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THE 'DIG OUT' OF A 75 MV.A HIGH-CARBON  
FERROMANGANESE ELECTRIC SMELTING FURNACE

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INTRODUCTION

The examination of the contents of smelting furnaces, whether small, pilot-plant furnaces or production-scale units, that have been switched out under fairly normal operating conditions, is generally considered to be a worthwhile exercise(1-11). Several such studies have been undertaken on furnaces of moderate size but there have been no reports on 'dig outs' of large ferro-alloy furnaces - the 48 to 75 MV.A units that operate at high MW loads.

The National Institute for Metallurgy (NIM), in South Africa, was invited by metallurgical staff at the Metalloys plant of Samancor Ltd to participate in the excavation or 'dig out' of the large 75 MV.A M10 furnace at their plant, in the Southern Transvaal. This furnace produces high-carbon ferromanganese and was shut down during October 1977, because it was to be rebuilt.

This paper deals briefly with the procedure followed during the 'dig out' of furnace M10. The nature of the zones, and the mineralogy of samples taken from the furnace are described. A detailed examination of most of the seventy-five samples taken from the furnace was carried out by Koursaris at the University of the Witwatersrand during 1978 and the first part of 1979, and the more salient findings are discussed(12). Koursaris also studied the reduction of Mamatwan ore in laboratory-scale tests(13,14).

Our objective in undertaking this study was the attainment of an improved understanding of the processes that occur in a furnace such as M10. We sought to achieve this by an examination of the zones within the furnace. We hoped that better strategies for the control of raw materials and for electrode penetration could be derived from our study, and that the average stable operating

load of such large furnaces for the production of high-carbon ferromanganese could be increased to match the transformer capacity that is available.

The Procedure for the 'Dig Out'

Several months before the excavation of the M10 furnace a 'dig out' of a large ferrochrome furnace was carried out. On the basis of the experience gained during this earlier 'dig out' the sampling campaign on furnace M10 could be planned in detail. This section of the paper is intended as a guide for similar 'dig outs'.

Equipment

The equipment necessary for a 'dig out' could be assembled easily, and few preparations need to be made until the shut-down of the furnace is imminent. The equipment used included ladders, picks and shovels, geologists' hammer and pick, sampling tins and bags, tape measures, safety equipment, and a camera fitted with a flash unit. The provision of flood-lighting and heavy moving equipment was the responsibility of the personnel at Metalloys, and included a back-hoe and two front-end loaders.

Marker blackboards were made so that the localities that were photographed could be identified from the photographs.

Manpower

A team of four metallurgical engineers, two research students, and three technicians from Metalloys and the Department of Metallurgy of the University of the Witwatersrand in Johannesburg were responsible for sampling the furnace during the 'dig out'. It was decided that the sampling should be conducted in eight-hour shifts, and that these shifts should not coincide with the normal plant shifts.

Metalloys provided technical personnel to assist in a supervisory capacity. There was usually at least one senior member of the Metalloys' staff on standby during each shift.

Sampling Localities

The sampling localities selected are shown in Figure 1, which shows the M10 furnace in plan and in elevation.

Samples were chosen from a wide cross-section of regions. We realized when the 'dig out' was planned that it would not be possible to retrieve all the samples because of the crumbly nature of the loosely sintered burden in the upper part of the furnace. The code by which sampling localities are designated in Figure 1 can be explained by the following example: C/1/D/3 refers to the Central Region/Electrode No. 1/Level D/Position 3. Level D is 3m below level A, which is in line

with the roof of the furnace. Position 3, in the central region, is the mid-point of the furnace. This logical and unambiguous method of coding made the identification of samples straightforward and prevented confusion when reference was made to localities.

gressed beyond the no. 1 electrode towards the centre of the furnace. In the upper part of this region the mix was loose and crumbly, and the removal of many representative samples from this area was almost impossible.

The uppermost reference point for the vertical distance between sampling layers was the inside or lower face of the water-cooled roof beams of the furnace, as shown in Figure 1. Measuring tapes were used as a check on the distance from the roof to the horizontal sampling layer. Very few samples were taken from the top of the burden because of contamination of the furnace by refractories that collapsed from the refractory sections of the roof as they were being broken. Thus, most of the samples were obtained from the C to F levels as shown in Table I, which identifies the samples that were successfully taken, as well as their basic characteristics (e.g. siliceous, sinter, metal, or carbonaceous). Samples were excavated with a shovel or geologist's pick. The material was often red-hot and was handled with leather or asbestos gloves. The samples were placed in 5-litre metal tins, and labels carrying the identifying code were put in the tin. When they were cool the samples were transferred to plastic sample bags, which were also marked with the locality code.

Photographing the manganese furnace was no an easy task, since the lighting, focus, and exposure time are critical. There was little colour contrast in many regions, and this made it difficult for clear definition to be obtained.

#### Furnace Operating Conditions Prior to the Shut

Figure 1 includes a plan view of the furnace and shows the positions of electrodes 1, 2, and 3 relative to the two metal tap holes and one slag tap hole. The centre line of the metal tap hole was 300mm above the furnace hearth, whereas the centre line of the slag tap hole was 1300mm above the hearth (i.e. 1000mm above the metal tap hole). This configuration ensured the presence of a metal pool beneath the lower tap hole, and of a slag layer between the tap holes at all times during the normal operation of the furnace.

The operation of the furnace was somewhat erratic during the weeks prior to its being switched off. Several electrode breaks occurred and a number of electrode baking-in periods were responsible for reduced furnace loads. The energy input during the two days preceding the switch-out on 20 September, 1977, was 494 and 422 MW.h respectively, which indicates that an abnormal smelting zone probably existed within the furnace. Good energy values should, in fact, total 840 MW.h per day and higher. The no. 1 electrode broke on 20 September, and at that time the furnace was switched off for the 'dig out' and rebuilding.

The furnace was not completely tapped during the last hours before switch-out, although the reduced furnace load indicated the presence of only a relatively small quantity of metal inside the furnace.

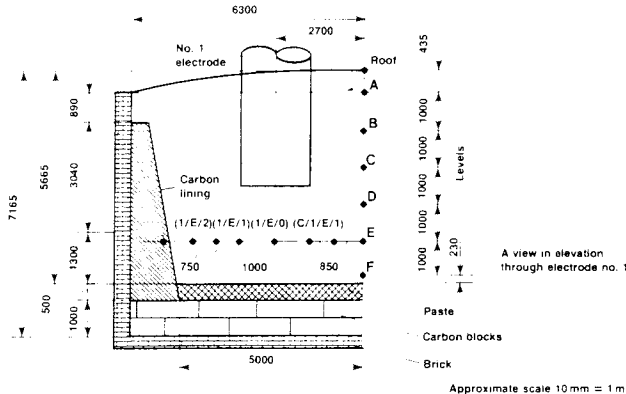
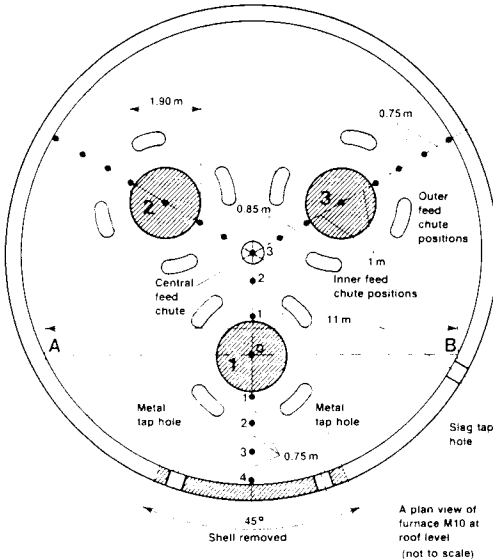


FIGURE 1 Selected sampling localities for furnace M10

#### Sampling Procedure

Entry to the furnace was by way of a ramp constructed from lumps of discarded manganese slag. Front-end loaders and a back-hoe were able to drive up to and into the furnace as the 'dig out' progressed. An arc of about 45° was cut in the shell of the furnace so that the physical integrity of the interior of the furnace could be maintained. Entry was through the front of the furnace at the no. 1 electrode (i.e. between the two metal tap holes). This arrangement ensured a successful exposure of the face of the no. 1 electrode, and gave the best possible profile of the burden surrounding the electrode.

