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Thermal aspects of the smelting of iron ore in reconstructed South African Iron Age furnaces

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SYNOPSIS

A study was made of the smelting process in two experimental furnaces patterned on Iron Age furnaces excavated at Melville Koppies Nature Reserve, Johannesburg. In a number of smelting experiments, the influences of air supply, temperature, time of operation, fuel consumption, and other operational factors were investigated.

Metallurgical and metallographic aspects of the furnace operation and smelting products are discussed, and the experiments are compared with similar research work conducted in Europe and Africa.

SAMEVATTING

Daar is 'n studie gemaak van die smeltproses in twee eksperimentele oonde wat gebou is volgens die patroon van oonde uit die Ystertydperk wat in die Natuurreservaat Melville Koppies, Johannesburg, uitgegrawe is. Die invloed van die lugtoevoer, temperatuur, bewerktyd, brandstofverbruik en ander bedryfsaspekte is in 'n aantal smelteksperimente ondersoek.

Die metallurgiese en metallografiese aspekte van die oondbedryf en smeltprodukte word bespreek, en die eksperimente word vergelyk met deeglike navorsingswerk wat in Europa en Afrika gedoen is.

Introduction

The work described in this paper is a continuation of the archaeo-metallurgical investigations undertaken over the past ten years at the Archaeological Research Unit of the University of the Witwatersrand[1-3]. One of the previous studies on the correlation of slag characteristics and operational furnace temperatures had led to the conclusion that further work in this field, based on smelting experiments, would be desirable[3]. The present paper reports on such experiments, and on the results obtained by temperature measurements in furnaces and by the construction of temperature profiles.

Since slag is the principal, and often the only, preserved material from ancient smelting sites, various methods were investigated by which information on the thermal characteristics of the smelting process could be obtained from samples of slag: chemical/physical analysis, phase-diagram studies, determination of liquidus temperatures, and metallographic examinations. In addition, the problem of preheating of the air injected into such furnaces was investigated.

Experimental Work

Construction of Furnaces

The shapes and dimensions of the reconstructed furnaces were based on two Iron Age furnaces excavated at Melville Koppies Nature Reserve, Johannesburg: furnace A (A.R.U. 7/63), found on the upper eastern plateau of the Reserve (Fig. 1), and furnace B (A.R.U. 28/64), found on the lower northern slope[4,5]. The experimental furnaces were built on level ground in Marks Park, just below Melville Koppies.

The shapes and dimensions of the experimental furnaces are given in Table I (Nos. 9 and 10) and Fig. 2. The same methods of construction were used as in the previous experimental studies of iron-smelting techniques[1].

Care was taken to follow the basic procedural rules established in experimental archaeology[6]. As far as possible, use was made only of methods and materials that were available to African prehistoric societies. Where this was not feasible, acceptable substitutes were employed as, for example, charcoal and ore that closely matched excavated materials of the same type. Some difficulty arose in the choice of the air-supply equipment. The making of traditional skin bellows is an almost forgotten craft, but suitable leather material and stitching techniques were finally found and a team of four bellows blowers was trained for the strenuous task.

Air-blowing with skin bellows became difficult and costly when the mass of iron and slag obtained in some of the experiments had to be re-smelted, which required high temperatures (1350 to 1400 °C). After it had been ascertained that this condition could be achieved by the use of four bellows, one pair of bellows was replaced with a small air compressor (air delivery 110 l/min) so that the re-smelting would be adequate.

Smelting Experiments

Batches 1 to 4. These batches, which were made in the small experimental furnace (B), served to acquaint the operators with the performance of the equipment and with the working conditions.

Batches 5 and 6. These batches were run in experimental furnace A (Fig. 2), which had three times the capacity of furnace B. The firing gave information on the performance in furnaces like the larger two-slotted Tswana/Melville Koppies furnaces, on the thermal efficiency and heat distribution in such furnaces, and on the economic operation of the process. The yield of metallic iron from batches 5 and 6 was low (4 and 7,5 per cent respectively).

Batch 7. In this batch (run in furnace B), the temperature characteristics of the smelting process in the range 1250 to

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Fig. 1—Iron-smelting furnace 7/63, Melville Koppies Nature Reserve, Johannesburg

1350 °C were evaluated when the air input was halved by the blocking of one of the two tuyère slots of the furnace with stones — a feature that was noticed in a Tswana-type furnace that had been excavated some years before at the farm Schietkraal[7]. With the air input reduced from approximately 250 to 125 l/min, the average temperature was still 1275 °C, occasionally rising to 1350 °C. However, the separation of the iron from the slag was unsatisfactory, and the yield was accordingly low.

Batch 8. This batch was run in furnace B, two pairs of bellows being used. The temperatures were kept between 1230 and 1300 °C, except for a very short interval when the pumping rate went up to between 120 and 130 strokes per minute and the temperature reached 1400 °C. The iron separated in thin platelets, but the iron yield was still low (4,5 per cent). Part of the ore (about 45 per cent) consisted of fines (smaller than 2 mm in diameter). It had been expected that the reduced size and the larger surface of these fines would favour a higher output of iron, but this did not occur. The fines quickly moved through the charcoal bed and settled on pieces of slag as a thin unreacted layer of ore.

Batch 9 (re-smelt batch). A compressor was used for the air supply, and this batch was run at a sustained high temperature, estimated as being between 1300 and 1350 °C. (The temperature was estimated from the white colour of the heat radiated in the furnace interior as observed

Fig. 2—Experimental smelting furnace A, Marks Park, Johannesburg (in the background the potentiometer used for the temperature measurements and experimental furnace B)

through a tuyère). No ore was used in this case, the furnace being charged with the slag bloom produced in batches 5, 6, and 8. After a relatively short time, the slag in the furnace liquified. When the test was stopped after 4½ hours, good separation of iron, slag, and gangue had taken place. Part of the iron (350 g) was found as an irregular-shaped block; another part (200 g) was picked up in small platelets after the conglomerated, rather soft pieces of crude iron had been hammered out. The total yield obtained from the 15 kg of ore, slag, and bloom charged was 950 g of crude iron (including the primary recovery). The calculated yield was 10,4 per cent. This can be regarded as a satisfactory result in that 'a yield of iron of about 10% of that charged is very typical of the bloomery process at all times'[8].

