Evaluation of Furnace Refractory Linings after Sixteen Years of Producing Silicomanganese

Paul O'Shaughnessy[1] and Ferdus Le Roux[2]

1. OCTC Limited, Hull, England
2. BHP Billiton, Johannesburg, South Africa

Abstract:

The South Plant of BHP Billiton at Meyertonin South Africa has five furnaces in which UCAR®ChillKote™ freeze linings had been installed for the production of silicomanganese between 1996 and 2012. A core drilling program was carried out to determine the integrity of the linings after service and the thickness of slag freezing on the carbon brick hot face. A total of 180 cores of lining material and slag were collected, mapped and analysed. The paper explains core selection, analytical results of the cores, mapping of the linings and the operating performance of the furnaces to demonstrate the interconnection between the process and refractory lining.

1. INTRODUCTION

BHPBilliton operates a manganese ferroalloy plant at Meyerton in South Africa, which is divided into three sections known as the South, North and West plants. South Plant is the oldest section which started operations more than sixty years ago. The furnaces in South Plant have been upgraded over this period [1,2,3] and by 1996, only the 15 MW furnaces remained. Five furnaces of the same size were established over a ten year period up to 2006. South Plant was decommissioned in January, 2012. A demolition program started in 2013 to clear the equipment and buildings and generate a brownfield site.

While the UCAR freeze lining had been applied to blast furnaces since the 1950's [4], it was during the 1980s that Samancor Manganese started to investigate the technical background for a freeze lining for submerged arc furnaces producing manganese ferroalloys [5,6]. This investigation was initiated as a result of frequent lining failures caused by the erosion of carbon materials by process slags. The first complete freeze lining was installed on M4 at South Plant in 1996 which was then producing silicomanganese. During the next ten years, the other four furnaces, namely M1, M2, M3 & M5 were rebuilt with freeze linings.

South Plant had a single raw material day bin and batching plant which feeds all of the five furnaces in a single building. Each furnace has a tapping pit for ladles and slag pots. The metal was transferred to a casting section at one end of the building while the slag was dumped into a pit at the other end of the building. The five South Plant furnaces were essentially the same with an electrode diameter of 1,143 mm or 45 inches, and with a Pitch Circle Diameter (PCD) of about 2,950 mm.

GrafTech and ChillKote are trademarks of GrafTech International Holdings Inc. UCAR® is a registered trademark used under license by GrafTech International Holdings Inc.

2. UCAR CHILLKOTE LININGS

The basic design used on all five furnaces is shown in Figures 1 and 2.

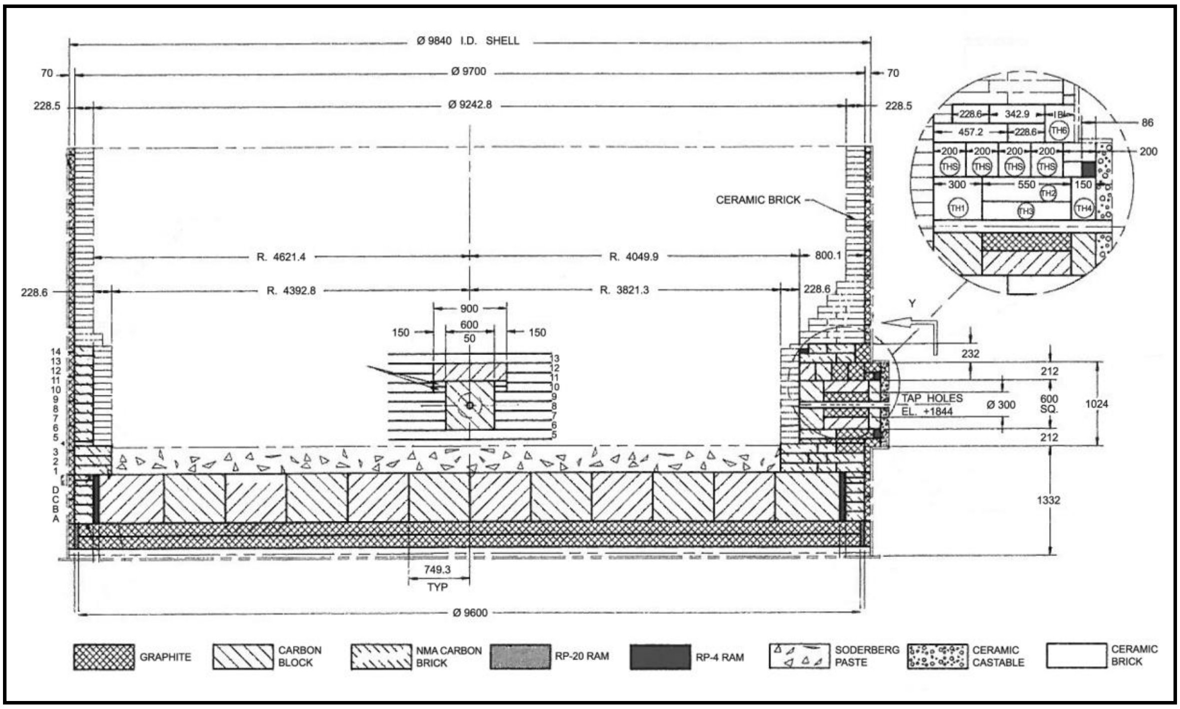


Figure 1: Furnace Lining

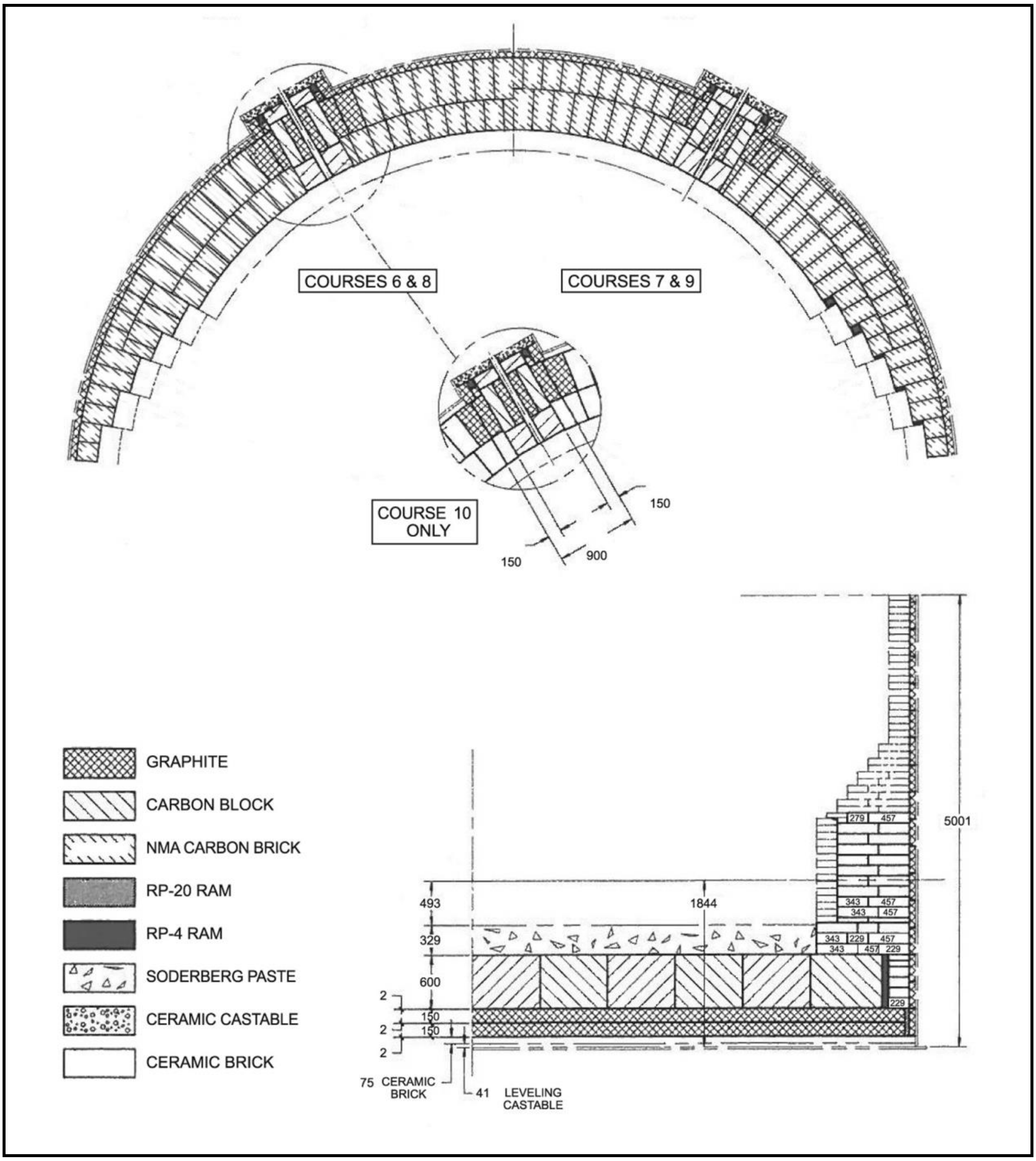


Figure 2: Taphole abutment and hearth details

The hearth is made up of alumina brick, graphite block, carbon block and carbon paste. The sidewalls have a graphite tile against the shell, then carbon brick and an alumina brick layer for protection during start-up. The thickness of the carbon brick depth was increased between and to the sides of the two tap holes, in what is termed an abutment. The shells were water cooled and the bottom plates raised onto grillage beams and air cooled. A record of ChillKote lining campaigns is given in Table 1.

Table1: ChillKote lining campaigns on all the South plant furnaces since 1996.

Furnace	M1	M2	M3	M4	M5
Start up	2000	2003	2006	June, 1996	2005
Campaign	11.5 years	8.8 years	5.2 years	15.5 years	6.6 years
Operating Time	10.5 years	8.0 years	4.7 years	13.8 years	6.2 years
Thermal cycles	5	5	2	6	2
Total GWh	1,186.45	875.14	517.08	1,541.54	726.03

A thermal cycle is defined as when the lining is heated to operating temperature and then cooled down again. The M4 lining was in use for the longest period, during which there were six thermal cycles amounting to a total of 2.7 years, as shown in Figure 1. The next longest lining campaign was on M1, during which there were five thermal cycles of 1.0 years. The linings on M4 and M1 therefore represent the greatest combination of full power operations combined with thermal cycling, leading to conditions in which lining deterioration might be expected to occur.