A photographic record of this entire face was obtained with the aid of markers. Once photographs of a locality had been taken, the sample or samples were removed. However, it was not always possible to excavate the furnace along a vertical face, especially once digging had pro-

TABLE 1

Samples taken from furnace M10 during the 'dig out'

Electrode no.	Level*	Position*				
		0	1	2	3	4
1	A			Outer region		
	B	-	Mix+Sin	Mix-Sin	-	-
	C	-	Sin+C	-	Mix+Sin	-
	D	-	Sin+M-C	-	-	SL-C
	E	MnO+SL-C	MnO+SL+M	SL-M+G	SL-M+G	SL-C+Car
	F	MnO+M-G	MnO+M-G	MnO-M-G	Sl+M	M-G-Car
2	A					
	B					
	C	-	Mix	Sin	Sin	Sin
	D	C+SL+Sin	C+Mix	Sin-Red	Sin	C-Car
	E	SL+Sin	SL-C-Sin	C-SL	C+SL	C-Car
	F	M-MnO-G	MnO-C+G	MnO-C-M	-	Car
3	A					
	B					
	C	-	Sin	Sin	Sin-C	-
	D	Mix-Sin	Sin	Sin	Sin-C+SL	-
	E	Sin	Sin	C-G-SL	C-SL	Car
	F	-	M+MnO-G+C	C-SL	-	Car
2-Wall	C		Special sample in outer region	C-Sin	Sin+C+Mix	-
	D			C-Sin	Sin	-
	E			-	C-SL-G	Car
3-Wall	C			Mix-Sin	Sin	
	D			Sin	C	
	E			-	C	
Central region (Position 0 coincides with the outer region)						
1	B		Mix			
	C		-			
	D		-			
	E		SL-Sin	SL+Sin-MnO	MnO-C-M+G	
	F		M+MnO	M-MnO	MnO-C-M-G	
	2	C				
D						
E			SL+C	MnO-C+M	Common to all electrodes	
F			MnO+C+SL+M	MnO-C+M		
3	C		Mix+Sin	-		
	D		Mix-Sin	-		
	E		-	MnO-C-M		
	F		MnO-SL+M	MnO+M-C	Common to all 3 electrodes	

Mix Raw material mixture.  
Sin Sintered material or partly reacted burden.  
SL Slag (MnO, CaO, SiO<sub>2</sub>).  
MnO MnO melt.  
C Coke or carbonaceous reducing agent.  
M Metal carbide + metal.  
G Graphite or graphitized material.  
Car Carbon paste or blocks in lining.

\*Figure 1 shows the designations of the levels.

The furnace was water-quenched shortly after switch-out until an explosion in the west gas-cleaning plant put a stop to the use of water for this purpose. If more water had been used, it could have adversely affected the contents of the furnace.

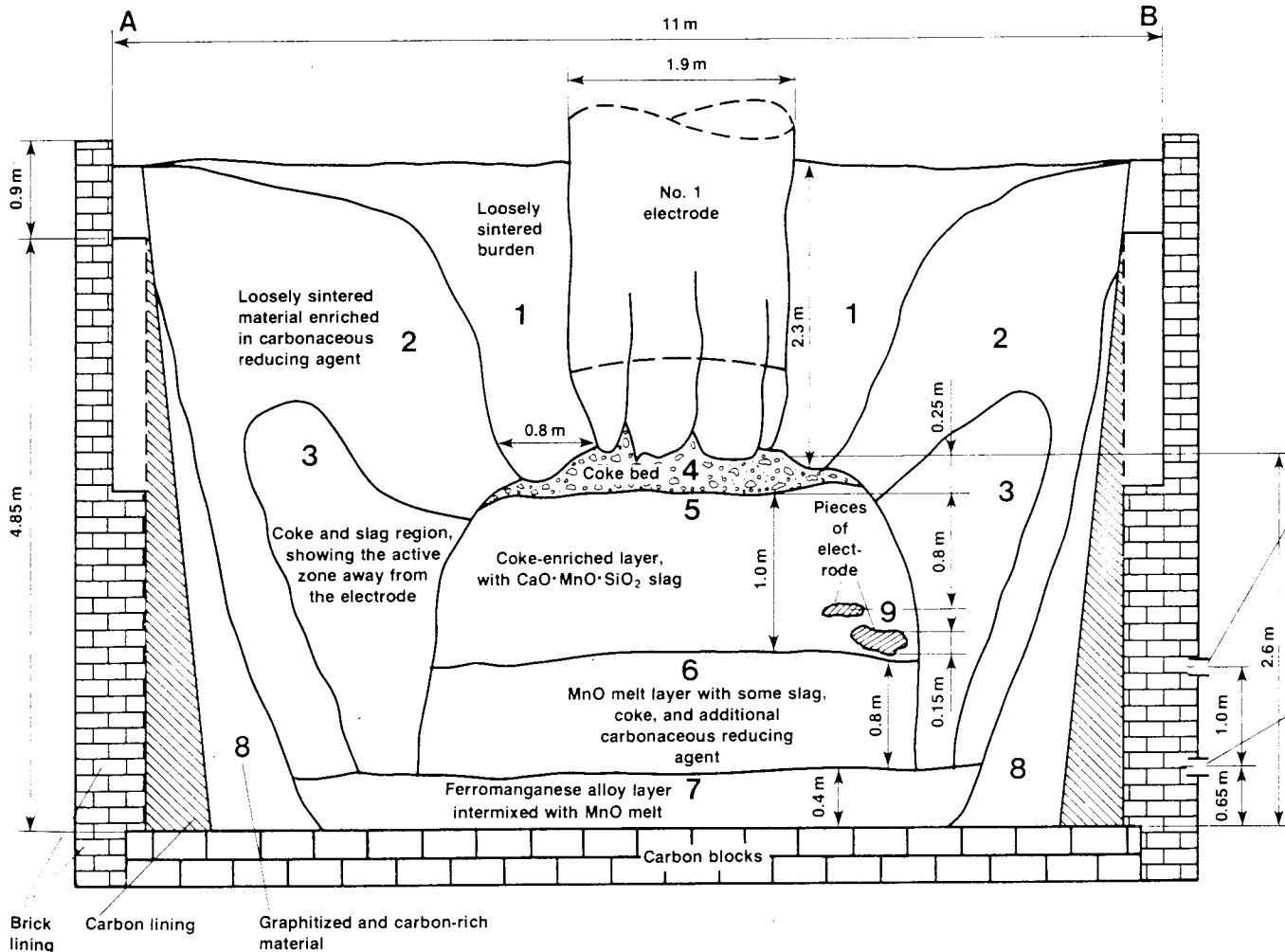
Because of the geometry and operation of the furnace, some of the current flowed from the electrodes to the side-walls of the furnace. The reason for this behaviour was that the original 48 MV.A transformers had been replaced with 75 MV.A transformers without enlarging the furnace shell. The higher loads made possible by the larger transformers exceeded the design load and resulted in the current flowing to the side-walls. This eroded the lining, and several break-outs occurred during the months preceding the 'dig-out'. The normal path of the current is from the electrode tips through the bath to the other electrodes. The abnormal flow of current resulted in a relatively inactive furnace centre, as was reflected by the low demand for raw materials in this region. Attempts were made to counteract this behaviour by selective raw material charging but without much success. These considerations were in part responsible for the rebuild.