Comparison with Similar Experiments

Table I gives a number of dimensional and functional data for smelting experiments in reconstructed bloomery

TABLE I

RESULTS OF EXPERIMENTAL WORK ON BLOOMERY FURNACES*

No.	Furnace type (pattern)	Date	Internal diameter m	Stock height above tuyère m	Type of air supply	No. of tuyères	Air l/min	Air rate l/min/cm^2	Max. temp. °C	Time to process h	Ratio of charcoal to ore	Size of charcoal mm	Size of ore mm	Ref. no.
1	Polish	200–400AD	0,49	0,44	—	2	320	0,17	1300	9	1:1		<4	12
2	Britain Weald No. 2	50–300AD	0,30	0,66	Electr. blower	1	≈300 (?)	0,40 (?)	1300	9	1:1	25–80	10–25	12
3	Britain Norfolk Ashwicken	Roman Iron Age	0,30	1,0	Compressor	1	300	0,41	1400	5	1:4	20–50	<3	12
4	Germany Siegerland	La Tène	0,5	0,5	Compressor	1	—	—	1000	8,5	1:1	—	≈20	13
5	Ethiopia Dimi	Direct observation of traditional process	0,4 (top) 1,2 (base)	1,00	Bowl bellows	18	3544	0,47	1420	4	3,28:1	20–50	15–25	17
6	Tanzania Buhaya	≈1st C AD	Bowl 1,1m diam., 0,6m deep, shaft 1,5m high	—	Drum bellows	8	—	—	1600–1800	8	—	≈10	20	14,15
7	South Africa Schuinshoogte-Venda type	18/19C AD replica	0,67 (top) 0,70 (middle) 0,60 (bottom)	—	Skin bellows	3	—	—	1200	13	10:1	>10	30–60	16
8	South Africa Kaditshwene/ Melville Koppies B type	18/19C AD replica	(Oval) 0,2 × 0,35	—	Compressor and skin bellows	2	250†	0,45	1220–1250	7,5	4:1	14–18	2–10	1
9	South Africa Kaditshwene/ Melville Koppies B type	18/19C AD replica	(Oval) 0,25 × 0,50	0,27	Skin bellows	2	250†	0,25	1300–1350 (4 batches)	6–7	Av 5:1	3–30	2–10	This paper, 1984
10	South Africa Melville Koppies A type	11th C AD replica	0,6	0,35	Skin bellows	2	250†	0,09	1300	7,5	4,7:1	3–30	2–10	This paper, 1984

* This table is based on a compilation by Tylecote[12]. Nos. 4 to 8 and information from this paper are included for comparison.

† These figures were calculated assuming an efficiency of 20% of the capacity of the bellows (5 litres water volume) and a pumping rate of 70 strokes per minute.

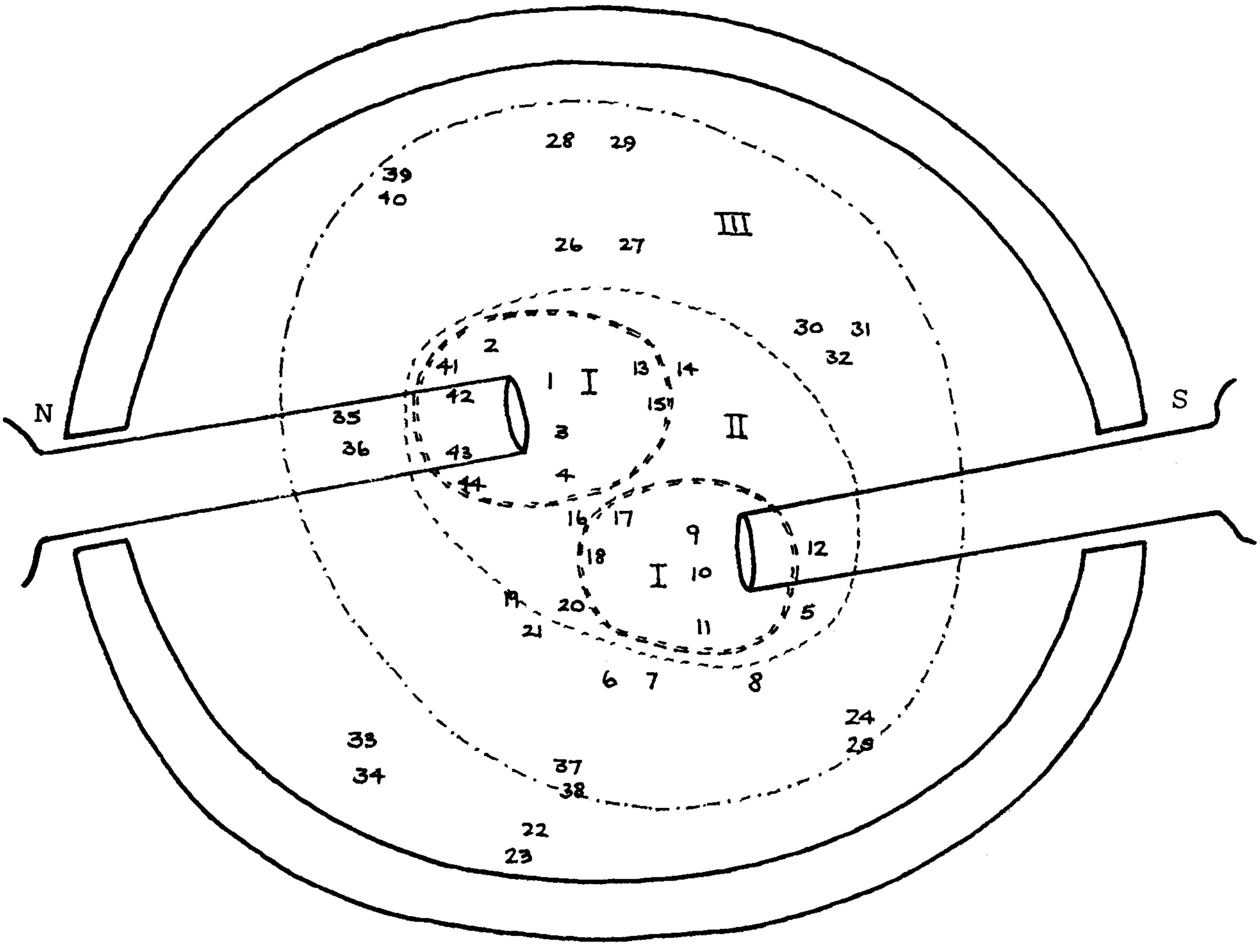


Fig. 3—Two-dimensional (vertical and horizontal) temperature distribution in experimental furnace A (test batch 6)