3. FURNACE OPERATIONS OVERVIEW

Hot metal production at South Plant from 1996 until 2012 is shown in Figure 3 below:

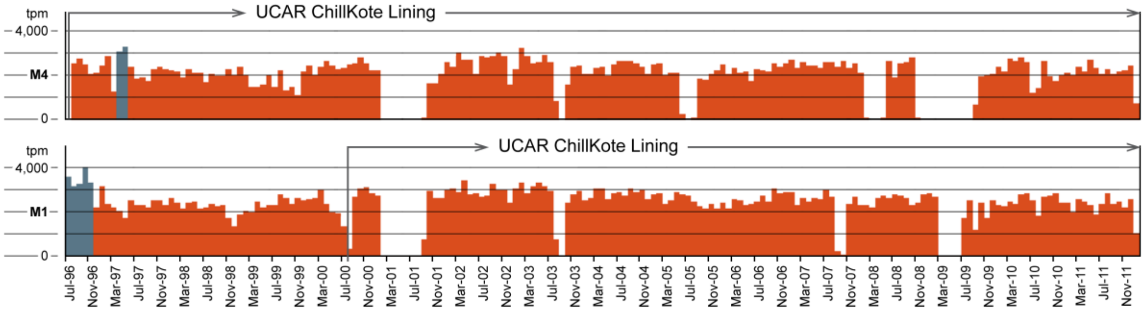


Figure 3: Hot metal production on South Plant furnaces.

The principal product was silicomanganese, with only short periods when high carbon ferromanganese was produced.

Operating parameters on M1 and M4 are shown in the following figures 4 to 7 from 2003 onwards, periods when the UCARChillKote linings were in use.

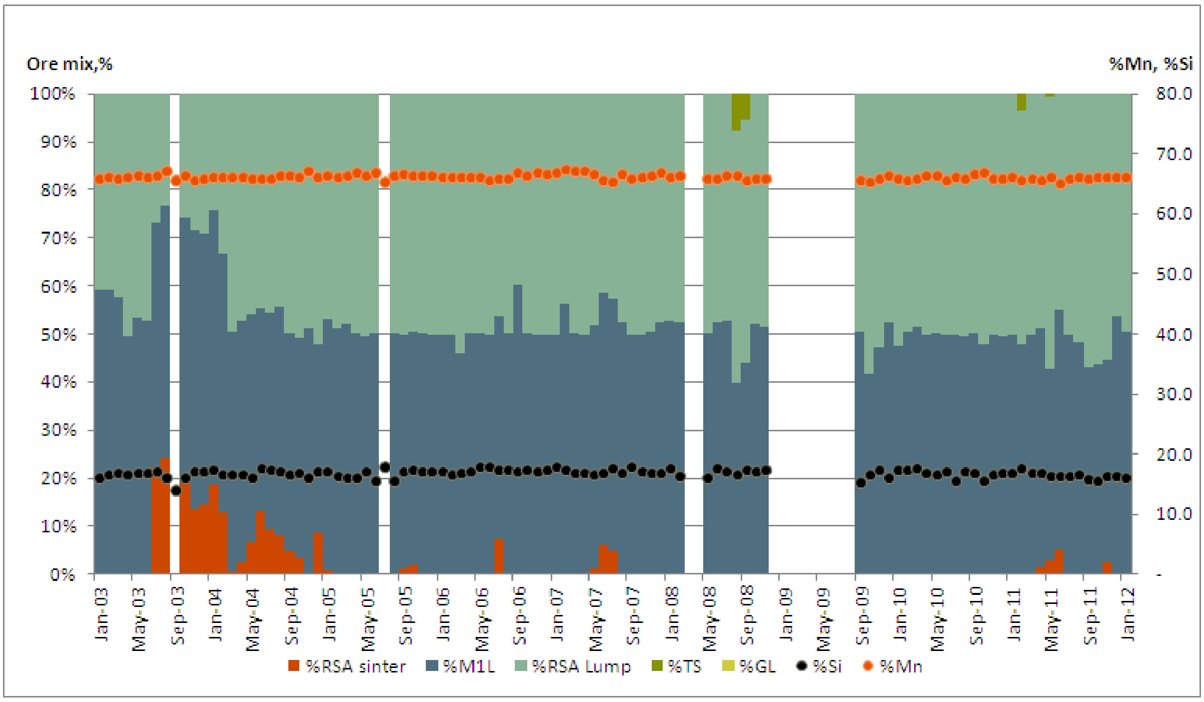


Figure 4: M4 ore mix and alloy analysis (RSA sinter is sinter from Mamatwan mine, M1L is lumpy ore from Mamatwan mine, RSA Lump is either W1L or W4L from Wessels mine, TS is Temco sinter and GL is Gemco lump)

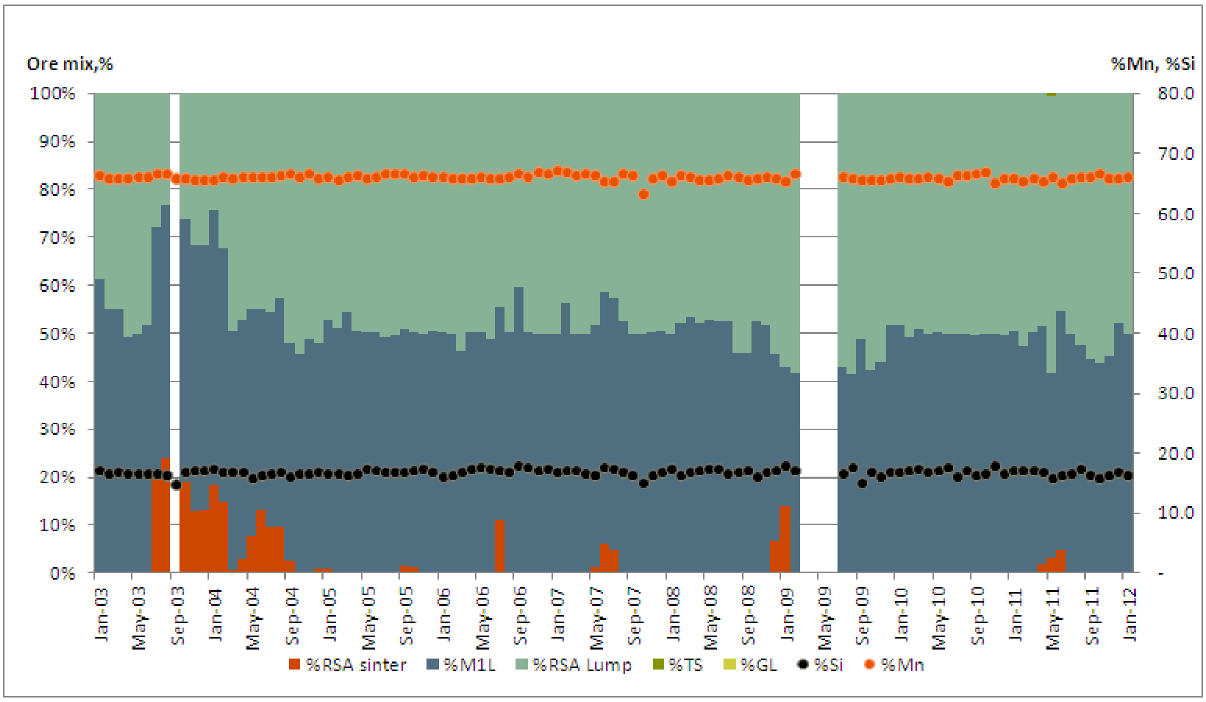


Figure 5: M1 ore mix and alloy analysis (RSA sinter is sinter from Mamatwan mine, M1L is lumpy ore from Mamatwan mine, RSA Lump is either W1L or W4L from Wessels mine, TS is Temco sinter and GL is Gemco lump)

The principal ores were Mamatwan and Wessels lump, standard grades mined by BHPBilliton, with occasional use of sintered ore produced in South Africa. Alloy grade was consistently maintained at about 66 percent manganese and 16 to 17 percent silicon.

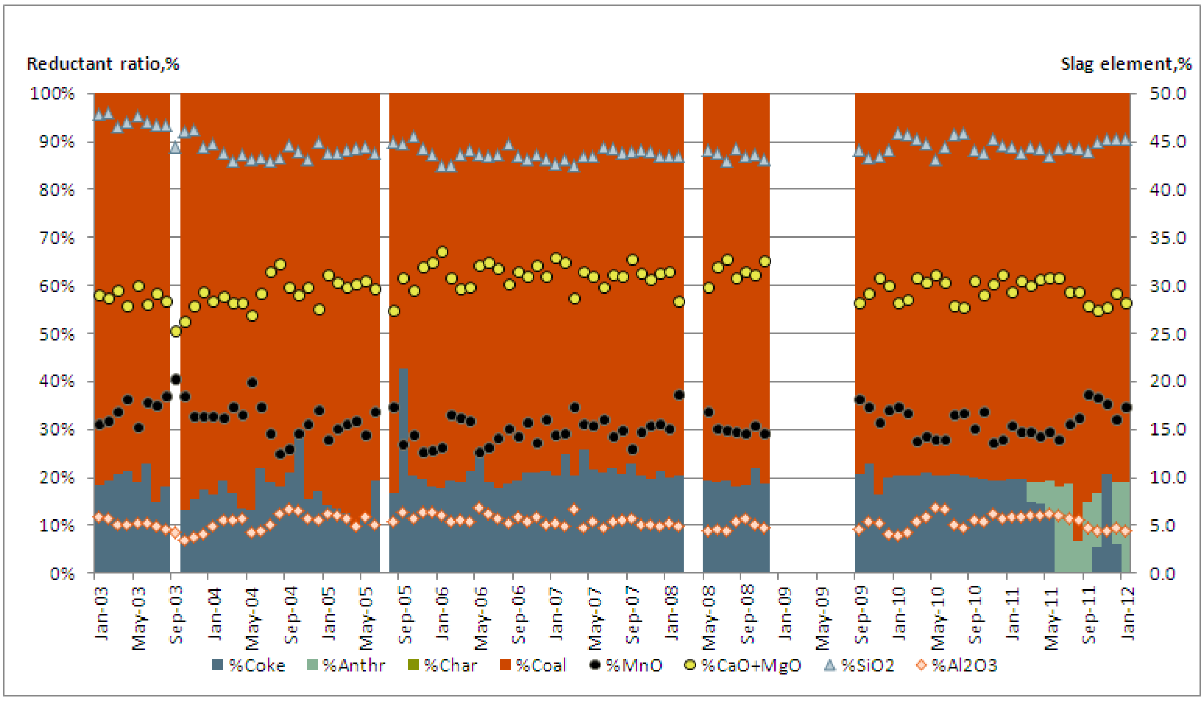


Figure 6: M4 reductant blend and slag chemistry.