Observations during the 'Dig Out'

The best view of the zones in furnace M10 was obtained during the first stages of the 'dig out'. The no. 1 electrode was exposed *in situ* with the contents of the burden surrounding it left undisturbed. Figure 2 illustrates the more apparent zones that were found around this electrode and towards the shell of the furnace. The zones surrounding the no. 2 and no. 3 electrodes looked slightly different, but a comparison of these zones with those around the no. 1 electrode was difficult because the upper part of the burden in the central region of the furnace collapsed, preventing a similar exposure of a vertical face at the back of the furnace.

The zones in the region surrounding, close to, and beneath the no. 1 electrode are shown respectively in Figures 3, 4, and 5. Most of these zones were delineated as fairly discrete boundaries, as illustrated in the sketch of the contents of the furnace in Figure 2, but it was necessary to mark their outlines more clearly in some of the photographic figures for greater clarity.

Zone 1, next to the no. 1 electrode, con-



sisted of loosely sintered burden, and corresponds to the funnel-shaped region where the material descends rapidly into the active area below the electrode, as was suggested by studies in which radio-active isotopes were used as tracers. These studies were carried out prior to the 'dig out'(15,16).

Zones 2 and 3 are shown in Figure 3. These semi-active regions extended up and away from the coke bed and the layer of coke and slag beneath the no. 1 electrode. Zones 2 and 3 consisted of carbonaceous reducing agent, partly-reacted mix, and some slag, although there was an enrichment of the carbonaceous reducing agent in zone 2, especially towards the walls of the furnace. The material in these two zones exhibited characteristics indicative of a slow rate of movement of the burden. Slow movement of the burden in this region was predicted from earlier tracer tests(15,16).

Zone 4 consisted mostly of carbonaceous reducing agent in what is commonly termed the 'coke bed'. Figure 5 is a close-up view of this coke bed, immediately below the tip of the no. 1 electrode.

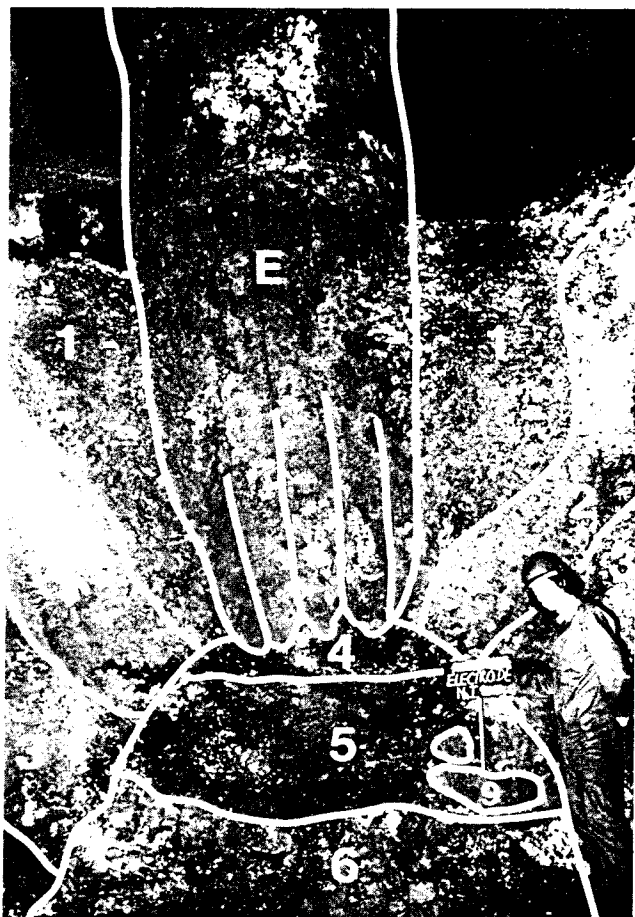


Fig. 3. A general view of the zones surrounding the no. 1 electrode of furnace M10.

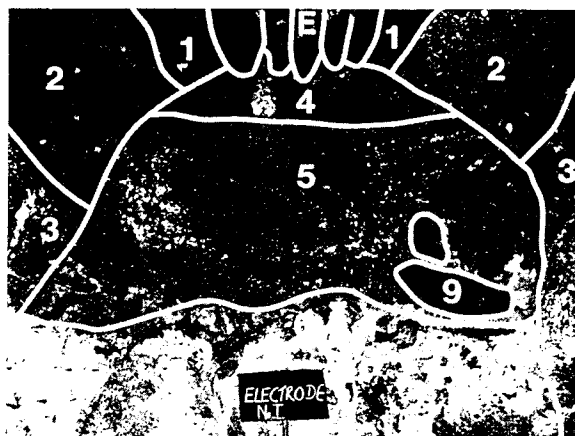


Fig. 4. A close-up view showing the region beneath the no. 1 electrode.

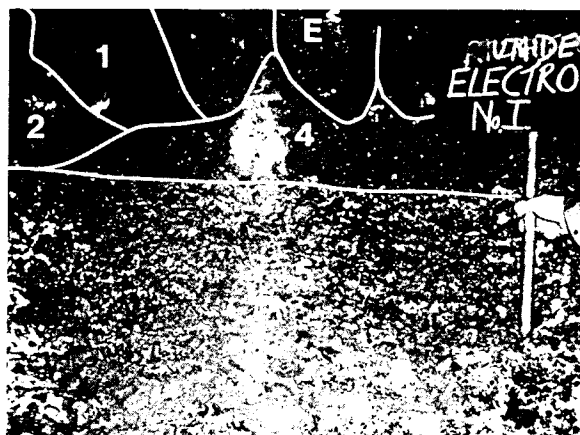


Fig. 5. A close-up view of the coke bed (zone 4) and of the layer of coke and slag (zone 5).

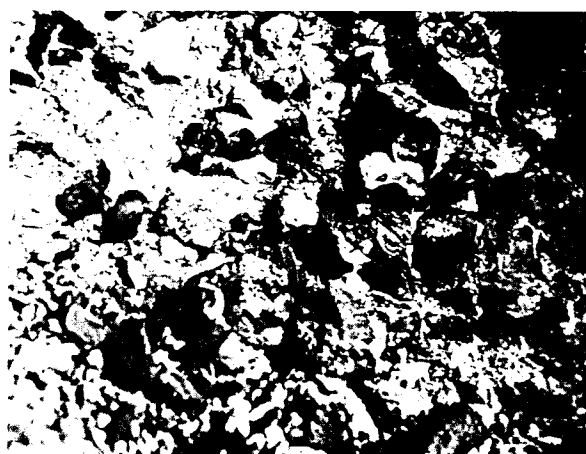


Fig. 6. A close-up view of the coke and degrading slag in zone 5 (size of coke 20 to 60 mm).