Measuring point	Depth from top, cm	Temperature °C	Measuring point	Depth from top, cm	Temperature °C
1	10	1050–1100	23	30	180
2	10	890	24	10	860
3*	30	1290	25	25	920
4†	25	1240	26	20	920
5	25	930	27	30	1100
6	25	750	28	20	760
7	30	690	29	30	820–840
8	30	680	30	10	875
9	30	1140	31	20	900
10	20	1260	32	30	885
11	10	1170	33	10	295
12	20	1090	34	30	320
13	30	1160	35	10	685
14	20	1200	36	30	720
15	10	1030	37	20	635
16	10	753	38	30	640
17	20	1020	39	20	755
18	30	1210–1220	40	30	650
19	10	625	41	15	1050
20	25	750	42	30	967
21	30	770–810	43	15	1240
22	20	190	44	15	1245

* Close to tuyère level
† At tuyère level

furnaces. The values for some of the characteristics (dimensions, operational temperatures, time of operation) fall into relatively narrow ranges, resulting from the general conditions of the bloomery process. Other values, such as the number of tuyères, the rates of air supply, and the ratios of fuel to ore show the great variety of models and processes.

For a number of parameters the figures given are insufficient by themselves and additional information is necessary. This is especially so in the case of the air-supply rates, which depend on the sources of air supply (whether skin-bag bellows, drum-bowl bellows, air compressors, or electric blowers), the performance of the bellows used (volume of air discharge), the pumping rate, and the size and position of tuyères.

It is also important to know the yield of an experiment (iron and slag) and also some constituents of the raw materials and the products of the process. Some of these parameters are given in Table II and in the text of this paper.

Measurement of Furnace Temperatures

It is obvious that the temperature profile has a decisive impact on the successful operation of a furnace. In most of the experiments, numerous temperature measurements were carried out in the operating furnaces both in the vertical and horizontal directions so that realistic temperature profiles could be obtained. Lower temperatures (up to about 1200 °C) were measured with Chromel–Alumel thermocouples, and higher temperatures with Pt 6RH/Pt 30RH thermocouples protected by sintered-alumina sheaths. Care was taken that the sheaths were not exposed to excessive temperatures for too long since such sheaths are prone to attack by molten slag. The recording was carried out with a Cambridge potentiometer. The results of the measurements are summarized in Figs. 3 to 5.

From these diagrams there appear to be well-developed active areas in the furnaces brought about by the action of the air blown in from the tuyères. Here the formation of metallic iron proceeded partly in the molten state of the charge with visible slag-crust formation around a restricted area. Beyond that, the bulk of reduction proceeded by a gas–solid reaction in the charge, being favoured by fast kinetics at the high temperatures before any melting of the charge could take place.

Based on the measurements conducted in test run 6 (Fig. 3), together with the results given in Fig. 4, a fairly