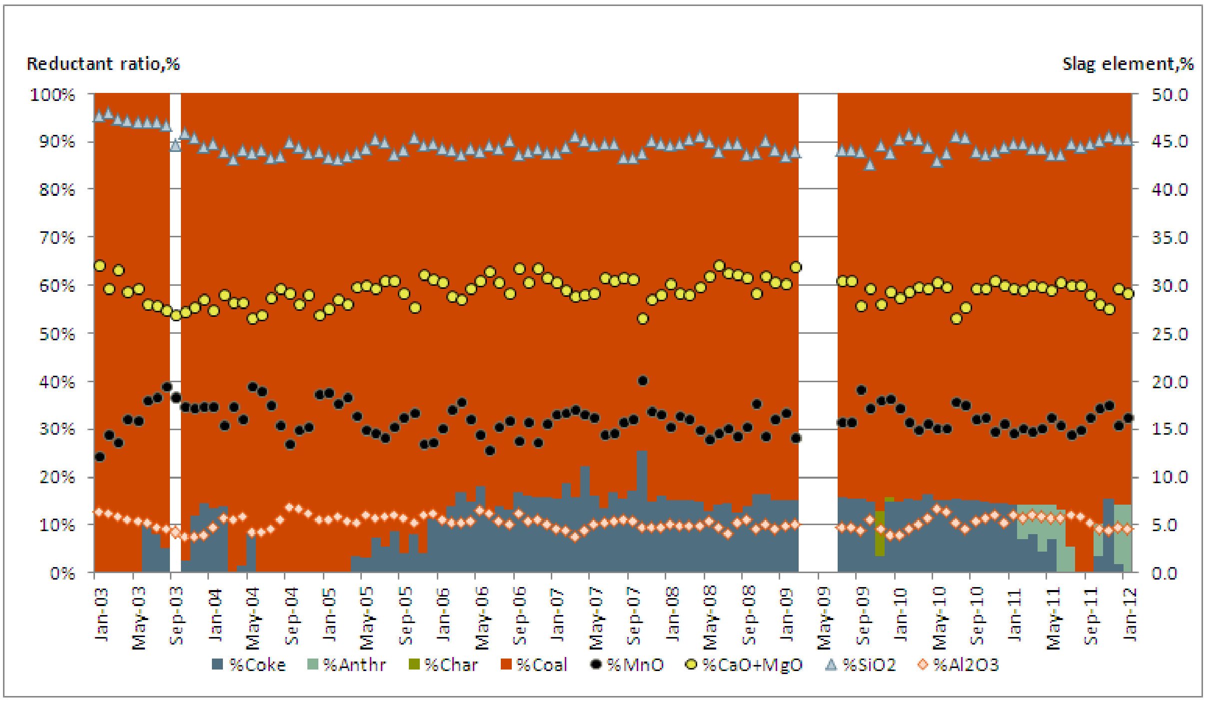


Figure 7: M1 reductant blend and slag chemistry.

Reductant was principally coal with between 10 and 20 percent coke which was replaced in the last 12 months of operation by anthracite. The slag contained on average about 16% MnO, 45% SiO_2, 5% Al_2O_3 and 30% CaO and MgO. The slag basicity was about 0.6 to 0.7.

4. CORE DRILLING PROGRAM

The plan for core drilling was to divide each lining into six sections in the horizontal and vertical planes. The principal horizontal sections have been designated as follows and are illustrated in Table 2 and Figure 8.

Table 2: Horizontal drilling pattern and designation.

N	North	Between tap holes, closest to the front electrode, inside the abutment
NE	North East	To the right of one tap hole, inside the abutment
SE	South East	Close to one back electrode
S	South	Furthest from the smelting zone
SW	South West	Close to the other back electrode
NW	North West	To the left of the other tap hole, inside the abutment

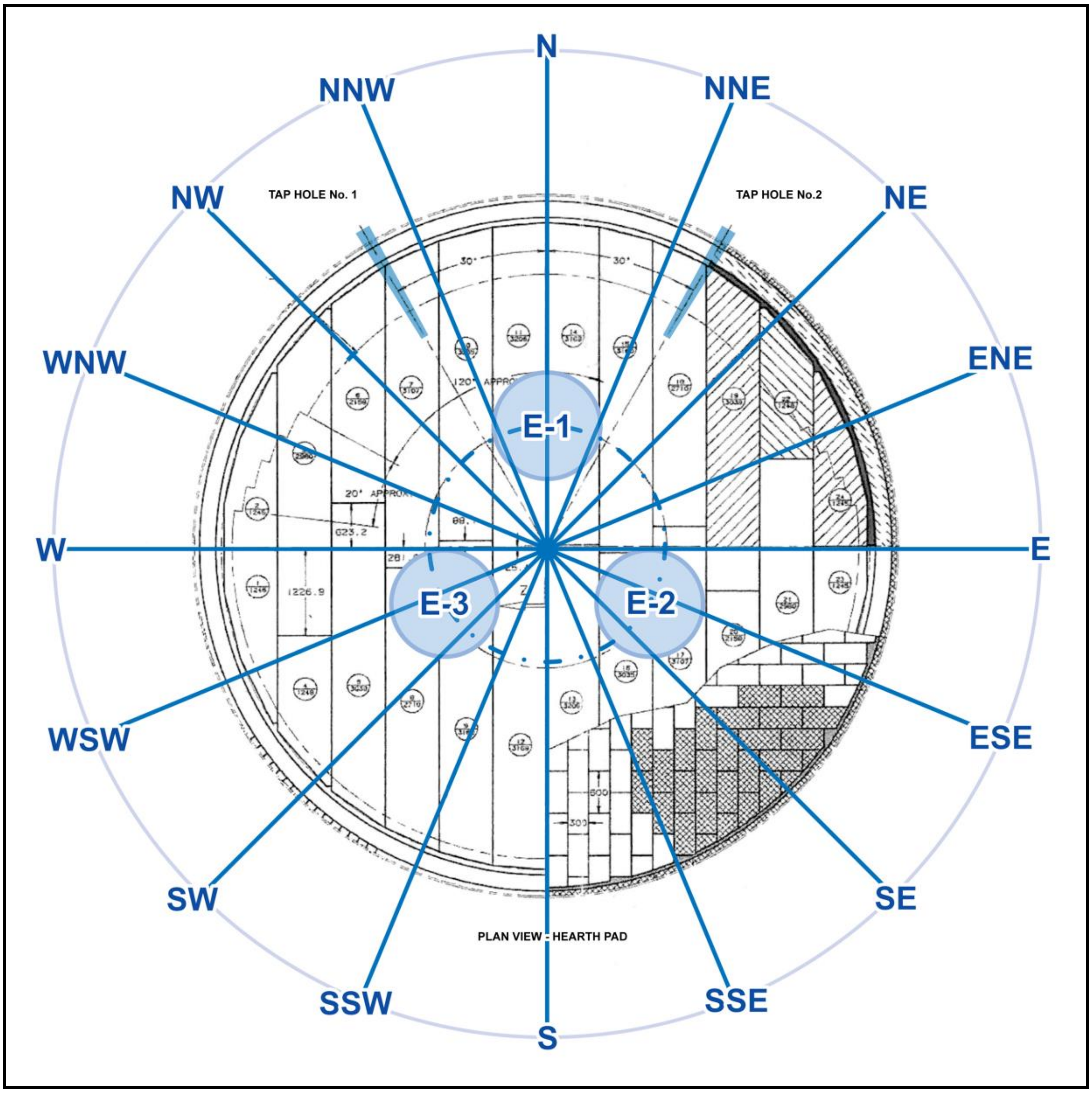


Figure 8: Nomenclature used to describe core positions

In this three-electrode configuration, the N, SE and SW positions are where the process heat source is closest to the lining. The NE and NW positions are adjacent to the channels through which the metal and slag are tapped. The S position will therefore be least affected by the smelting conditions, being furthest from the electrodes and the tap holes.

The vertical sections, which are referred to as Levels, are shown by the shell cut-outs in Figure 9 below. Levels 1 to 3 are above, and Levels 4 to 6 are at and below the taphole centreline. The elevations on furnaces M1 and M4 are different because of practical considerations. Access to level 6 was generally problematic and required partial removal of concrete platforms. In addition, the water feed pipes and the return launder needed to be partially removed to allow for access to levels 5 and 6. Figures 10, 11 and 12 provide details of the core drilling equipment that was used.

Figure 9: Work environment

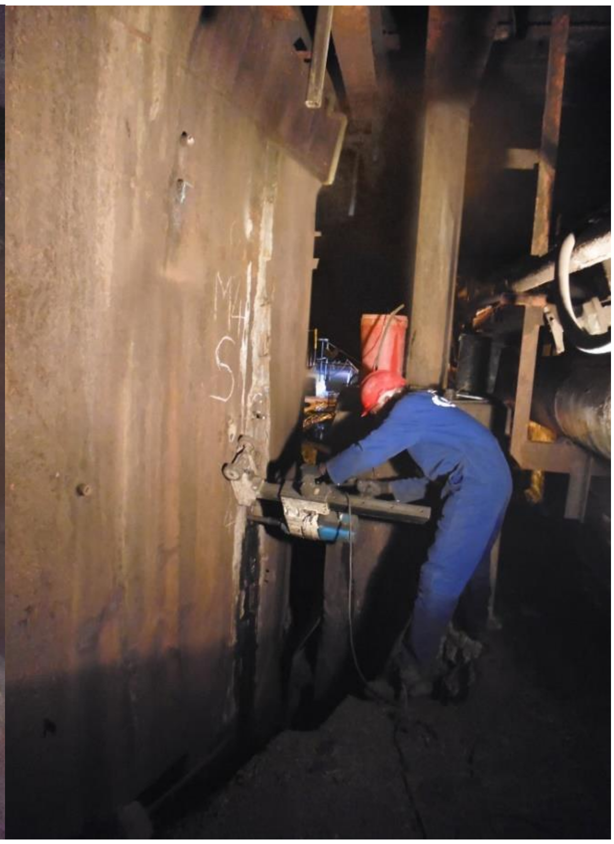


Figure 10: Core Drilling Equipment

Figure 11: Core Drilling Equipment

Figure 12: Drill Detail

A 50 mm diameter core was extracted. During the first stage, cores were drilled to a depth of 700 mm which is about 200 mm deeper than the carbon lining in the sidewalls outside of the tap hole abutment. At a second stage, the depth of some cores was extended a further 500 mm to complete data collection on the condition of the abutment and the extent of slag freeze.

5. CORES RECOVERED FROM FURNACES M4 AND M1

The cores recovered from the linings are shown in the following series of photographs. The positions of these cores have been superimposed onto the furnace outline shown in Figure 13.