Zone 5 contained a coke-enriched layer of slag and is clearly visible just below the coke bed in Figure 5. Much of the region of coke and slag in zone 5 was very crumbly, and the slag decrepitated readily, as can be seen from Figure 6. This whitish slag contained very rounded pieces of carbonaceous reducing agent, usually coke, as shown in the close-up view in Figure 6.

Zone 6, in which an extensive layer of unreacted MnO was found, is shown in Figures 4 and 7. This clearly defined layer was called the MnO melt.

Zone 7 consisted of a mixture of mostly alloy, some MnO melt, a little slag, and flakes of graphite. Figure 7 is a close-up view of zones 6 and 7.



Fig. 7. A close-up view of the layer of MnO melt, and of the high-carbon ferromanganese in the hearth beneath the no. 1 electrode (zones 6 and 7).

Zone 8 consisted mostly of the original rammed-paste lining. Some carbonaceous material had formed a bank in this region (see Figure 2).

Zone 9 was comprised of pieces of broken or detached electrode, and Figure 8 illustrates the influence of this material on the surrounding zones of coke and slag, and MnO melt.

In the central regions of the furnace, in between the electrodes from levels E and F, a zone similar to zone 6 was identified. This region consisted of an MnO melt, as well as carbonaceous reducing agent. Reduction of the MnO to metal, or to metal carbide, had occurred in this central zone, as can be seen in the regions surrounding the pieces of carbonaceous material in Figure 9.

This region of MnO melt was extensive and had built up into a mound. A large 100kg sample was retrieved from this zone for detailed analysis.

Chemical analyses of a limited cross-section of samples taken from the furnace are shown in Table II. The major problem with the chemical analysis of the heterogeneous samples taken from the furnace was the combination of metallic and

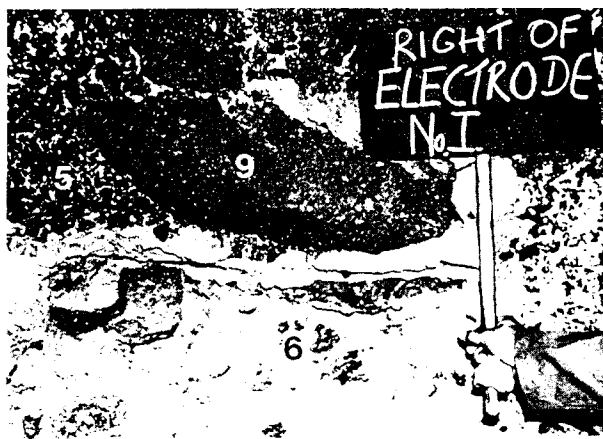


Fig. 8. A close-up view showing the influence of broken off pieces of electrode on the interface between the layer of coke and slag and the MnO melt, beneath the no. 1 electrode.

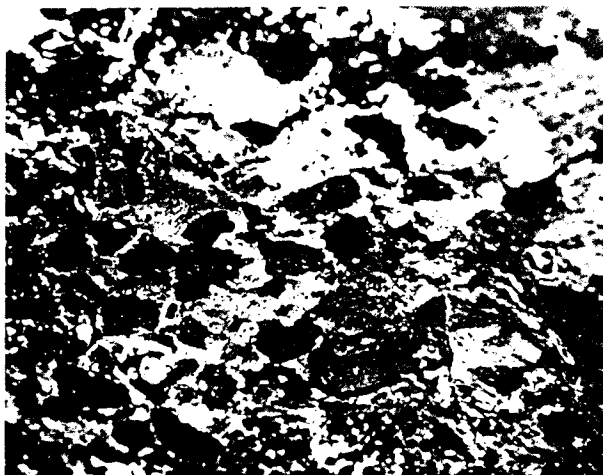


Fig. 9. A close-up view of the layer of MnO melt in the central region of the furnace, showing the formation of metal carbide round particles of coke (size of coke 20 to 50 mm).

oxide phases, and the presence of carbonaceous material. We considered mineralogical examination to be more worthwhile, since the interpretation of the constitution of these samples would more profitably be based on the identification of elements, phases, and minerals than on overall chemical composition.

#### Mineralogical Investigation of Samples

Microscopic examination of polished sections of samples, as well as X-ray diffraction analysis, energy-dispersive analysis of X-rays (EDAX), (or energy-dispersive spectroscopy (EDS), as it is also known), and electron-microprobe analysis were carried out by Koursaris, and by Wedepohl (12-14, 17). Transparent sections (30μm thick) were also made from specially chosen samples. Some of the material taken from the furnace was not suitable

TABLE II

The chemical composition of a limited cross-section of samples from furnace M10

Sample code	Material (predominant phase)	Total analysis, %							
		CaO	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Basicity ratio*	MnO **	C	Fe
1/E/0	Slag	33.9	8.2	4.2	31.2	1.35	17.8	0.05	-
1/E/1	MnO melt+slag	13.7	4.7	0.3	10.4	1.76	68.6	4.5	-
3/D/0	Coke+slag	37.4	0.3	2.5	8.6	4.38	22.0	15.9	-
1/E/4	Metal+mainly slag	37.6	9.4	3.3	28.7	1.64	13.8	2.6	-
1/F/3	Metal+some slag	5.7	9.7	0.3	0.8	19.3	79.9	0.21	-
1/F/0	Metal+graphite	-	-	-	-	-	74.6	10.8	13.6

\* $(CaO + MgO)/SiO_2$

\*\*Mn expressed as MnO

for the preparation of polished sections, because of its crumbly nature, but a reasonable cross-section of suitable samples was nevertheless obtained.

The structure and constitution of the unreacted Mamatwan ore was examined by Koursaris, and Figure 10 shows a typical polished section of this ore(14). The predominant phases in the ore are shown in Table III.

A polished section of a sample taken from region 1/D/1 (where the partly sintered burden enters the mixture of coke and slag in zone 5) is

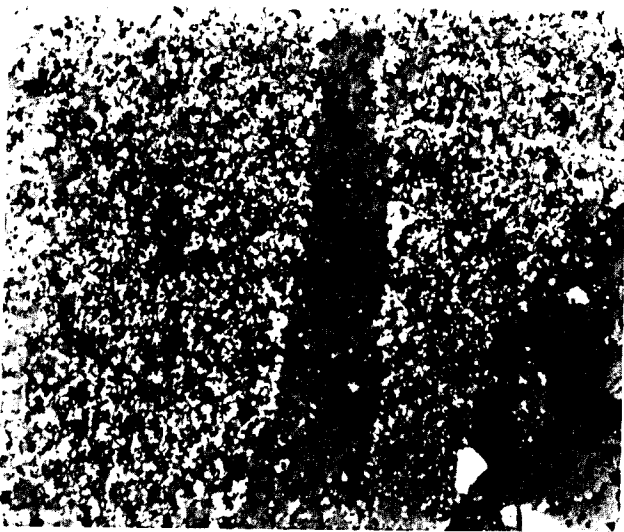


Fig. 10. Mineralogical characteristics of Mamatwan ore. Oolites and a vein of calcite and dolomite gangue (grey), and bright specks of metal oxides (Mn and Fe) are visible. Black specks are pores (polished sample, reflected light, magnification 160 X).

shown in Figure 11, in which the phases are identified. This sample shows the partial reduction of MnO to metal and metal carbide, and the presence of slag containing little MnO, as well as some almost pure MnO in the form of small rounded grains that appear to have nucleated from higher oxides of manganese in the ore. This was typical of partly reduced and fused ore.