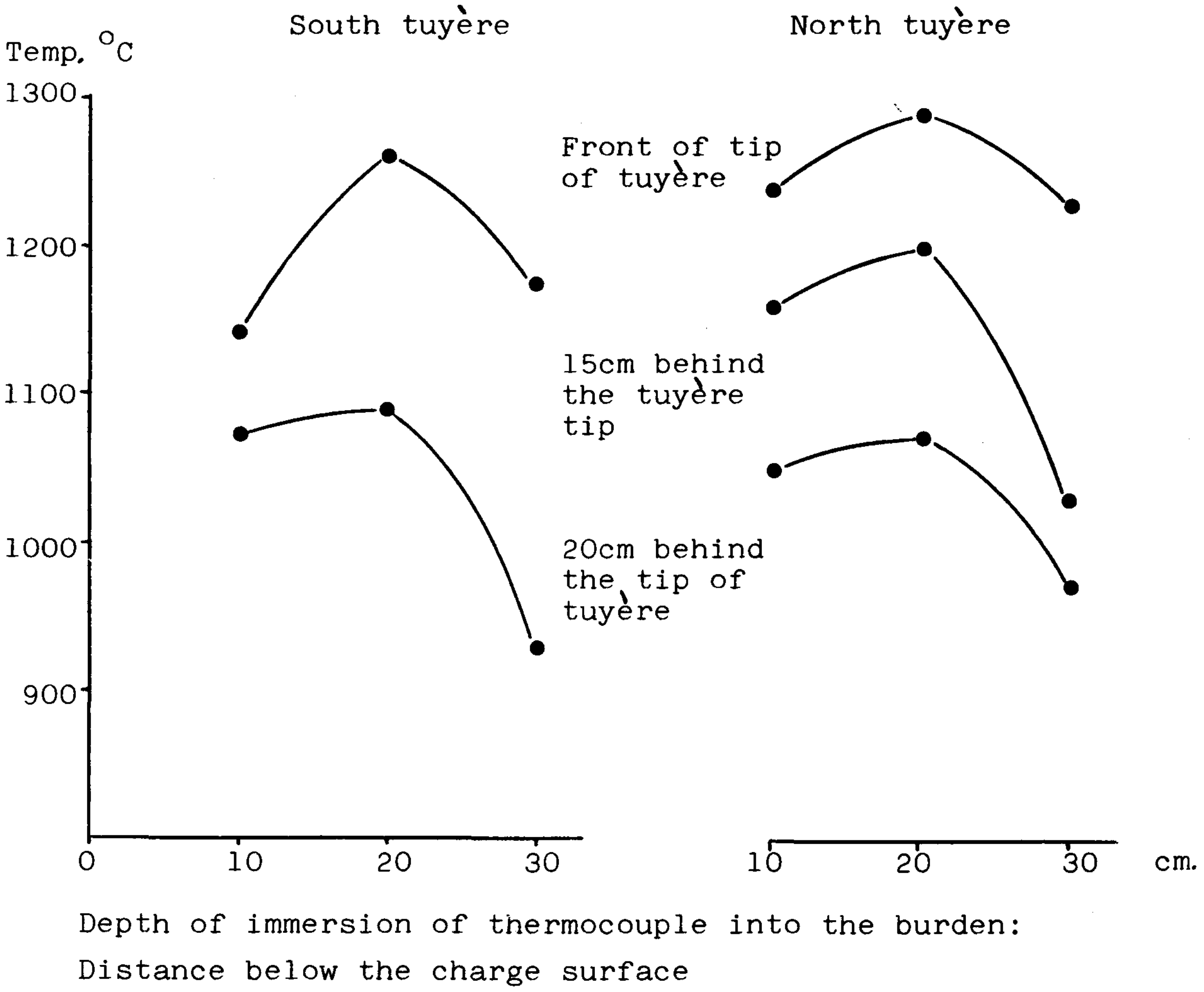


Fig. 4—Vertical temperature gradients in experimental furnace A around the tuyères (test batch 6)

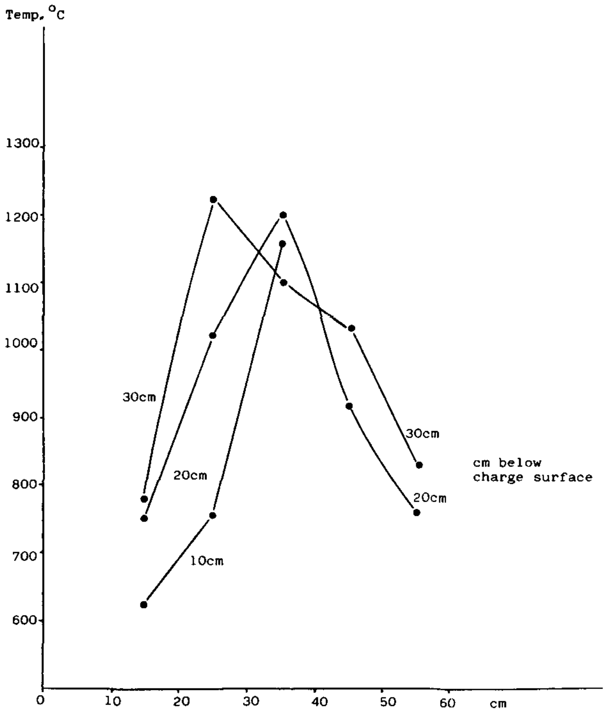


Fig. 5—Temperature gradients measured across the width of experimental furnace A (test batch 6)

complete picture of a tuyère in terms of a modern raceway model can be obtained. A reconstruction of the raceway and active zones around the tuyères from temperature measurements and from inspections after the furnace had cooled and been dismantled is given in Fig. 6. Here the pattern of gas composition is only speculative.

Zones I in Fig. 3 are high-temperature zones in which the melting of the solid charge can take place. Zone II represents a high- to medium-temperature area in which very good kinetic conditions exist for a gas–solid reaction without softening of the charge. Zone III in Fig. 3 represents a temperature range between 650 and 1000 °C, which is still favourable for gas–solid reaction. This would roughly correspond to the temperature conditions existing in the lower half of the stack of a modern blast furnace.

From this outline of the temperature measurements, it appears that the volume utilized in effective reduction was about 20 to 25 per cent of the total furnace volume, to which an additional maximum 8 to 10 per cent could be added under ideal conditions for the performance of extra indirect reduction. In view of the simplicity of the construction, these values can be regarded as rather impressive.

As will be apparent from the results, the maximum sustainable furnace temperatures measured during the tests were around 1280 to 1350 °C, not taking into account short-lived temperature rises. A further increase in temperature would not have served much useful purpose because the bulk of the reduction in these furnaces, as was