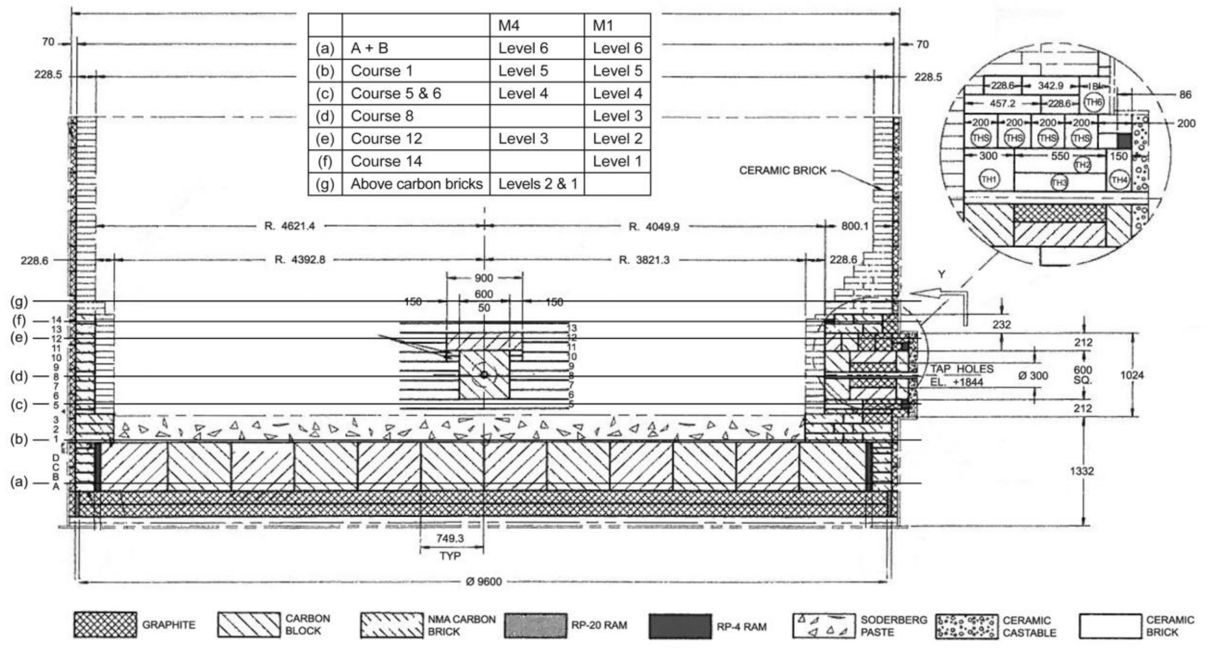
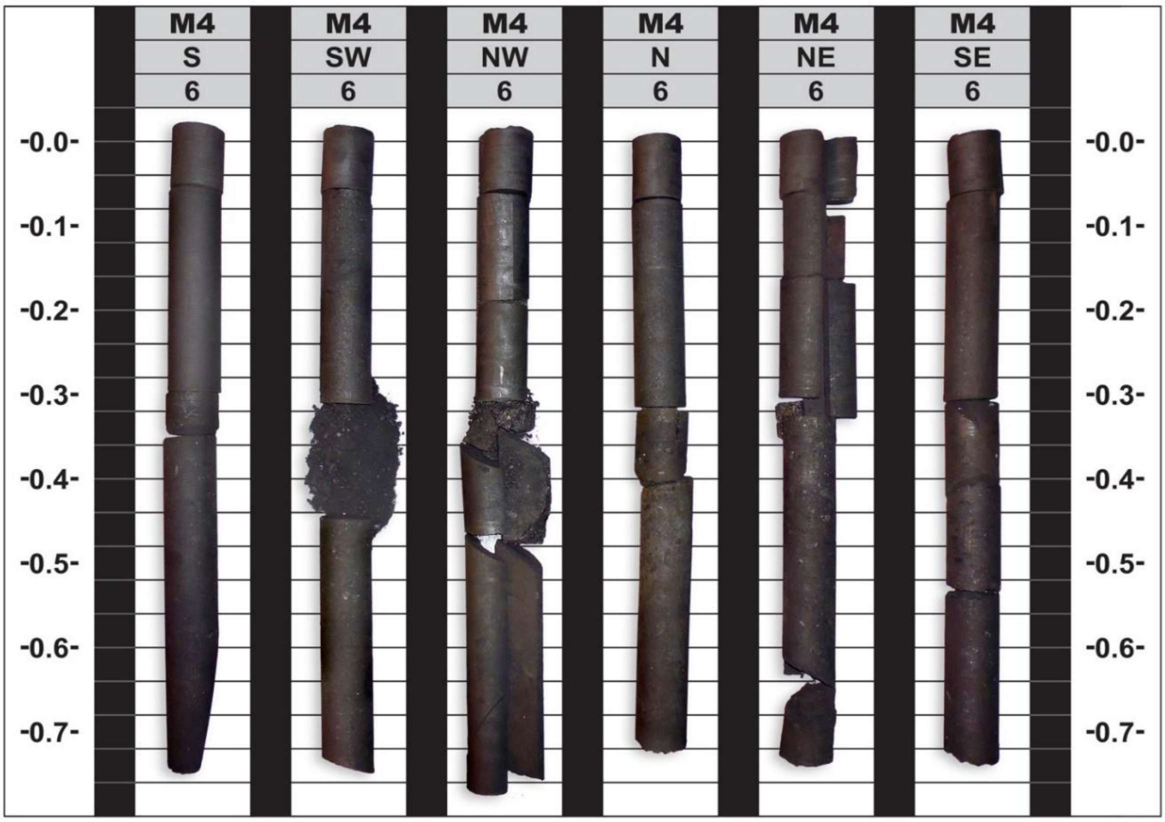
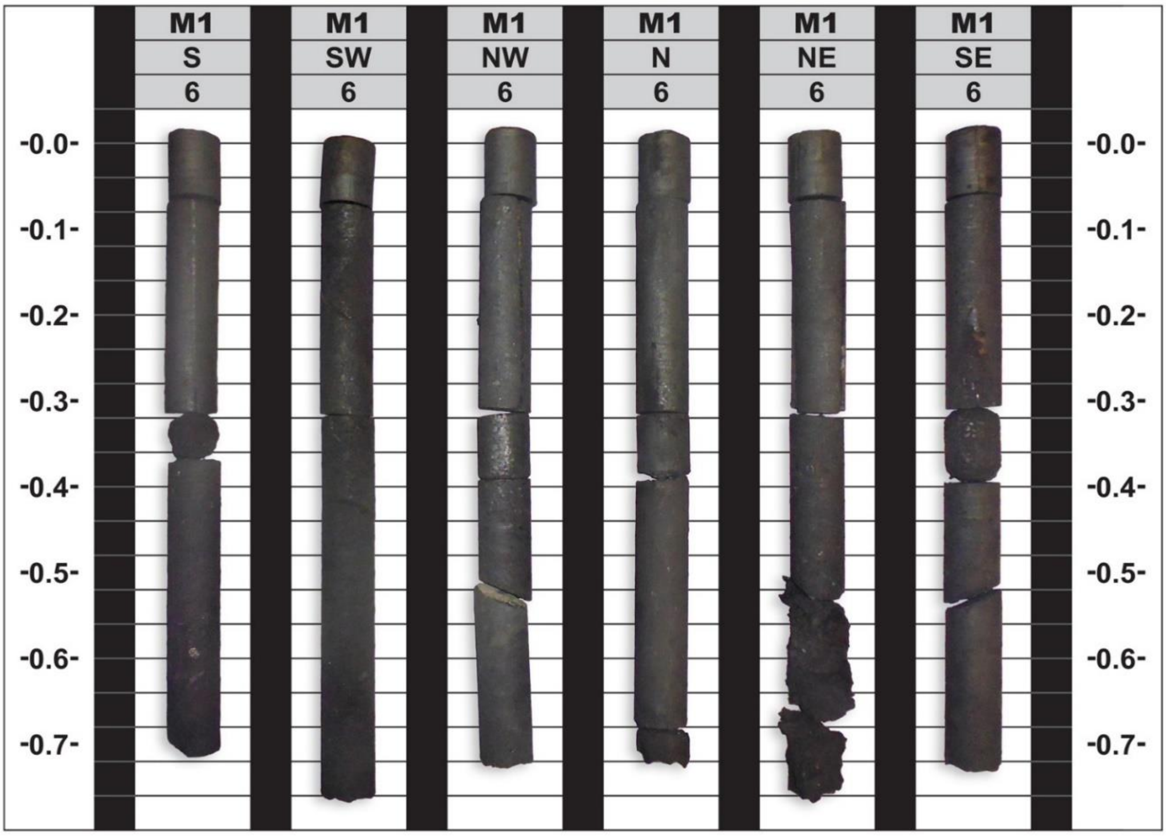


Figure 13: Position of Cores superimposed on the Lining Drawing

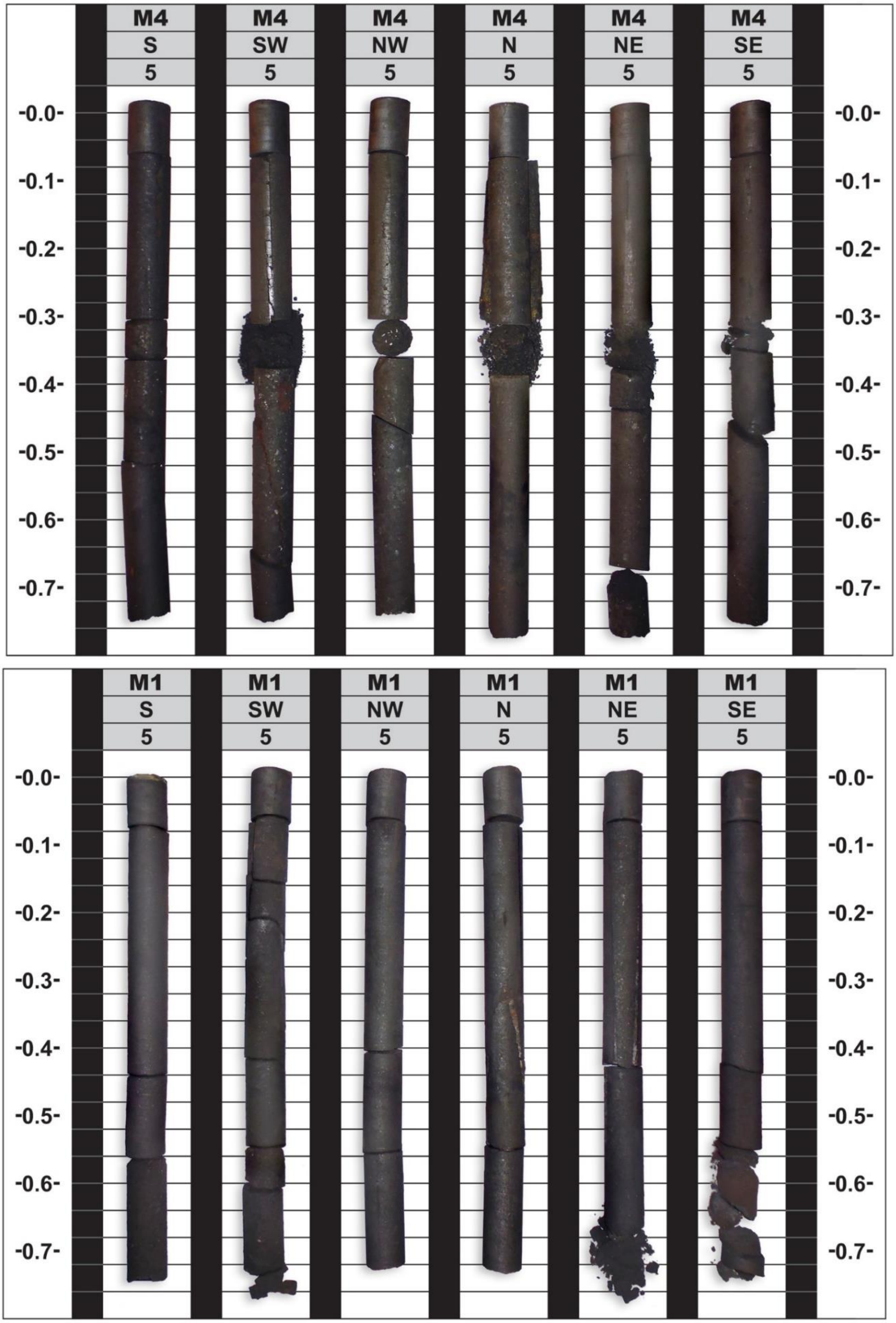
Brick Course A-B: level 6 on M4 & M1: At the lower end of the carbon blocks and above the graphite layer in the hearth





