	225	1.8	0.125	481.6	484	225	0
FeSi FINES	140	1.5	0.093	359.6	124	140	0
STEEL	18	52	0.000	1.3	123	18	0
TOTAL	1678	3.86	0.435	1676.9	123	1531	-147

Negative figure in Thickness Eroded shows a deposit

Table No. 5



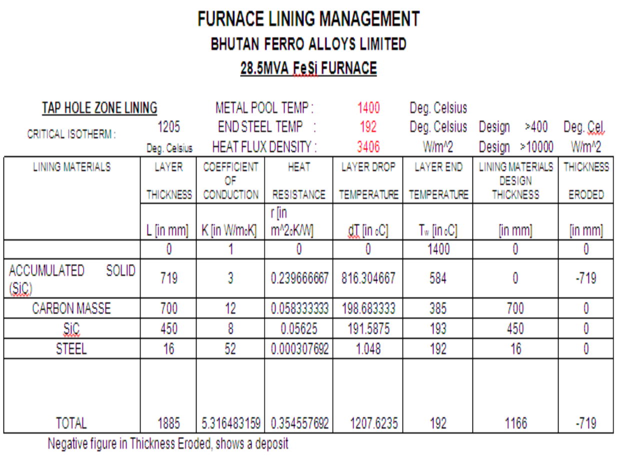
FURNACE LINING MANAGEMENT
BHUTAN FERRO ALLOYS LIMITED
28.5MVA FeSi FURNACE

SIDE WALL LINING METAL POOL TEMP : 1400 Deg. Celsius
CRITICAL ISOTHERM : 1205 END STEEL TEMP : 167.6 Deg. Celsius Design 163 Deg. Cel.
Deg. Celsius HEAT FLUX DENSITY : 2459 W/m^2 Design 4120 W/m^2

LINING MATERIALS	LAYER THICKNESS	COEFFICIENT OF CONDUCTION	HEAT RESISTANCE	LAYER DROP TEMPERATURE	LAYER END TEMPERATURE	LINING MATERIALS DESIGN THICKNESS	THICKNESS ERODED
	L [in mm]	K [in W/m°K]	r [in m^2°K/W]	dT [in °C]	T_w [in °C]	[in mm]	[in mm]
	0	1	0.000	0.0	1400	0	0
ACCUMULATED SOLID (SiC)	602	3	0.201	493.8	906.2	0	-602
CARBON MASSE	700	12	0.058	143.4	763	700	0
UNICAST REFRACTORY	30	2	0.015	36.9	726	30	0
45% Al_2O_3	300	1.8	0.167	409.8	316	300	0
MINERAL WOOL	30	0.5	0.060	147.5	168	30	0
STEEL	16	52	0.000	0.8	168	16	0
TOTAL	1678	3.35	0.501	1232.3	167.7	1076	-602

Negative figure in Thickness Eroded, shows a deposit

Table No. 6



FURNACE LINING MANAGEMENT
BHUTAN FERRO ALLOYS LIMITED
28.5MVA FeSi FURNACE

TAP HOLE ZONE LINING METAL POOL TEMP : 1400 Deg. Celsius
CRITICAL ISOTHERM : 1205 END STEEL TEMP : 192 Deg. Celsius Design >400 Deg. Cel.
Deg. Celsius HEAT FLUX DENSITY : 3406 W/m^2 Design >10000 W/m^2

LINING MATERIALS	LAYER THICKNESS	COEFFICIENT OF CONDUCTION	HEAT RESISTANCE	LAYER DROP TEMPERATURE	LAYER END TEMPERATURE	LINING MATERIALS DESIGN THICKNESS	THICKNESS ERODED
	L [in mm]	K [in W/m°K]	r [in m^2°K/W]	dT [in °C]	T_w [in °C]	[in mm]	[in mm]
	0	1	0	0	1400	0	0
ACCUMULATED SOLID (SiC)	719	3	0.239666667	816.304667	584	0	-719
CARBON MASSE	700	12	0.058333333	198.683333	385	700	0
SiC	450	8	0.05625	191.5875	193	450	0
STEEL	16	52	0.000307692	1.048	192	16	0
TOTAL	1885	5.316483159	0.354557692	1207.6235	192	1166	-719

Negative figure in Thickness Eroded, shows a deposit

Table No. 7

Table 8: Side Wall Lining Parameters

[1300 mm Height From Bottom]

PLACE	FLUX DENSITY (W/m2)	TEMP. (Deg. Celsius)	THIC. EROD. (mm)
T.H.1 Right			
500 mm	2459	167.6	-602
1000 mm	3321	187	-195
T.H.1 Left			
500 mm	3062	198.1	-277
1000 mm	3637	191.4	-96
T.H.2 Right	[Running Taphole]		
500 mm	2561	164	-547
1000 mm	2835	176.6	-393
T.H.2 Left	[Running Taphole]		
500mm	2734	185.9	-431
1000 mm	3260	188.9	-214
T.H.3 Right			
500mm	2436	161.1	-625
1000 mm	2850	208.1	-354
T.H.3 Left			
500 mm	3026	184.2	-305
1000 mm	3869	202.8	-27
T.H.4 Right			
500 mm	3366	235.2	-137
1000 mm	3451	216.3	-128
T.H.4 Left			
500 mm	2613	211.6	-463
1000 mm	3312	206.4	-181
T.H.5 Right			
500 mm	2470	234.6	-514
1000 mm	2748	219.2	-388
T.H.5 Left			
500 mm	3430	194	-154
1000 mm	4020	180.9	-9