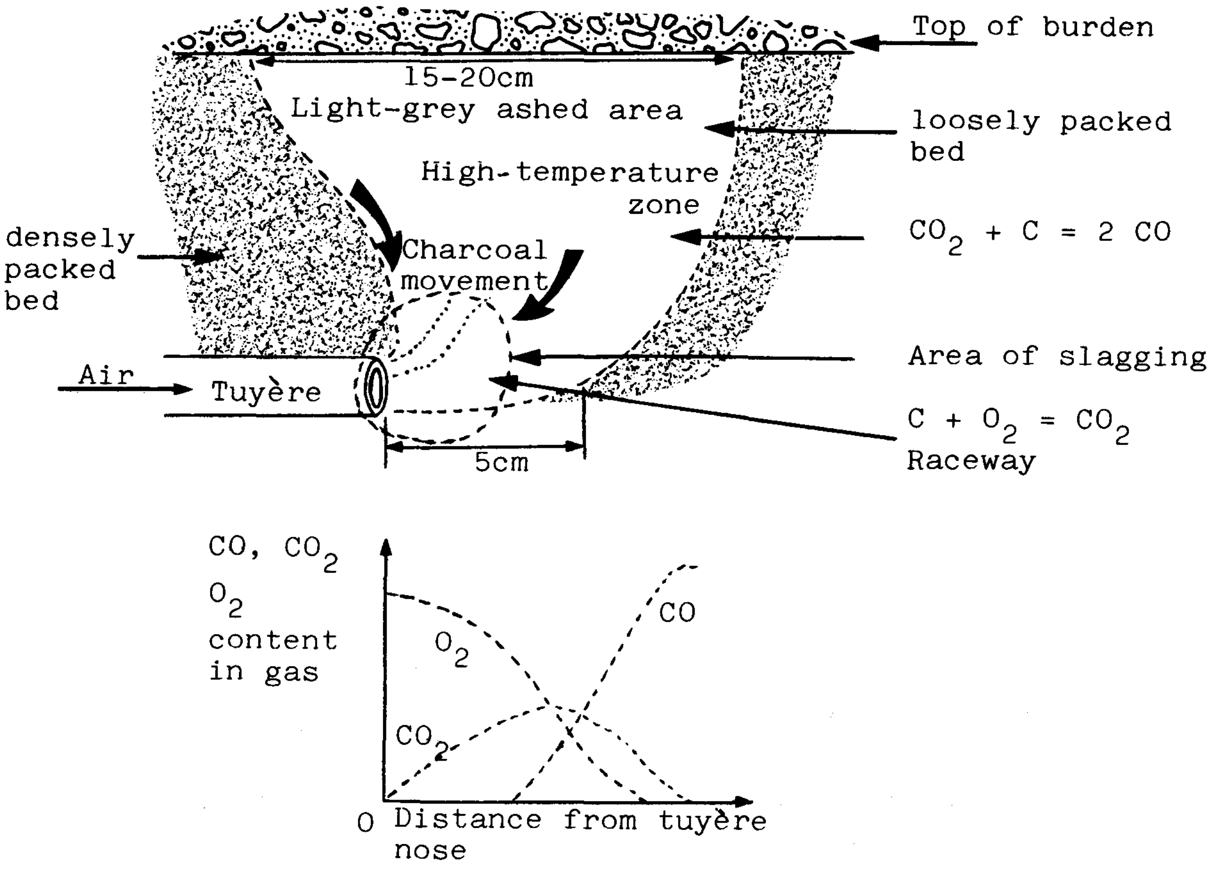


Fig. 6—Conditions in tuyère zone of bloomery furnace

mentioned earlier, was gas–solid reduction. Higher temperatures would have brought larger portions of the charge into the sticky state, and would have hampered the operation, reducing even further the low efficiency of the metal production.

Slag Characteristics and Furnace Temperatures

The efficiency of the smelting process conducted in the experimental furnaces was tested by chemical analyses (Table II) and by metallographic examination of the slag and crude iron produced. The slag from experiment 2/6, conducted in experimental furnace A at a temperature of about 1300 °C, showed a relatively low iron content (37,4 per cent). It is likely that the smelting time for this experiment was too short in view of the large size of furnace A. Slag from re-smelt experiment 2/9, which was conducted in the smaller furnace B at about 1350 °C, had a total-iron content of 49,8 per cent, a value falling into the range of iron contents found in a large number of slag samples from Iron Age sites in South Africa.

Electron-microprobe investigations on slags from experiments 2/8 and 2/9 (Table II, 6 to 7) showed the sample from experiment 2/8 to contain slag inclusions between metal particles, while slag from re-smelt experiment 2/9 contained glass-like matter on the edges of metal particles. This shows structural micro-changes brought about by the re-smelting process.

Two samples of crude iron separated from the bloom of experimental smelts 8 and 9 were submitted to the Research and Development Section of Iscor for analysis. Both samples showed a high content of metallic iron (98,7 and 98,4 per cent) and a low content of iron oxides (0,7 and 0,54 per cent expressed as FeO).

For some time, phase diagrams have been used in the correlation of the chemical–mineralogical composition of smelting slags with the temperatures at which certain phases exist. A frequently used quasi-ternary system is based on the plotting of three components of many slags (iron oxide, silica, and anorthite) against corresponding