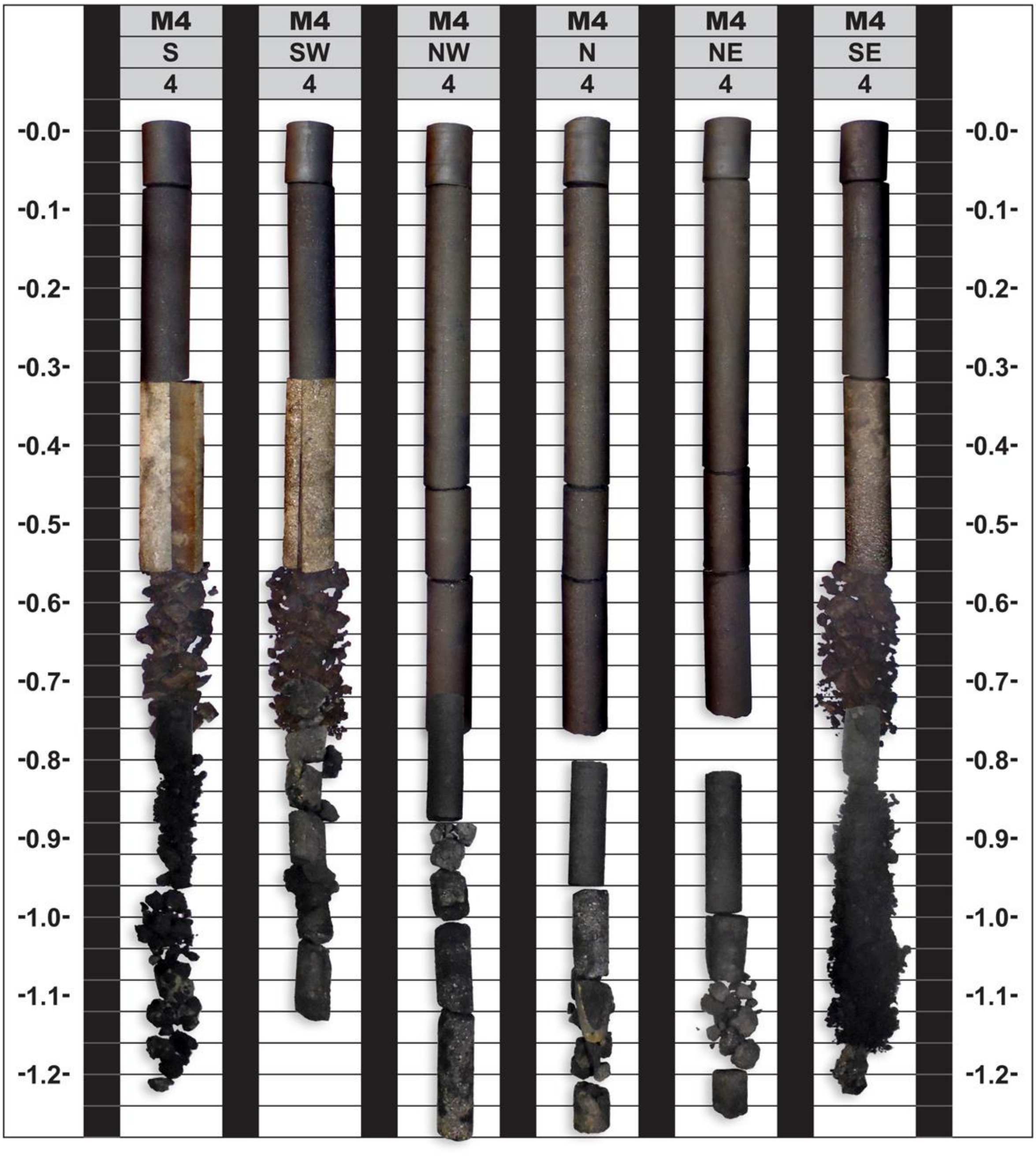
All cores included 70 mm of graphite and 230 mm of carbon brick before intersecting the carbon block. Ramming paste, used as filler at the periphery of the carbon blocks adjacent to the carbon bricks, was also recovered. The paste did not always retain its structure during drilling operations.

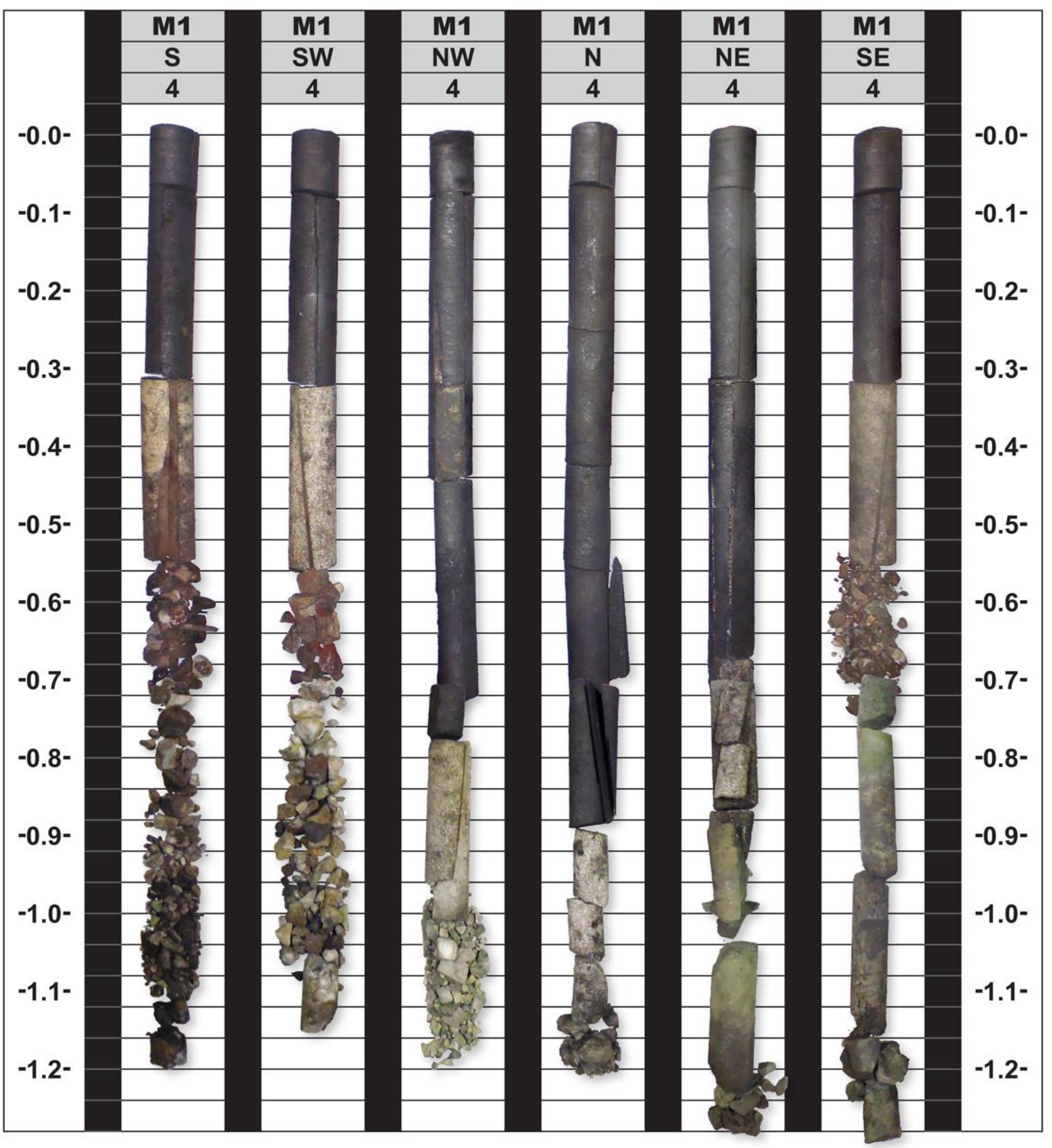
Brick Course No.1: level 5 on M4 and M1: In the carbon paste layer and above the carbon blocks in the hearth


M4 S 5
M4 SW 5
M4 NW 5
M4 N 5
M4 NE 5
M4 SE 5
-0.0-
-0.1-
-0.2-
-0.3-
-0.4-
-0.5-
-0.6-
-0.7-
M1 S 5
M1 SW 5
M1 NW 5
M1 N 5
M1 NE 5
M1 SE 5
-0.0-
-0.1-
-0.2-
-0.3-
-0.4-
-0.5-
-0.6-
-0.7-

All cores included 70 mm of graphite and 230 or 460 mm of carbon brick before intersecting the carbon block. Ramming paste was also in place on M4 but not on M1. According to the drawings, the hearth ramming should have been intersected. It is possible that the carbon block was installed higher than indicated on the drawing.

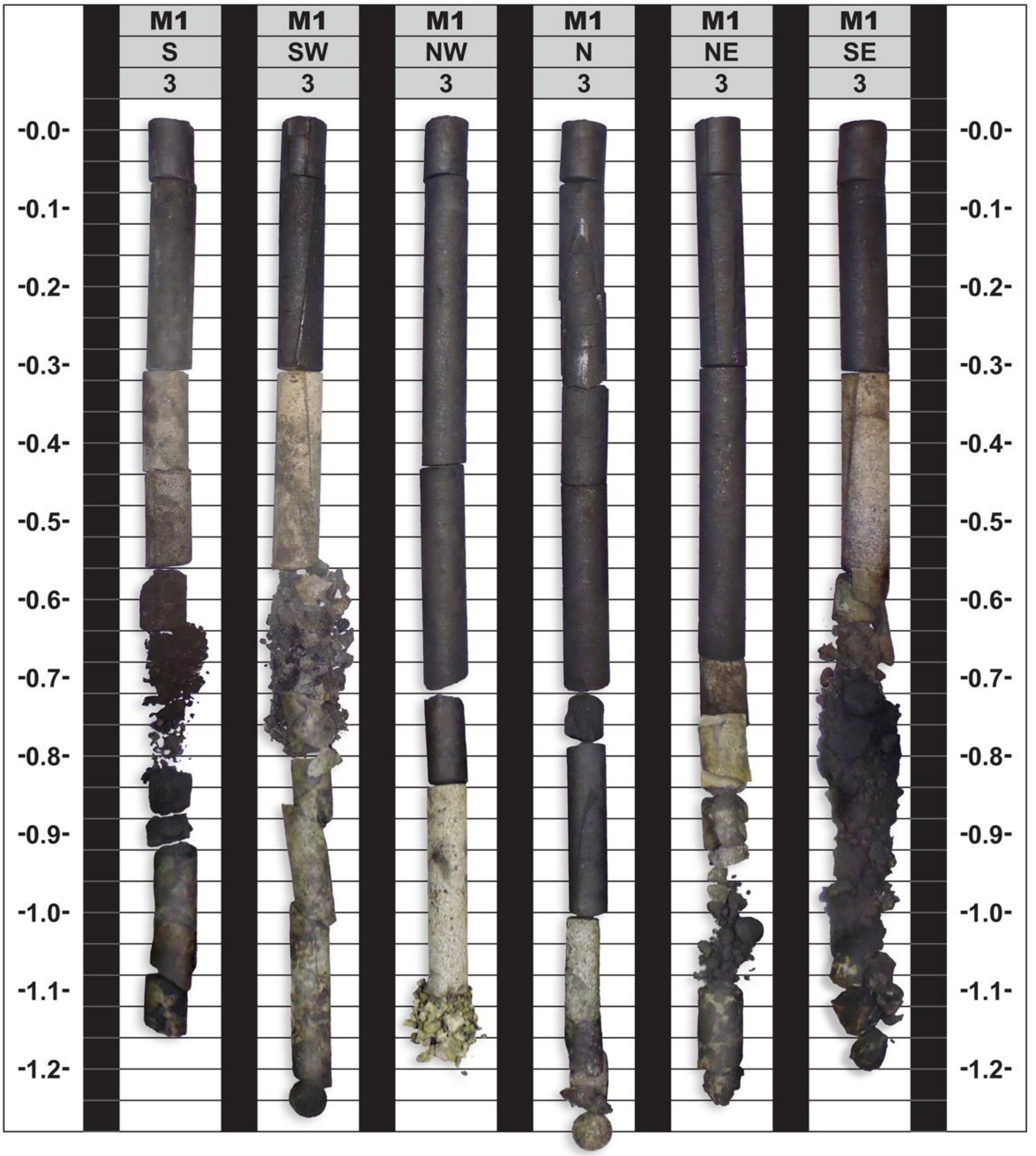
Brick Course Nos.5 & 6: level 4 on M4 and M1: In the sump below the tap hole