Samples taken from the region between the electrodes (central position 3, levels E to F) were examined in detail, since evidence of the reduction of manganese from the MnO melt and the slag phases was observed in hand samples. These samples contained somewhat rounded particles of carbonaceous reducing agent surrounded by metallic carbide and MnO melt, and minor amounts of slag. A micrograph of a thin section of sample from this zone is shown in Figure 12.

From X-ray diffraction patterns of the MnO melt the predominant mineral was identified as manganosite (MnO), which has a NaCl-type structure. An analysis of the results of EDS showed

Table III. The mineral composition of unreacted Mamatwan ore(14)

Mineral	Chemical formula
Braunite	$MnO \cdot 3Mn_2O_3 \cdot SiO_2$
Dolomite	$CaMg(CO_3)_2$
Calcite	$CaCO_3$
Hausmanite	$Mn_3O_4$
Hematite	$Fe_2O_3$
Cryptomelane	$KMn_8O_{16}$

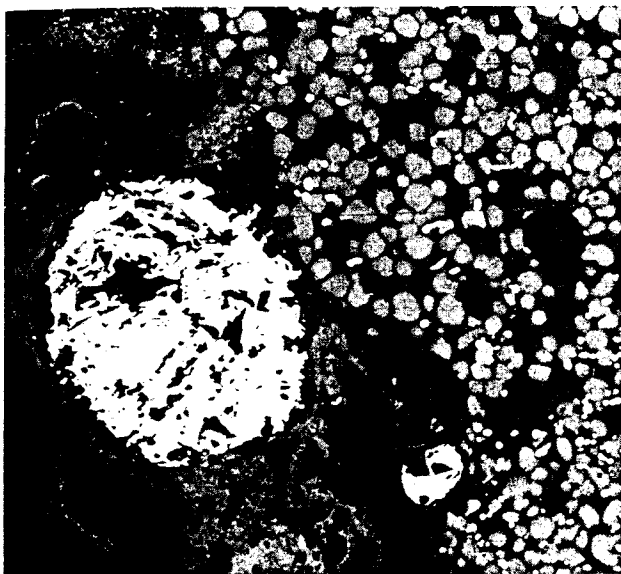


Fig. 11. Mineralogical characteristics of partly reduced Mamatwan ore. Visible are slag, small grains of MnO, metal (rich in Fe) associated with the MnO, and coalesced metal carbide near to the interface between the altered ore and some coke (polished sample 1/D/1, reflected light, magnification 160 X).

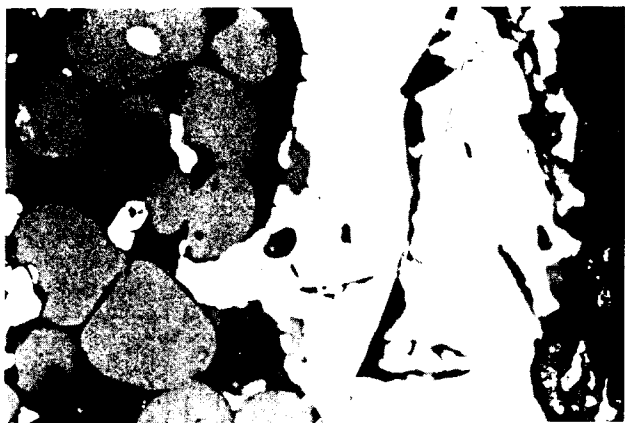


Fig. 12. Mineralogical characteristics of the phases in the layer of MnO melt from the central region of the furnace. There is little slag, but large grains of MnO are visible, as are interstitial metal carbide (low ratio of Mn to Fe) within grains of MnO, and metal carbide coating a particle of coke and within the body of the MnO melt at the interface between the MnO and the slag (high ratio of Mn to Fe). (Thin section sample 1, 2, 3/E/3, reflected and transmitted light, magnification 160 X).

that magnesium was present in very minor quantities, and silicon and calcium were present as trace elements. There was no iron in these grains of MnO. The minor amount of slag phase that was present between the MnO grains consisted of  $(Ca,Mn)_2SiO_4$  (glaucroite).

Many of the samples contained two types of metal: one between or close to the carbonaceous reducing agent and the mixture of slag and of grains of MnO, and the other within the body of the MnO grains (see Figure 12). The two rather different compositions, as determined by the use of the EDS system are shown in Table IV. The metal in the interior of the grains of MnO was much richer in iron than that between the carbon and the mixture of slag and of grains of MnO. The high-carbon ferromanganese metal that is produced from the furnace is similar in composition to the metal formed between the carbon and the mixture of slag and of grains of MnO but some dilution with the interstitial metal which is richer in iron must occur. X-ray diffraction analysis of the metal phases indicated that the two main carbide phases were  $(Mn,Fe)-C$  and  $(Mn,Fe)_5C_2$ , with possibly minor amounts of  $(Fe,Mn)_3C$ , although there are no ASTM standards for these compounds and hence some uncertainty exists.

A detailed analysis by electron microprobe was carried out across various particles in polished sections of samples taken from this central region of the furnace. The traverses used in this analysis covered the coalesced metallic phases, the slag, the MnO grains, and metal in the interior of MnO grains. The occurrence and concentration of the following elements were identified:

Table IV. Typical energy-dispersive spectroscopy analysis of the metallic phases in samples C/1/E/3 and C/1/F/3, and a typical analysis of high-carbon ferromanganese(17)

Locality of metal phase	Mn,%	Fe,%	C,% *	Mn/Fe	Total
Carbon/metal/melt interface	79.6	10.9	9.4	7.3	99.9
Interior of MnO grains	60.5	32.6	7.3	1.9	100.4
Typical composition of metal product	76	14.5	7.0	5.2	97.5

\*microprobe results.

## Carbon

There was some carbon distributed throughout the slag phase (2 to 3%), and lesser amounts in the MnO grains (0 to 1%). The carbon in the coalesced metal was about 8 to 9 per cent, and in the interstitial metal 5 to 7 per cent.

## Manganese

The manganese in the glaucroite slag phase was fairly constant (25 to 26%). The manganese content of the MnO grains was 70 to 75%. The manganese in the coalesced metal was close to 80 per cent, which also confirmed the EDS results.

## Magnesium

The magnesium was fairly constant in the MnO grains (2 to 3%), and this was similar to the amount found in the slag phase.

## Calcium

The amount of calcium was fairly constant in the slag phase (21%), but usually only a trace was present in the MnO grains (0 to 1.2%).

## Iron

The iron content of the slag phase and of the MnO was very low (0.1 to 0.2%). Most of the iron was associated with the metal phases but the iron content of the interstitial metal, was higher than that in the coalesced metal carbide. This confirmed the results of the EDS analysis.

## Silicon

Silicon was found only in the slag phase and varied very little (15 to 16%) from one locality to another.

## Discussion

There is a tendency for the observations made during the 'dig out' of a furnace to be interpreted subjectively. Care was therefore taken that these observations should be regarded objectively and related to those of other investigators. The conditions inside a furnace that has cooled over a period of nearly two weeks cannot be expected to reflect actual operating conditions directly. In fact, slow cooling might have enhanced some of the phase separations. It must also be stressed that the interior of this furnace, prior to the 'dig-out' would not necessarily represent the conditions prevailing under normal operating conditions of load, slag basicity and raw material distribution. Despite these shortcomings, much useful information was gleaned.