TABLE II

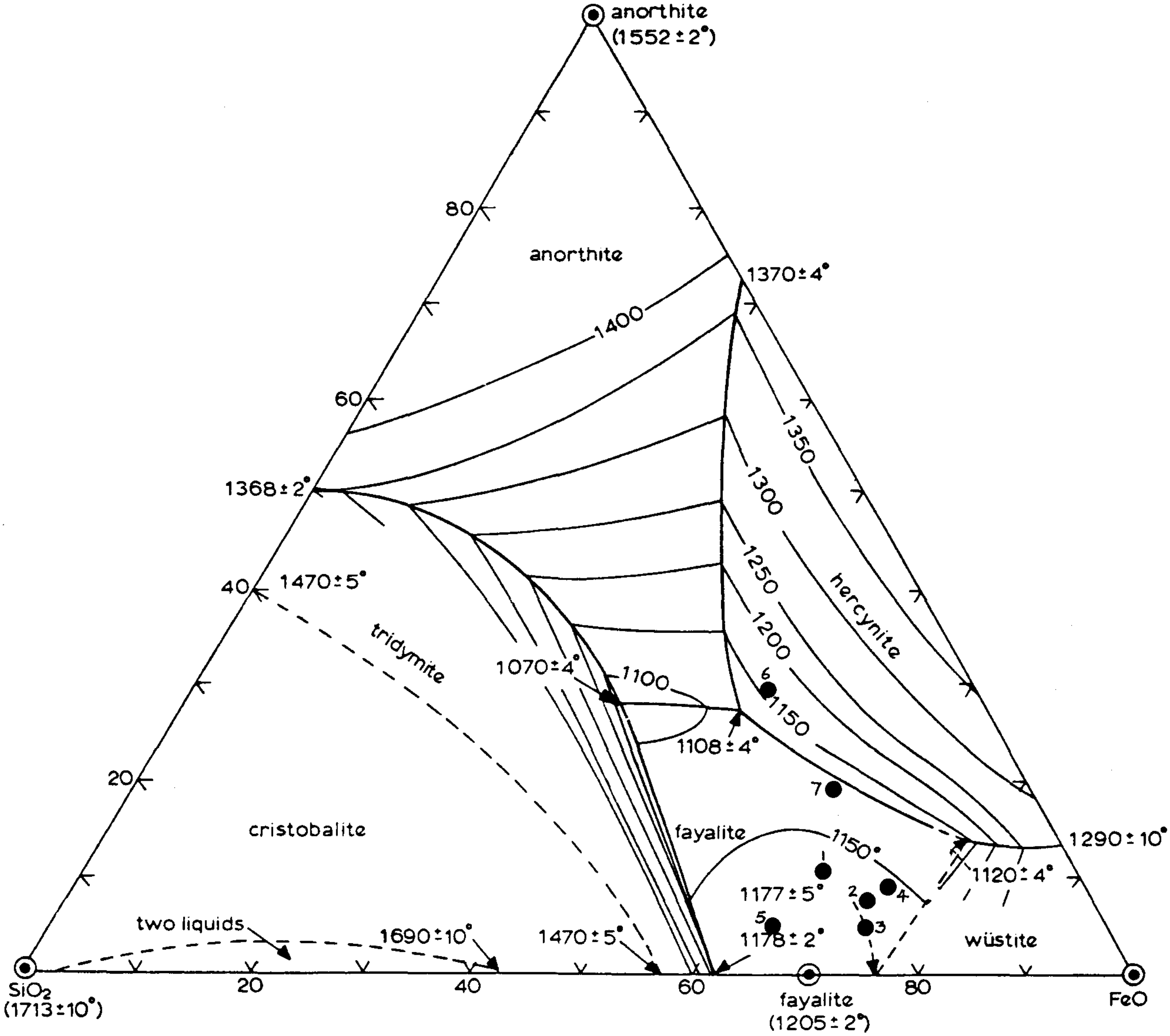
ANALYSES OF SLAG SAMPLES

		1	2	3	4	5	6	7	8
Access Identif. No of sample		7/63	28/64	Exp. batch 1/26	Exp. batch 2/6	Exp. batch 2/9	Slag inclusion in crude iron extracted from exp. batch 2/8	Slag inclusion in crude iron extracted from exp. batch 2/9	Iron ore from Bomvu Ridge Mine, Swaziland Iron Ore Development Co.
Site		Melville Koppies Nature Reserve	Melville Koppies Nature Reserve						
Sample taken to		Base of upper (11th cent.) furnace	22 cm below rim of lower (19th cent.) furnace	Exp. furnace B constructed at Univ. Wits. (1977)	Exp. furnace A constructed at Marks Park, Johannesburg (1983)	Exp. furnace B constructed at Marks Park, Johannesburg (1983)	—	—	
Max. operational furnace temp., °C		—	—	≈1250	1300	1300–1350	1300–1400	1300–1350	
Initial sintering temp., °C				1430	1440	1425			
Liquidus temp. of final phase (fully molten), °C		1480	1445	1490	1460	1460+	—	1460+	
Constituents	Expressed as	%	%	%	%	%	%	%	%
Silicon	SiO_2	25,28	21,76	24,5	33,4	20,1	33	55	9,37
Aluminium	Al_2O_3	6,94	5,16	5,3	8,1	3,2	12	17	2,18
Ferric iron	Fe_2O_3	13,38	11,64	7,1	n.d.	n.d.	—	—	
Ferrous iron	FeO	44,66	56,28	60,0	n.d.	n.d.	25	—	
Magnesium	MgO	0,96	0,52	0,37	0,72	1,4	1,5	3	
Calcium	CaO	1,92	1,47	1,04	1,8	2,9	25	12	
Sodium	Na_2O	0,32	0,39	0,13	0,05	0,14	—	—	
Potassium	K_2O	0,79	0,77	0,99	2,8	2,2	5	10	
Titanium	TiO_2	0,38	0,31	0,17	—	—	—	—	0,12
Phosphorus	P_2O_5	0,03	—	0,37	0,27	0,27	—	—	0,08
Chromium	Cr_2O_3	<0,01	<0,01	0,05	0,04	0,05	—	—	
Manganese	Mn_3O_4	3,55	0,13	0,16	0,18	0,19	—	—	0,44
Total iron	Fe	calc 44,07	calc 51,89	calc 51,61	37,4	49,8	—	—	52,35
Analyst Ref.		Mintek Analytical Science Division Ref. List No. 1		ISCOR R&D Lab. Ref. List No. 1	GENCOR Group Lab. (East)		ISCOR Research & Develop. Lab.		Swaziland Iron Ore Dev. Co. Ref. List No. 1

temperature graphs[9]. This practice works well under some well-defined conditions, including low calcium and aluminium contents, fairly high iron content, medium silica content, and absence of higher percentages of other elements.

Fig. 7 is a diagram representing a number of slags from Transvaal smelting sites, as well as from experimental furnaces. The plotted positions of some of these slags are concentrated in the fayalite area, and the corresponding temperatures read on the graphs (1150 to 1180 °C) compare well with the temperatures observed in experimental furnaces of similar types. However, some of the phase diagrams constructed for slags from other regions indicate a different placing between the fayalite and the hercynite areas (Fig. 7). Such slags frequently contain high amounts of calcium, magnesium, alkalis, or titanium. The positions are distributed irregularly in the phase diagram, and the corresponding temperatures read from the temperature graphs do not agree with the determined melting points for such slags. It is thought that certain elements and minerals associated with a slag could influence the equilibrium of the phase system. Another objection to the general validity of the system FeO–SiO_2–anorthite is the improbability that CaO, Al_2O_3, and SiO_2 will always form only anorthite in the slag; other minerals such as wollastonite, gehlenite, and similar silicates could also be present in slag and make the construction of such a phase diagram unreliable[10].

Attempts were recently made to replace the coarse estimates based on phase diagrams by norm-calculation procedures. With this method, the depiction of the mineral



ref.: E. M. Lewin *et al.*, 'Phase diagrams for ceramists, 288, Fig.869; 1964, Ohio

Fig. 7—Phase diagram for the system SiO_2–FeO–anorthite (by courtesy of The American Ceramic Society, Inc.). The positions of 7 slags from Transvaal smelting furnaces are shown as follows:

1. **Melville Koppies 7/63**
2. **Melville Koppies 28/64**
3. **Experimental furnace 1–26**
4. **Experimental furnace 2–9**
5. **Broederstroom 24/73KC**
6. **Schuinshoogte (Venda) 27/73**
7. **Neck B (Ref. 16)**