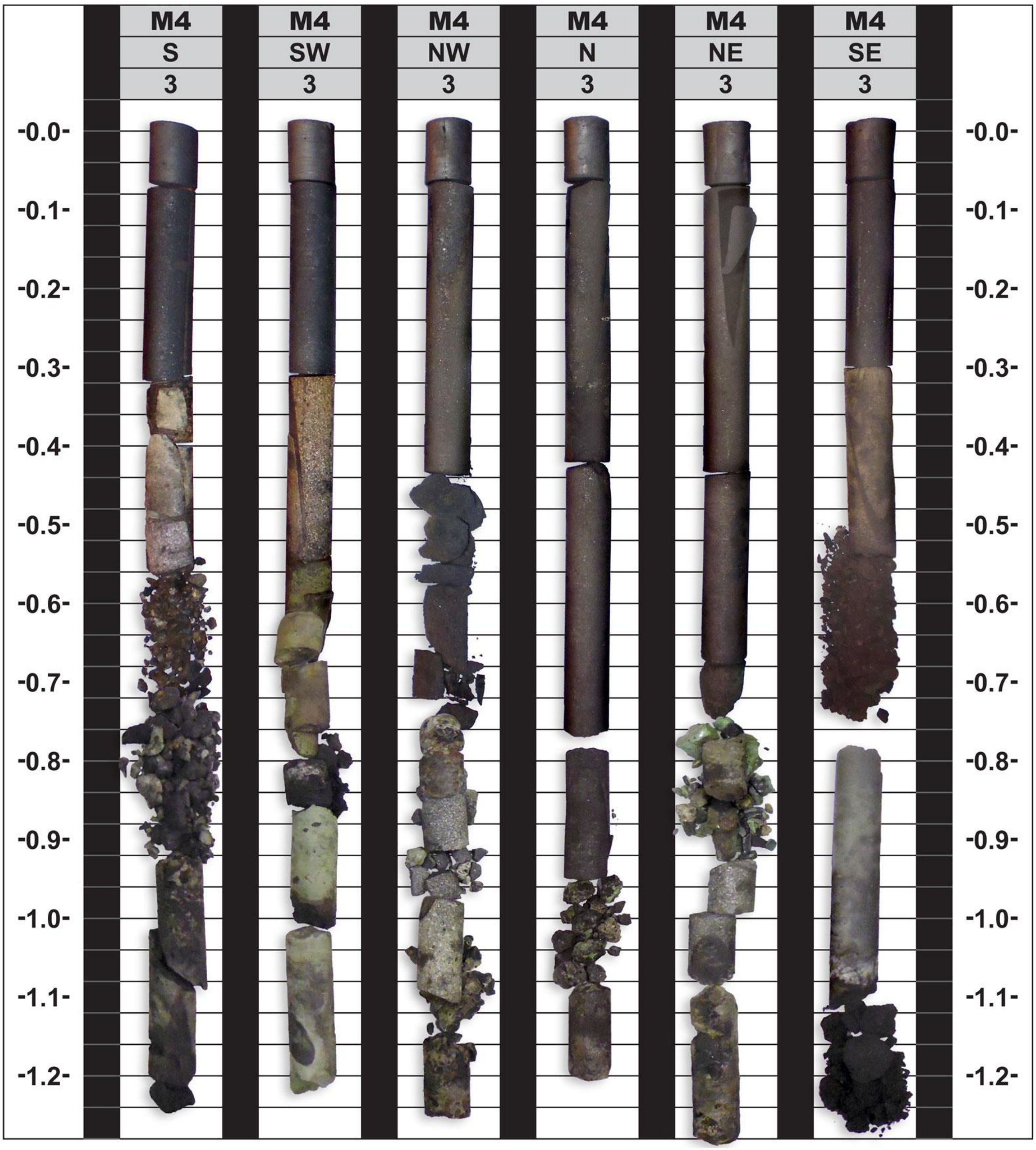
All cores included 70 mm of graphite. Within the abutment, ceramic brick was recovered at the hot face of the carbon brick in M4 which extended to about 900 mm from the steel shell. The design of the abutment on M1 was apparently not as wide, such that frozen slag was recovered at 800 to 900 mm from the steel shell. Outside of the abutment, a combination of slag and raw materials was located at the hot face of the ceramic brick.

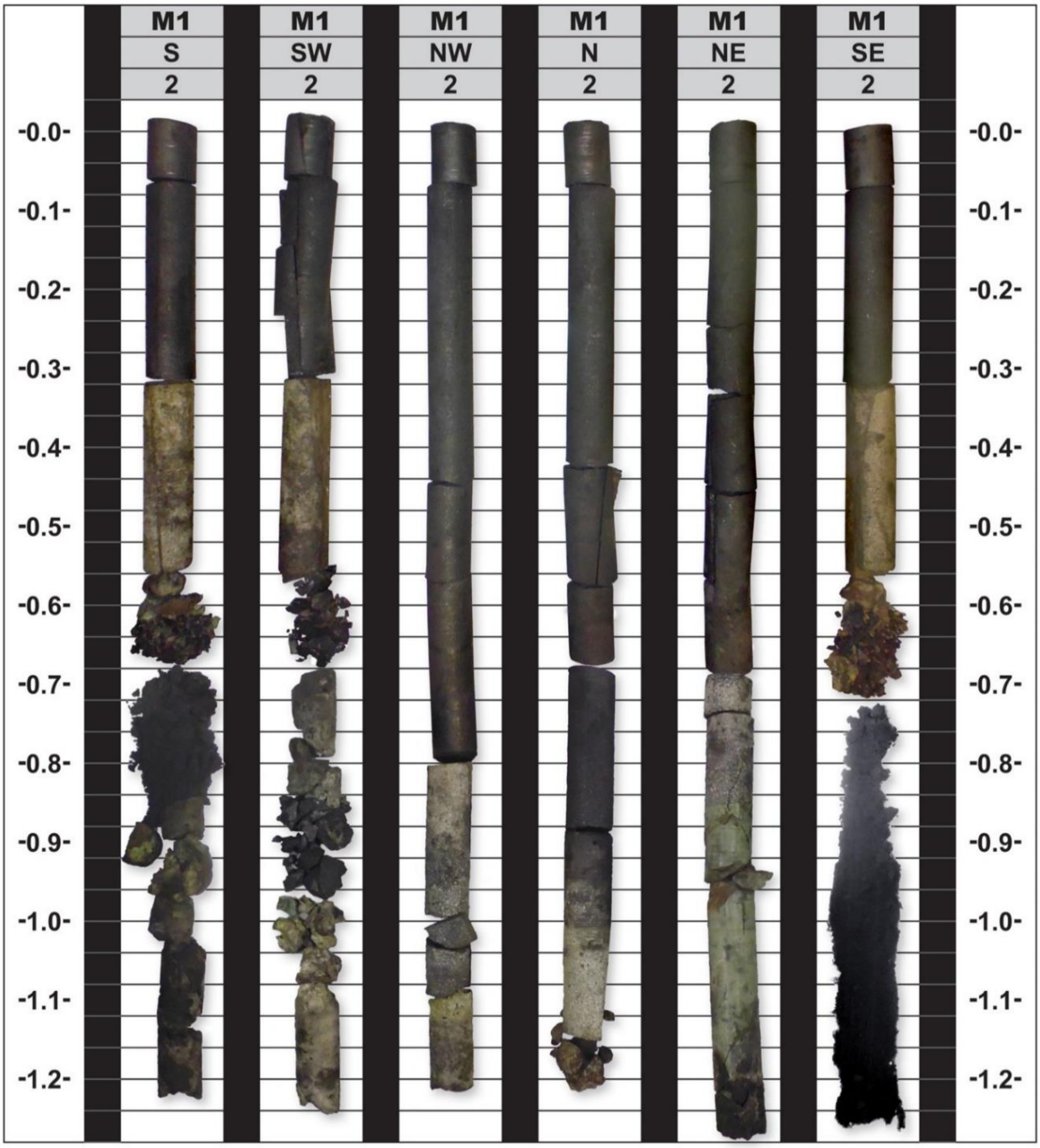
Brick Course No.8: level 3 on M1: at the centreline of the tap hole



All cores included 70 mm of graphite. Within the abutment, ceramic brick was located at the hot face of the carbon brick which extended to about 950 mm from the steel shell. Outside of the abutment, a combination of slag and raw materials was found at the hot face of the ceramic brick.