## Movement of the Burden, Smelting and Distribution of Material

On the basis of the observations made on the furnace, the analysis of samples, and previous research work in this field, we formulated the following hypotheses.

(1) The burden of raw materials descends rapidly around the electrodes and is therefore only loosely sintered (zone 1). The extremely high resistivities of the mixture of Mamatwan ore, of both coke and coal at the relatively low temperatures in this zone indicate that there is little conduction of current in the upper region of the furnace(13).

(2) The partly sintered raw materials segregate beneath the electrode as smelting takes place and the segregation causes the formation of a 'coke bed' approximately 0.25m thick (zone 4) at the top of a coke-enriched layer of slag about 1m in depth (zone 5). The resistance of the furnace would be expected to be governed mainly by the conditions at the electrode tips, and in the layer of coke and slag, as discussed by Rennie. The reduction reactions in this very hot zone of coke and slag appear to have almost reached equilibrium during the cooling down of the furnace. Virtually no metal carbide remained and the slag contained little manganese oxide and no iron oxide. Nevertheless it is this region in which most of the ferromanganese is produced since samples entering this region showed the first stages of reduction. Both CO and carbon are responsible for reduction(14). The presence of 2 to 3 per cent carbon in the slag phase and amounts in the grains of MnO melt suggests that the carbon can diffuse to carry out reduction away from the interface between carbon particles and slag or grains of MnO.

(3) The layer of coke and slag rests on a layer of MnO melt of about 0.8m thick, that contains minor quantities of slag, metal carbide, and graphite flakes, as well as some carbonaceous reducing agent (zone 6). This zone is thought to be formed essentially from the material that descends relatively slowly in the semi-active regions (zones 2 and 3) and in the central region of the furnace. The enrichment of the carbonaceous reducing agent in the outer region of the furnace is the nett effect of the melting, and of the incomplete reduction of the ore as well as segregation caused by the difference in particle size and density of the materials.

(4) The metal carbide descends from the zone of coke: slag reaction through the layer of MnO melt and into the hearth of the furnace (zone 7). Secondary refining of the metal carbide appears to take place as the metal carbide descends through the MnO melt. This lowers the carbon content of the coalesced metal from about 8 to 9 per cent to 5 per cent (the value of the carbon in the alloy product). The layer of metal carbide rested on carbon blocks in the hearth of the furnace, which showed little signs of erosion although the normal layer of rammed paste had disappeared. The apparent reason for the observed integrity of

carbon blocks seems to be related to the extensive distribution of graphitized material associated with the metal carbide in the lower part of zone 7. The average carbon analysis of metal carbide plus graphite in the lower parts of this region was almost 11 per cent, which is above the saturation value of a mixed  $(Mn,Fe)_7C_3$  carbide, as well as above that of the normal high-carbon ferromanganese alloy. Alloys in the manganese-iron-carbon system can contain carbon contents well above 11 per cent when in the liquid state. If little or no refining of the carbon in the metal occurs, apparently as a result of limited contact with  $MnO$ , then the carbon content would increase above the saturation value for the solid phase. The graphite flakes presumably resulted from an exsolution of carbon from carbon-saturated areas of the liquid metal carbide as they cooled (see Figure 13).



Fig. 13. Metallographic characteristics of metal carbide in the lower region of locality 1/F/1. Flakes or lamellae of graphite that have exsolved from the carbide phase can be seen. (Scanning electron micrograph, polished sample, magnification 40 X)

(5) The central region of the furnace is influenced by the power distribution, and at the reduced furnace operating loads prior to 'dig out', the active zones around the electrodes would not have overlapped. This situation resulted in the build-up of the  $MnO$  melt and in incomplete reaction of the carbonaceous material observed in layers E and F in the central region of the furnace. Normal smelting conditions at higher operating loads should limit this occurrence. The reduction of the  $MnO$  melt and the lesser amounts of  $MnO$  in the slag in the region never went to completion while the furnace was cooling. This result was mainly because of the lower initial temperature in the central region. The metal carbide coated car-

bonaceous particles that were found preserved in this region were studied mineralogically in greater detail as discussed earlier on with the object of establishing the mechanism for reduction.

#### Control of the Process as a Function of the Smelting and Reduction Mechanisms

The design recipe for the proportioning of raw materials charged to a submerged-arc ferro-manganese furnace is based on the chemical analysis of the ores, the fluxes, and the carbonaceous reducing agents, as well as on the desired manganese content in the alloy, the basicity ratio of the slag, and the requirements of stoichiometric carbon. The design normally assumes homogeneous smelting (i.e. that there is plug flow of material through the furnace).

The segregation of components and the different time constants that result for material through-put complicate the corrective feedback control of the process. The feed-forward carbon control, based on the stoichiometric requirements, can easily be calculated on the basis of steady state conditions, but the complex dynamics of the process can upset the equilibrium between the carbon and the metal oxides and hence the carbon balance within the reaction zones. Over-carboned and under-carboned situations could therefore result inside the layer of coke and slag, despite the use of a good feed-forward control strategy. Normally there would be a shortfall of carbon in the  $MnO$  layer owing to the segregation of carbon in the outer region of the furnace and the association of most of the carbonaceous material with the layer of coke and slag.

In an over-carboned situation it would appear that the  $MnO$  layer is denuded progressively by dissolving in the slag until the amount of  $MnO$  in the slag (which would remain reasonably constant up to this point) suddenly decreases. As a result the carbon builds up and causes decreased resistance, and hence electrode penetration. The converse is also, apparently, true in that in an under-carboned situation, the amount of material in the  $MnO$  layer may increase to a point at which the amount of  $MnO$  in the slag suddenly increases dramatically as the carbon is depleted. The large amount of  $MnO$  raises the liquidus temperature of the slag, and this again leads to tapping and operating difficulties. In other words, the  $MnO$  melt appears to act as buffer. The existence of this  $MnO$  melt region might well have been predicted from the investigations of the process of reduction of Mamatwan ore by Koursaris, who observed the formation or nucleation of grains of almost pure  $MnO$  within partially reduced ore, in laboratory-scale experiments(19).

The high liquidus temperature of the  $MnO$ ,  $1775^{\circ}C$ , would explain why this layer of semi-fused material in the  $MnO$  melt is seldom, if ever, tapped from the furnace(19). The role of this  $MnO$  melt can be postulated only from observations both before and after the 'dig out'.

These conditions of dynamic equilibrium can best be explained with the aid of Figure 2. The dynamic equilibrium occurs between the manganese ore, which smelts from zone 1 into reaction zone 5, where most of the carbothermic reduction of MnO takes place. The quantity of carbonaceous reducing agent in this zone, and the MnO in the slag, are affected by the carbon balance in the feed but even more so by the nature of the raw materials and operation of the furnace as a whole (e.g. basicity ratio, electrode penetration, operating load).

The basicity ratio of the slag would be expected to influence the formation of the MnO layer, as would the power distribution in the furnace. The smelting and reduction mechanisms therefore influence the formation of the MnO layer, and hence affect the control of the furnace.