Table 9: Bottom Lining Parameters

PLACE	FLUX DENSITY (W/m2)	TEMP. (Deg. Celsius)	THIC. EROD. (mm)
EL-1	3853	123.3	-147
EL1 & EL2	3892	142.9	-119
EL-2	3606	131.9	-229
EL2 & EL3	3971	151.1	-87
EL-3	4285	142.4	-2
EL3 & EL1	3835	126.1	-151

Table 10: Tap Hole Zone Lining Parameters [1300 mm Height from Bottom]

PLACE	FLUX DENSITY (W/m2)	TEMP. (Deg. Celsius)	THIC. EROD. (mm)
T.H.1 Right 100 mm	3406	192	-719
T.H.1 Left 100 mm	4303	245.7	-460
T.H.2 Right 100 mm	[Running Taphole] 2100	141.5	-1453
T.H.2 Left 100 mm	[Running Taphole] 3516	232	-652
T.H.3 Right 100 mm	3363	213.5	-713
T.H.3 Left 100 mm	3990	234.3	-532
T.H.4 Right 100 mm	5650	242.2	-270
T.H.4 Left 100 mm	6269	271	-196
T.H.5 Right 100 mm	4573	262	-402
T.H.5 Left 100 mm	5589	289.7	-251

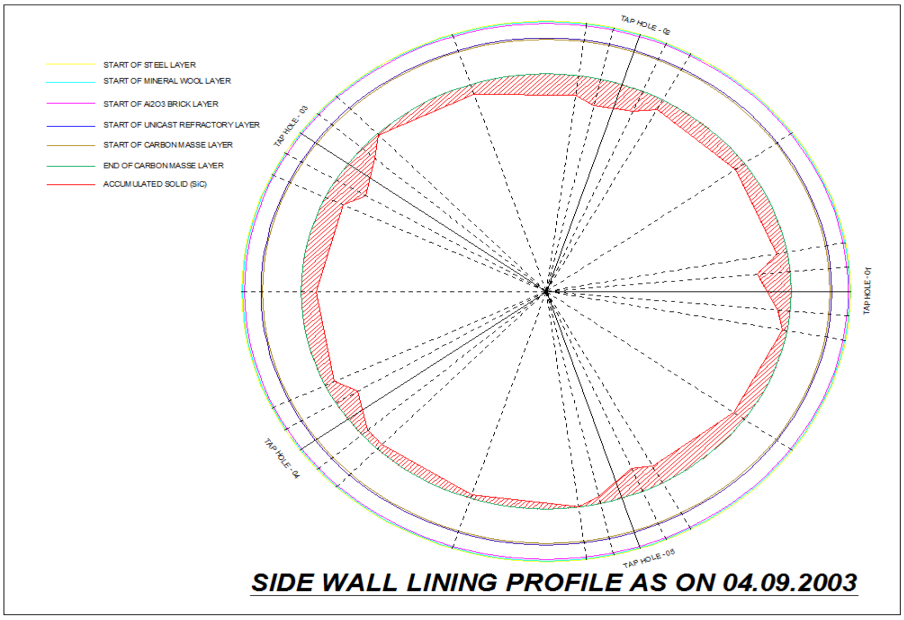


Figure 10: Side Wall Lining Profile

In the given example (Table No. 5) it is clear that there is a deposit on the bottom (at the point of measurement) of 147 mm of Silicon Carbide. As noted in the Table No. 6, the deposit at the point of measurement on side wall lining is 602 mm and according to Table No. 7, the deposit at the point of measurement on tap hole zone lining is 719 mm.

Different measurement points can be fed back to PLC/DCS to draw the 3 dimensional view of the remaining lining. This can be done online or offline. Online data will be able to present the dynamic 3D lining profile of the furnace.

5 CONCLUSION:

The Lining Management system provides the operations staff with tools to predict long term lining life and process optimization. It provides knowledge that can be used to insure the longest life possible for refractory, as well as effective and efficient operation of a furnace.

The Lining Management system will prove to be of huge benefit to any furnace operation. It is the only means to get detailed information on ever changing refractory lining. It gives the ability to constantly monitor the furnace refractory lining. It monitors the refractory wear and hot face temperatures at various points in the furnace, and have the following main benefits:

- Prolong refractory life.
- Makes it possible to draw 3D view of remaining refractory for the furnace & isothermal view of the furnace refractory hot face.
- Provides real–time refractory wear, heat flux, hot face temperature and shell temperatures.
- The various images give the furnace operator an overall view of the current lining conditions.
- Identifies problem areas, and gives sufficient warning to take remedial action.
- Prevent costly down time from burn through.

In this way the common temperature-dependent wear mechanisms are prevented and a long lifetime of a furnace is assured.

6 REFERENCES:

[1] Holman, J.P., “Heat transfer”, Mechanical Engineering series, McGraw-Hill Book Co., 1989
[2] P. L. Duncanson, P. Sylven, New Refractory Lining Direction at Jindal Stainless - first Indian
[3] Hugo Joubert, DanieBenade, Wayne Burmeister and Louis Meyer1, A LINING MANAGEMENT SYSTEM FOR SUBMERGED ARC FURNACES
[4] A.V.L. Narasimham, REFRACTORY LINING FAILURES IN FECR FURNACES AN OVER VIEW

7 DEDICATED TO:

My Parents GopinathMohanty&SnehalataMohanty
For giving me the gifts of Roots & Wings
&
My Wife Susmita Jena
For inspiring me to dream and for encouraging me to dare.