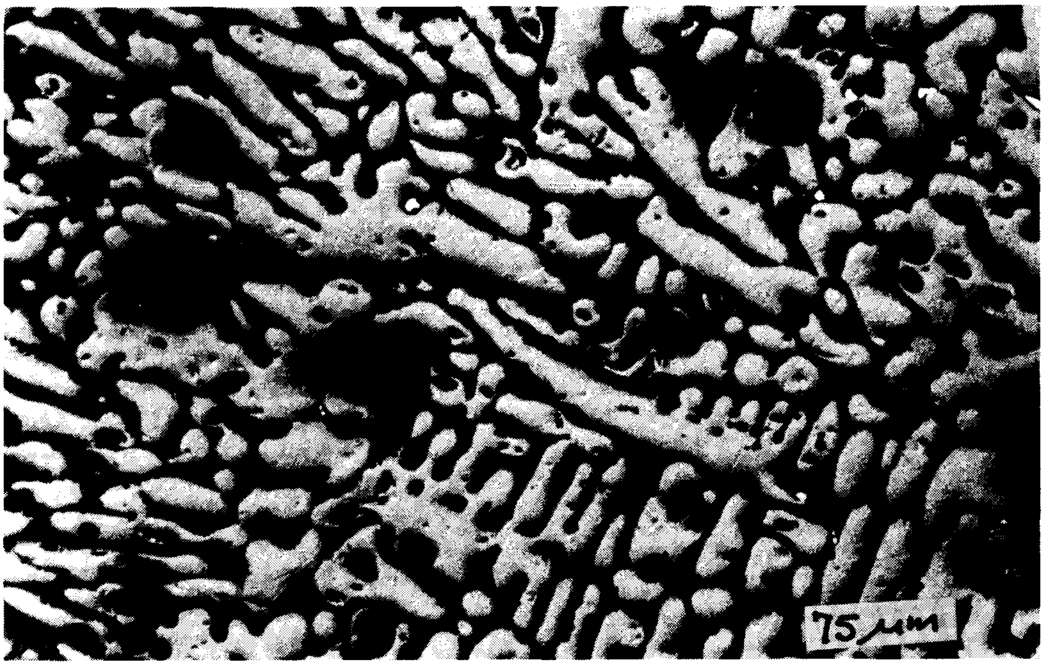


Fig. 8—Dendrites and grains of iron oxide in a background of fayalite. Polished

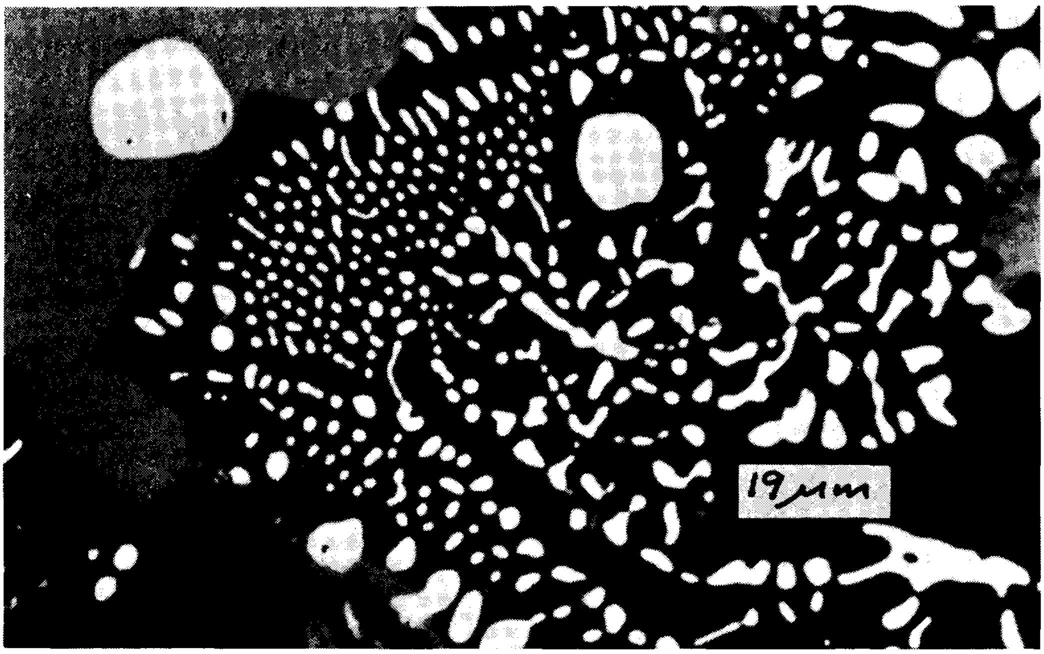


Fig. 9—Fayalite (grey) and an island of eutectic. Polished

assemblages of slags and the plotting of the converted analyses of slags are more satisfactory[11]

Observed Furnace Temperatures and Slag Liquidus Temperatures

The liquidus temperatures determined for 28 slags from iron-smelting sites[3] and 3 slags from smelting experiments (Table II) are nearly all considerably higher than the maximum operational temperatures measured in the smelting experiments (1280 to 1350 °C).

One might find this discrepancy somewhat surprising, but the explanation of the apparent anomaly is not difficult. If a low melting formation, e.g. fayalite slag ($2 FeO \cdot SiO_2$), is assumed at an early stage of a smelting test, the semi-liquid or softened area will soon enclose solid particles, containing rather refractory high-melting Fe_2O_3, CaO, and some Al_2O_3 and MgO components. New slag phases will form, but only limited amounts of these high-melting oxides will dissolve in the semi-fluid viscous melt, since the actual furnace temperature does not rise above the quoted maximum values. Therefore, the refractory oxides would remain mostly in the form of solid enclosures. The determination of the liquidus temperature of this highly unhomogeneous system by hot-stage microscopic techniques[3] would lead to an increase of temperature to high levels during which the solid enclosures would form a homogeneous melt with the lower-melting phase(s) and would become incorporated into the system. The melting point of this system would then reach rather high values, close to 1500 °C. These complications in the evaluation of the liquidus temperatures of slags by hot-stage microscopic techniques and similar methods may make use of such measurements in certain cases questionable, since the results will not indicate the originally existing phase relationships in a homogeneous system.

Metallographic Examination of Slag Samples

Specimens of slag from experiments 2/6 and 2/9 were examined by optical and scanning electron microscopy to determine their mineralogical nature. X-ray-diffraction analyses and microanalyses were used to determine the phases in the specimens and the chemical nature of the different microconstituents.