As a result of the rapid movement of the burden near to the electrodes, not much smelting takes place until the zone at the tip of the electrode is reached. Most of the power is dissipated in this region, as the endothermic reduction reactions occur in the layer of coke and slag(20). The slow movement of burden in the outer regions contributes to the formation of this region of MnO melt, because the temperatures reached are insufficient to reduce the MnO grains to metal carbide.

The transfer of manganese oxides from the ore into MnO in the melt, and from the MnO melt to MnO in the slag phase, would also be expected to influence considerably the dynamics of the process.

The furnace was operated with a very high basicity ratio for much of the period prior to the 'shut down', and this too may have added to the formation of this MnO layer, since SiO<sub>2</sub> in the form of quartz should aid in fluxing this MnO melt layer. Basicities as high as 1.76 were identified in the (Ca,Mn)<sub>2</sub>SiO<sub>4</sub> slag, which decrepitated readily, like a di-calcium silicate slag. Even higher basicities, up to 4.38, were found in the region of the MnO melt. These high basicities are attributable to the small amounts of quartz that were fed to the outer region of the furnace as part of a feed-forward strategy to eliminate power dissipation away from the central region of the furnace. Extra quartz was charged to the central region to compensate partly for this imbalance, but the inactivity of the central zone resulted in a nett overall shortfall of SiO<sub>2</sub>.

It might, nevertheless, be expected that there is almost always some form of MnO layer present in the furnace when a Mamatwan type of ore is used, and probably when other ores are used.

The suggested ways of decreasing this layer would be to operate the furnace at higher loads, and to limit the extent of the semi-active regions by enlarging the furnace crucible and increasing the active regions or by feeding return slag to this outer region instead of ore. There must be a balance between furnace volume and operating load such that the movement of burden is reasonably

uniform. The normal operation of the furnace at higher loads should make its control easier, and should restrict the formation of the highly conductive MnO layer. The presence of an extensive layer of MnO melt would tend to limit furnace operation, especially when the electrodes penetrate deep into the furnace. In addition, segregation and accumulation of carbonaceous material in the outer regions of the furnace, and a widespread MnO melt layer would cause power to be adversely distributed, and control of the electrode penetration would become a serious problem as the resistance of the furnace decreased. Less carbonaceous reductant should possibly be fed in the outer region. Unstable operation as a result of the dynamics of the overall carbon balance can increase the probability of serious eruptions.

#### Comparison with Previous Work

Most 'dig outs' have been carried out on small-scale experimental furnaces for obvious reasons. Yamagishi *et al.* reported on their study of the interior of a small 500 kV.A unit which was used to produce ferrochromium(1). The zone identified included a charge or burden layer, a slag layer, an ore layer, a coke bed, and a metal layer. Melting and reduction of the charge began next to the tip of the electrodes, where particles of metal were observed. The furnace had been quenched with nitrogen, which assisted in the rapid cooling of the reaction zone and in preserving the integrity of the interior of the furnace.

Andryukhin *et al.* observed five structural zones in the 'dig out' of a small 160 kV.A furnace used for the pilot-plant production of silicon from manganese(2). These zones were: solid charge, metal (molten ore plus a primary slag), slag and metal, and coke. The position of the coke layer varied between tapping cycles, as did its thickness during smelting tests prior to the 'dig out'. Andryukhin *et al.* stated that the current path and hence the power distribution are markedly affected by these fluctuations in the coke layer. Furthermore, a major cause of process instability is the disequilibrium between the flow of coke into the zone and the rate of consumption within the zone as a result of reaction of the coke with the slag to form metal. The extent of the electrode movement between taps gives a reliable indication of the thickness of the coke layer.

Ando *et al.* also studied the silico-manganese process by excavating a 600 kV.A furnace that had been quenched with nitrogen(3). Epoxy resin was used to cement the material in place so that it would not collapse during the 'dig out'. The findings of Ando *et al.* were similar to those of Andryukhin *et al.*, but an additional observation was that metal droplets were present in the coke bed that had a high silicon content (up to 30%).

Kurosawa *et al.* studied the process for the production of silicon by 'digging out' a 6500 kV.A furnace(4). These authors found a decrease in the amount of quartzite with depth in the furnace,

particularly in the region close to the electrodes. This phenomenon would be expected in such a slag-free process.

Müller *et al.* studied the smelting of pig iron (a process with similarities to the smelting of high-carbon ferromanganese), and ferrosilicon(5-7). The findings of Müller *et al.* can be summarized as follows:

- (1) Under steady conditions of operation, there is a coke bed of a defined geometry and specific electrical resistance that forms the current path between the electrode tip and the metal bath. There is an arc between the electrode tip and the coke bed.
- (2) Most of the heat generated from the arc and from the resistance is concentrated in the zone close to the tip of the electrode. The heat is dissipated to the smelting zone above the crater zone, and also to the bottom of the crater, where the slag is superheated. This observation explains why the slag is hotter than the metal.
- (3) The variation of the ratio of the distribution of heat between the smelting zone adjacent to the electrode and the slag zone below the electrode can be used in the control of the temperature of the process. The ratio can be adjusted by alteration of the crater resistance. This resistance, in turn, depends upon the relation between the length of the current path and the area of the current-carrying cross-section. These two parameters determine the geometry of the crater.
- (4) The chemical composition of the pig iron, as far as silicon is concerned, can be altered if the process temperature, which is dependent on the crater resistance, is controlled. The process temperature can be changed by the alteration of any one of the following parameters:
  - (i) the slag-to-metal ratio, the basicity, and the liquidus of the slag,
  - (ii) the electrical resistance of the coke, and
  - (iii) the crater resistance.

Müller *et al.* also indicate that the best method for control of the coke bed is the use of a hollow electrode. If the electrode feeds coke directly into the coke bed, there will be better control of the balance between the supply to the region below the electrode tip and the consumption in that region.

Andersen, and Kiyoshi discuss the smelting of pig iron, and present illustrations of the internal structure of the zones in a furnace(8,9). Many of the zones referred to are the same as those referred to by Müller *et al.*(5-7).

Bezobrazov *et al.* investigated the structure of an experimental furnace used for the production of chromium silicide(10). It is interesting

to note that the zones in the chromium silicide process differ from those associated with the smelting of pig iron in an electric furnace. The zones identified were made up of

- (1) residual chromium ore, quartzite, and coke breeze in the upper region,
- (2) primary slag containing residual burden in the region below the ore,
- (3) slag, and
- (4) alloy.

As Bezobrazov *et al.* make no mention of a coke bed, it is assumed that no such zone was present.

The only 'dig out' reported in the literature of a furnace used to produce high-carbon ferromanganese is that by Ozeki *et al.*(11). In March 1968 the no. 2 furnace (19 MV.A) at the Mizushima plant in Japan started production. Five years later, in December 1972, the furnace was excavated. It was necessary to reconstruct the furnace for the following reasons.

- (i) Several break-outs occurred during 1971 and 1972, and the shell was in a poor state of repair.
- (ii) As a result of a transformer failure the furnace was off for two months in 1970, and subsequent to this accident stable operation was adversely affected by several eruptions during 1971 and 1972.