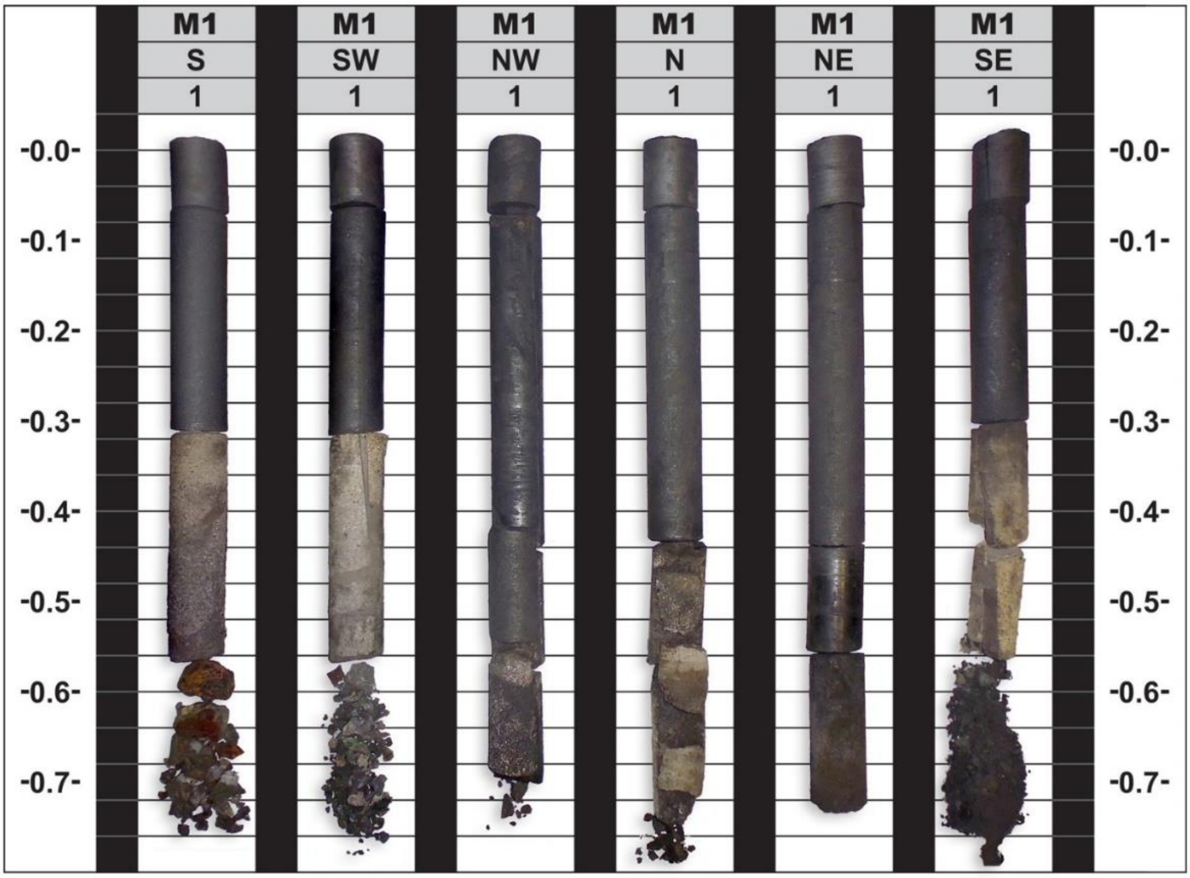
Brick Course Nos.12: level 3 on M4 and level 2 on M1: above the elevation of the tap block.


M4
S
3
M4
SW
3
M4
NW
3
M4
N
3
M4
NE
3
M4
SE
3
-0.0-
-0.1-
-0.2-
-0.3-
-0.4-
-0.5-
-0.6-
-0.7-
-0.8-
-0.9-
-1.0-
-1.1-
-1.2-



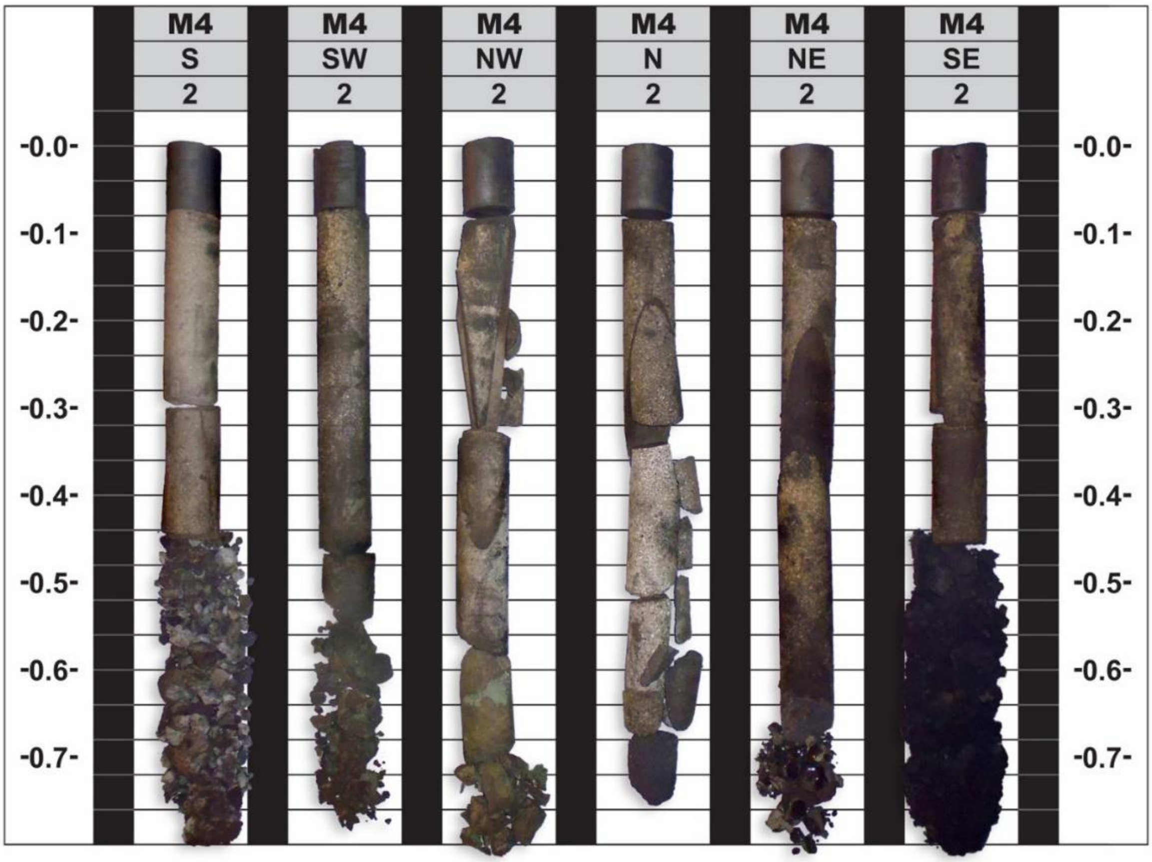
All cores included 70 mm of graphite. Within the abutment, ceramic brick was located at the hot face of the carbon brick which extended to about 900 mm from the steel shell at the centreline. Outside of the abutment, a combination of slag and raw materials was found at the hot face of the ceramic brick.

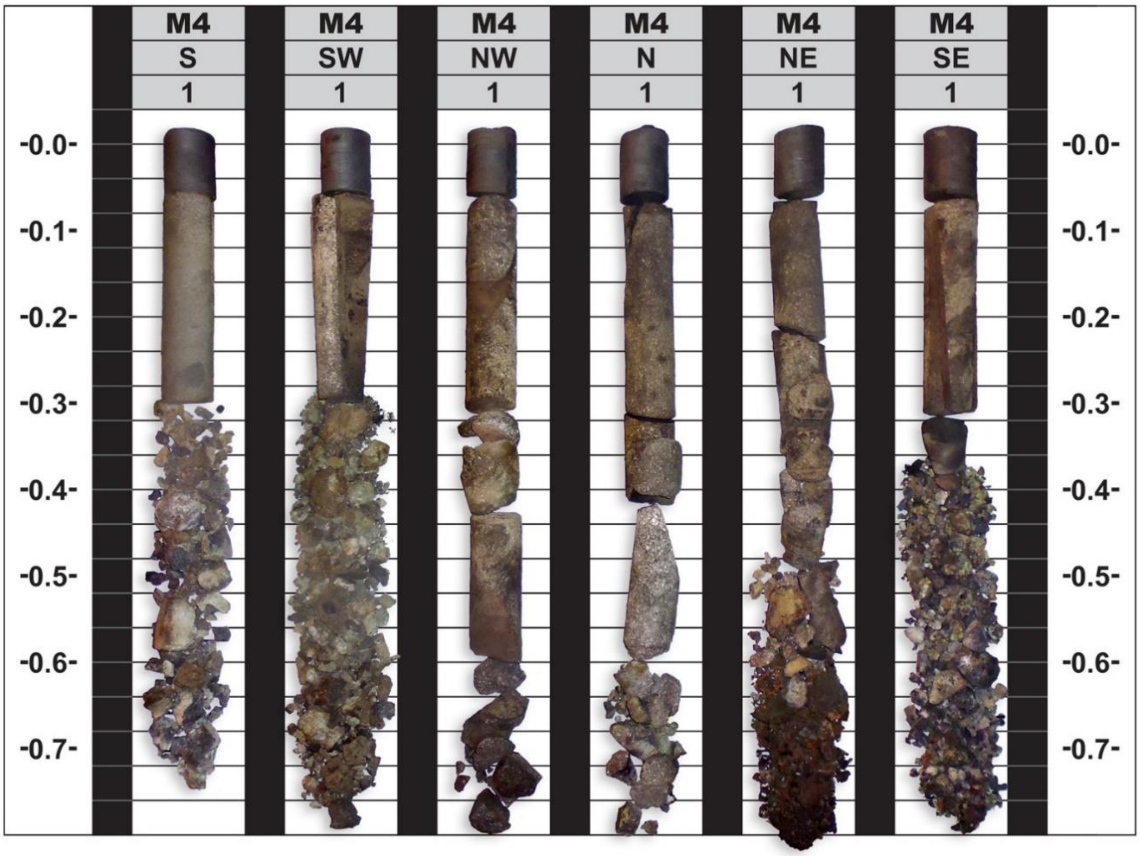
At the top Carbon Brick Course No.14: level 1 on M1: this elevation coincides with the limit of sidewall carbon brick.



All cores included 70 mm of graphite and between 230 and 450 mm of carbon brick before intersecting the alumina brick and then slag. Most of the alumina brick had retained its original dimensions.

Above Carbon Brick Course No.14: levels 2& 1 on M4:





All cores included 70 mm of graphite before intersecting the alumina brick and then slag and raw materials. Most of the alumina brick had retained its original dimensions.

6. CONDITION OF LININGS AT TIME OF SHUT DOWN

Hearth: The cores collected at hearth level (Brick Course A-B, level 6 on M4 and M1 and Brick Course No.1, level 5 on M4 and M1) all demonstrated that the carbon blocks and carbon bricks in the hearth under the sidewalls were in good condition when the furnaces were shut down in 2012.

Sidewalls in the Abutment: The North (N) core provides the best representation for the condition of the abutment, while the NE and NW cores represent the extremities of the abutment. The tap holes are located between the N & NW and the N & NE positions.

In the N cores, all original carbon and ceramic was still in place above and at the centreline of the tap hole. Below the tap hole, metal was intersected on the hot face of the ceramic, in the region of the sump. In the NE and NW cores, the presence of the ceramic brick confirms that the carbon brick was still intact both above and below the centreline of the tap holes. As a result, the abutment carbon bricks were confirmed to be in good condition.