The objectives of the 'dig out' at the Mizushima plant were to investigate erosion of the lining and the condition of the interior of the furnace. The findings can be summarized as follows:

1. Extensive erosion of the carbon blocks in the hearth of the furnace had occurred as a result of contact with molten metal under saturated in carbon.
2. The formation of molten metal containing an unsaturated level of carbon can occur if the furnace crucible is small, and if the amount of coke is substoichiometric.
3. The drainage pattern and crucible of the furnace depend on the geometry of the tap hole to a large extent.
4. Even at high loads and with good operating conditions the active volume of the furnace would be only 80 per cent.
5. The coke bed was thicker at the furnace walls and imbalances in the electrical system, electrode penetration can be caused by accumulation of the coke.
6. Crust had formed in several regions of the furnace. Likely causes were the high melt point of the charge, decreased load or stoppages, alkalines in the raw materials and high-basicity slags.

Many of the findings of these researchers in this field were observed in the 'dig out' of furnace M10, which, as far as is known, is the first large furnace for the production of high-carbon ferromanganese to feature in a paper on a 'dig out'. The most noteworthy difference between the observations on previously examined, smaller furnaces, and this furnace is the overall pattern of material flow. The features of the cone of loosely sintered material around the electrodes and the semi-active zones stretching upwards and away from the no. 1 electrode, towards the walls, were not observed on the smaller furnaces, probably because of the geometric considerations, and the differences in power dissipation that are attributable to the geometry. Most of the other features were found, for example the coke bed, the slag, and the so-called ore layer, which has been called an MnO melt in this case. The other major differences between the 'dig out' of furnace M10 and of the Japanese furnace were the minimal erosion of the carbon blocks in furnace M10 and the absence of crust formation. The carbon content in the metal carbide from furnace M10 must have been sufficiently high to obviate this problem of lining erosion.

Even though the slag produced in the Japanese furnace was a high-grade re-usable slag, unlike the discard-slag produced from furnace M10, the presence of some so-called 'metallic' slag was established. The composition of this 'slag' is almost identical to that of the MnO melt plus metal carbide: 82.08% MnO, 7.54% C, 4.16% SiO<sub>2</sub>, 1.22% CaO, 0.24% MgO, 2.85% Al<sub>2</sub>O<sub>3</sub>, and 19.5% FeO. This 'slag' was responsible for the attack on the carbon blocks in several regions. It seems possible that the MnO-melt region in furnace M10 could have contributed to the break outs near the slag tap hole for similar reasons.

#### Recommendations Based on Knowledge Gained During the 'Dig-Out'

The data from the 'dig out' can be used in improving furnace control, as a basis for recommending improved techniques for future 'dig outs', for establishing new design criteria, and in improving the sampling and analysing of the slag and metal tapped during operation of a ferromanganese furnace.

1. Ideally, the contents of the furnace should be preserved in a condition as similar as possible to that of a furnace in operation. Quenching with water is not a very good idea, since the water can react with the coke in the hotter regions of the furnace. The cooling effect of the water would probably lower the temperature of the furnace within two to three days, but the washing away of the fines and the reaction of the coke could severely alter the structure of the materials in the furnace. However, when one is dealing with a production unit, for which the unabsorbed fixed costs amount to thousands of dollars a day, and the prime objective is to return the unit to productivity, then maintaining the integrity of the furnace interior must yield priority to more dras-

tic procedures designed to make the furnace more accessible. The use of liquid nitrogen might therefore be a better solution.

2. A second consideration is the cutting open of the shell in only one locality. Access to the no. 1 electrode was successfully achieved in this way, but not to electrodes 2 and 3 as a result of material collapsing as shown in Figure 14. Had the shell been cut open at these electrode fronts as well, a comparison between equivalent localities at different electrodes would have been possible. The only major problem with such a 'dig out' in three directions would be the construction of three access ramps, rather than one. However, because 'dig outs' are infrequent, an attempt should be made to gain the maximum benefit from each 'dig out'.

3. The photographs of some regions were not marked with identifying tags because the blackboards were too large to be used for these close-up shots. For future 'dig outs', smaller markers should be available, as well as larger ones. Care should be taken that the markers provided are always used when photographs are taken.

4. The power dissipation suggested that the diameter of the furnace was too small in relationship to the pitch-circle diameter and that a somewhat larger shell was required. The central region was inactive at these moderate furnace loads. At greater furnace loads, this zone could become active because of the enlargement of the smelt zone.

The dimensions of the furnace before and after its rebuilding are shown in Table V. The diameter of the furnace was increased from



Fig. 14. A general view of the interior of the furnace showing material collapsing into the excavated central region. The two back electrodes no. 2 and 3, and the broken no. 1 electrode are evident.

13.2 to 15.5m, and the effective volume from 333.6 to 486.3m<sup>3</sup>.

5. The contents of the furnace were sampled

during the 'dig out' as were the slag and metal prior to 'dig out', but no detailed mineralogical analysis has been carried out on the slag and metal. Such a study would help to relate the state of the material in an active furnace to that in a cooled furnace. It has been found, however, that some MnO grains are present in the slag that is tapped. This indicates that all of the grains of MnO do not necessarily settle into a separate layer during the operation of the furnace. Radio-active isotope tracer tests, in which  $^{54}\text{Mn}$  is used, are being carried out to investigate the matter.

### Conclusions

1. Several zones of interest were identified around and beneath the no. 1 electrode, and they include a region of rapid material descent next to the electrode, a 'coke bed' and a coke-enriched slag layer, an MnO-melt region, and an alloy layer.
2. The active zones of the furnace in which most of the carbothermic reduction occurs were limited to the regions surrounding the electrodes. The semi-active zones at the centre and in the outer part of the furnace appear to have been responsible for the formation of the extensive MnO-melt region since incomplete reduction occurs.
3. Semi-active zones appear to extend from the layer of coke and slag beneath the electrodes upwards and towards the walls, which indicates that an increased concentration of carbonaceous mate-

rial in the outer regions was detrimental to optimal power dissipation. The build-up of the MnO-melt region in the centre of the furnace appears to have resulted from this abnormal flow of current and from the low operating load.

4. Very few of the carbon blocks at the bottom of the furnace had dissolved, probably because of the carbon saturation and exsolution of graphite from the metal carbide as it cooled in the hearth.
5. Mineralogical investigation rather than ordinary chemical analysis yielded the information necessary for the interpretation of the results for the contents of the various zones within the furnace and for the postulation of reduction and smelting mechanisms.
6. The feed-forward control of the process cannot in itself account for the dynamics of the process, and especially for the inter-relationship between the layer of coke and slag and the MnO melt. The development of a strategy of how formation of the MnO melt can be avoided, minimized or controlled is important even if higher loads partly obviate the problem.
7. The findings of this 'dig out' relate to a furnace that was operated under abnormal conditions and it would be logical to expect some changes in the zones at the normal higher loads. This 'dig out' does, however, indicate the disadvantages of reduced operating loads on large ferromanganese furnaces.

Table V. Dimensions of furnace M10 before the 'dig out',  
and after the rebuilding

	Before rebuilding	After rebuilding
Shell, inside diameter	13 200mm	15 500mm
Lining inside diameter:		
At bottom	9 900mm	12 600mm
At top of side-carbon	11 900mm	12 600mm
At top of refractory	12 400mm	14 380mm
Effective depth	5 265mm	5 490mm
Net volume of top of carbon	433.6m <sup>3</sup>	486.3m <sup>3</sup>
Net volume to top seal	271.7m <sup>3</sup>	258.2m <sup>3</sup>
Total	605.3m <sup>3</sup>	774.5m <sup>3</sup>
Tap hole height above floor:		
Metal	300mm	300mm
Slag	1 300mm	1 300mm
Arc between metal tap holes	30°	34°

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