Sidewalls Outside of the Abutment adjacent to the back two electrodes: The SE and SW cores provide a representation of the lining closest to the back two electrodes. In all cores at elevations above the hearth, most if not all of the ceramic brick was found to be intact. As a result the lining closest to the back two electrodes was confirmed to be in good condition.

Sidewalls Outside of the Abutment furthest from the back two electrodes: The South (S) core provides a representation of lining condition furthest from the smelting zone. In all cores at elevations above the hearth, the ceramic brick was found to be intact. Additional cores at level 2 on M1 in the East (E) and West (W) orientations were also found to have the alumina brick still in place, confirming good lining condition.

7. SLAG FREEZE LAYER

Under ideal conditions, metal freeze could be expected up to carbon brick course no.8, accounting for the sump or hearth below the tap hole. Slag freeze might therefore be expected to extend from carbon brick course 8 up to 14, approximately in line with the predicted electrode tip to hearth position.

The radius of the shell was 4,920 mm and the distance from the centre of the furnace to the outside surface of the electrodes was 2,050 mm. Therefore the distance between the shell and the outside surface of the electrodes was 2,870 mm.

Outside of the abutment, the total lining thickness was 530 mm, consisting of graphite, carbon brick and ceramic brick. Therefore the open space between the hot face of the lining and outer surface of the electrode was 2,340 mm. Since the drill core length was up to about 1,250 mm, a frozen slag zone to a depth of 720 mm was found to exist.

Inside of the abutment, the total lining thickness was up to 1,100 mm, consisting of graphite, carbon brick and ceramic brick. Therefore the open space between the hot face of the abutment lining and the outer surface of the electrode was 1,770 mm. Since the drill core length was up to about 1,250 mm, a frozen slag zone to a depth of 150 mm was found to exist.

Slag was intersected above carbon brick course no.14 where there is a 70 mm graphite tile fronted by ceramic brick. It is not known whether this condition represents standard furnace operations or an upset condition, but demonstrates that the 70 mm graphite tile water cooled on the cold face had been adequate to create a slag freeze layer.

The cores shown in Figure 14 are a selection from several furnaces at various levels and orientations.

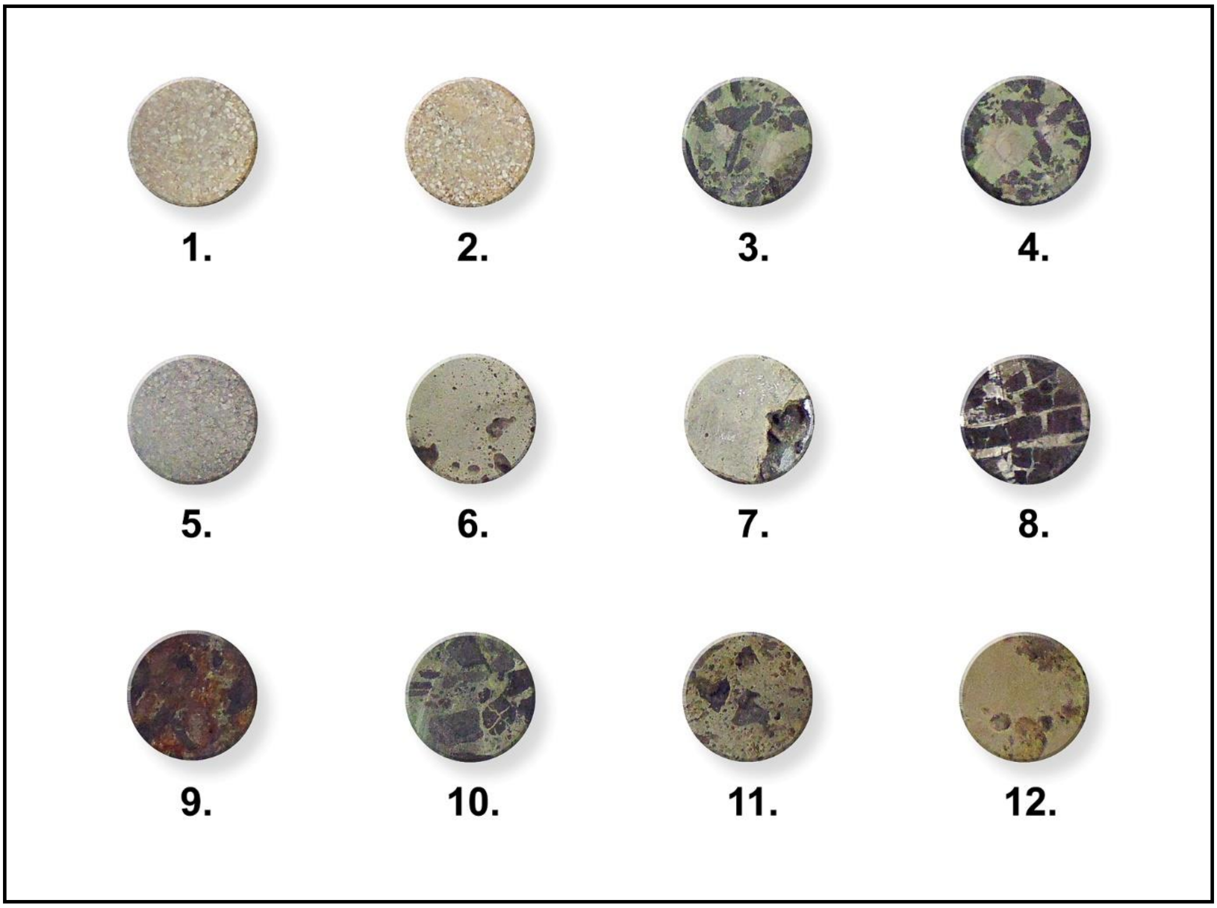


Figure 14: Core Samples submitted for physical and chemical analysis

Some physical properties of these samples are given in Table 3 below.

Table 3: Core Sample Physical Properties

ID	Location	Description	Density (g/cm^3)	Thermal conductivity (Wm/K)
1	SW, Level 2	Ceramic brick	2.7	1.03
2	SW, Level 3	Ceramic brick	2.6	1.04
3	SE, Level 3	Coke in slag	2.8	1.28
4	SW, Level 2	Coke in slag	2.7	1.46
5	SE, Level 4	Ceramic brick	2.9	1.89
6	E, Level 2	Porous slag	3.2	1.48
7	W, Level 2	Dense slag	3.2	1.41
8	S, Level 3	Metal in slag	4.2	1.23
9	S, Level 1	Mainly metal	5.9	1.19
10	S, Level 3	Coke in slag	4.6	2.34
11	SW, Level 2	Coke in slag	2.0	1.88
12	SE, Level 2	Metal in slag	4.3	2.30

Samples 1, 2 and 5 were shown to be alumina brick with a density between 2.7 and 2.9 g/cc. For the remainder of the samples, and as expected in general terms, the presence of coke in slag lowers the density of the freeze layer, while metal in slag raises the density. Within this range of samples containing metal, slag and coke, there is however no discernible trend relative to changes in the thermal conductivity of the freeze layer. The cores were submitted for physical and chemical analysis and the results are given in Table 4 below.

Table 4: Core Sample Analysis

ID	Description	MnO	Fe	SiO_2	Al_2O_3	CaO	MgO
1	Ceramic brick	0.2%	1.0%	36.0%	39.9%	< 0.1%	< 0.1%
2	Ceramic brick	0.2%	1.1%	38.8%	49.4%	< 0.1%	< 0.1%
3	Coke in slag	8.3%	2.5%	46.7%	18.6%	1.6%	0.5%
4	Coke in slag	21.6%	2.0%	36.6%	5.8%	12.8%	2.7%
5	Ceramic brick	3.8%	1.9%	35.8%	40.0%	< 0.1%	< 0.1%
6	Porous slag	15.9%	1.1%	44.1%	4.4%	25.9%	5.0%
7	Dense slag	47.5%	10.4%	19.7%	1.9%	10.7%	1.8%
8	Metal in slag	68.6%	13.2%	24.7%	0.1%	< 0.1%	< 0.1%
9	Mainly metal	6.9%	68.3%	6.3%	1.4%	2.9%	< 0.1%
10	Coke in slag	27.9%	1.7%	33.5%	4.4%	14.0%	2.6%
11	Coke in slag	27.7%	1.2%	43.1%	4.2%	15.5%	3.1%
12	Metal in slag	24.9%	0.4%	46.3%	5.0%	16.7%	3.3%
Slag		16%	0.3%	44%	5%	25%	5%

Sample 6 is the only one of these twelve which can be described by the chemical analysis as pure process slag and this sample has a thermal conductivity of about 1.5 Wm/K. Density and thermal conductivity variations may be due to the variable nature of the cores, particularly with respect to porosity and the presence of embedded carbon or quartz particles. The physical differences may well have more of an influence on density and thermal conductivity than the presence of metal or the chemistry of the slag.

8. THERMAL ANALYSIS

Thermal analysis of the composite lining including a freeze layer consisting of various compositions of metal and slag with a range of thermal conductivity values as presented in Table 3 indicates the likelihood that there is a stable freeze of about 800 mm outside of the abutment and about 100 mm inside the abutment. There is then molten slag adjacent to this frozen slag layer which is a dynamic phase from which solidification is expected to be initiated. The fact that most of the analyses of the freeze cores do not correspond to that of the process slag indicates that the chemical composition of the freeze lining cannot be readily predicted. Nevertheless, the range of thermal conductivity values between 1.2 and 2.4 Wm/K provides valuable information for first order predictions of freeze lining thickness.

9. CONCLUSIONS

The South Plant furnaces had been used to produce silicomanganese from a combination of South African ores. The UCAR ChillKote linings had been in place for up to sixteen years with several thermal cycles enforced by commercial considerations. After this time in service and before the plant was decommissioned, the furnaces were subjected to this core drilling program which established three principal facts:

1. The sidewalls and hearths were still in a condition suitable for many more years of service
2. The formation of a protective freeze layer was shown to exist, formed from a process slag containing about 16 percent MnO
3. The composition of the freeze layer was a variable containing not only slag but also metal, carbon and quartz particles, some porous and others compact or dense. Nevertheless the thermal conductivity values were reasonably similar in a range between 1.2 and 2.4 Wm/K.

10. ACKNOWLEDGEMENTS

The authors acknowledge the co-operation of BHP Billiton and Jet Demolition in providing access to South Plant, as well as the financial support provided to this project by both BHP Billiton and Graftech International.

11. REFERENCES

[1] The technical development of Amcor Limited, with particular reference to the production of ferroalloys, JJ Coetzee, INFACON, Johannesburg, 1974.
[2] Electric smelting furnaces in Southern Africa, SG King, INFACON, Johannesburg, 1974.
[3] A techno-economic assessment of large and small furnaces, W A Gericke, INFACON, Tokyo, 1983
[4] Symposium on Carbon as a Blast Furnace Refractory, Iron and Steel Society, 1962
[5] The design and development of furnace linings for manganese alloys smelting, NJ van der Walt, INFACON, Rio de Janeiro, 1986.

[6] Freeze lining concepts for improving submerged arc furnace lining life and performance, AM Hearn, AJ Dzermejko and PH Lamont, INFACON, Beijing, 1998.