The X-ray tracings obtained with specimens 2/6 and 2/9 were similar and showed a mixture of wustite (FeO) and fayalite ($2FeO \cdot SiO_2$), but the proportions of wustite to fayalite in the two specimens were appreciably different. Specimen 2/6 showed a greater amount of wustite than fayalite, and the amount of wustite in specimen 2/9 appeared to be lower than that of fayalite. In both specimens, low-intensity reflections were observed from minor constituents that could not be identified with certainty.

Microscopic examination showed that the two specimens consisted of particles of wustite in a matrix of fayalite slag. The particles of wustite often appeared to have a dendritic nature indicative of a primary phase (Fig. 8).

Metallic particles were observed mainly at the edges of the partially reduced ore particles. Specimen 2/9 showed a higher degree of metallization, confirming the results of the X-ray-diffraction analyses.

Islands of a eutectic were present throughout the specimens as shown in Fig. 9.

Metallization took place by the reduction of wustite particles near the edges of reacted ore lumps and was associated with the generation of porosity in the wustite particles (Fig. 10).

Examinations in a Cambridge S4 scanning electron microscope and qualitative microanalyses with an energy-dispersive system (EDS) attached to the microscope confirmed the results of the examination with the optical

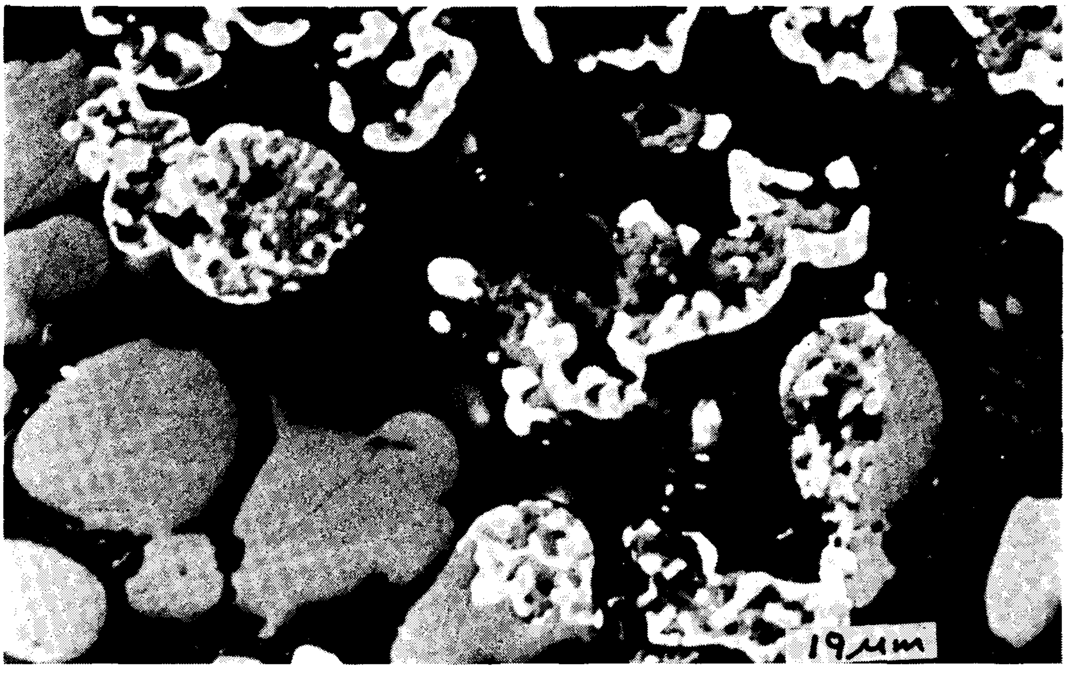


Fig. 10—Formation of metal by the reduction of iron oxide particles and the generation of porosity in the oxide. Polished

microscope. The results of the microanalyses (Table III) show the following:

(a) the particles of iron oxide were of high purity;
(b) the fayalite contained only traces of lime;
(c) the continuous phase in the eutectic varied in composition in different areas and contained appreciable amounts of potassium;
(d) the discontinuous phase in the eutectic was of a similar chemical composition in different eutectic areas.

TABLE III
QUALITATIVE MICROANALYSES ON DIFFERENT CONSTITUENTS

Constituent	Fe	Si	Ca	K	Al
1. FeO grains	VVS	—	—	—	—
2. Fayalite	VS	S	VW	—	—
3. Continuous phase in eutectic	W	S	VW	W	W
	VW	S	—	W	W
4. Discontinuous phase in eutectic	S	S	W	VW	W
	S	S	W	VW	W

Key:	
VVS	Very very strong
VS	Very strong
S	Strong
W	Weak
VW	Very weak

The microstructures of the specimens indicate that at the temperature of operation some of the reacted ore consisted of two phases, namely metal and non-metal. This would be the case for particles near the tuyère. Particles further away might contain some or no liquid at all.

The melting of particles resulted in a viscous liquid containing all the different oxides in solution. That the mixture was viscous was shown by the fact that the particles had not completely lost their original morphology. It follows from this that a limited amount of homogenization would have taken place and that the microstructures observed at room temperature would be typical of the original composition of the particles and of the conditions in the furnace.

The changes that took place during the cooling of the molten material may be followed, to some extent, by reference to the SiO_2–FeO system. The composition of the charge places it on the FeO-rich side of the eutectic that occurs at about 76 per cent FeO and at about 1180 °C. The liquidus temperature of the ore material could thus vary between 1180 and 1380 °C (the melting point of pure FeO) if it consisted only of wustite and silica. The presence of Al_2O_3, K_2O, and CaO reduced the liquidus temperature of the mixture as evidenced by the formation of islands of eutectic rich in these oxides. The formation of metallic iron reduced the proportion of wustite in the mixture and decreased the liquidus temperature.

During cooling, primary dendrites of wustite formed, followed by the eutectic reaction to form further quantities of wustite and fayalite as indicated in Fig. 8. The proportion of dendritic to non-dendritic wustite in this micrograph shows that the liquid was of near-eutectic composition and would thus have a liquidus temperature of about 1250 °C or lower. An actual liquidus temperature could be calculated along the lines indicated above, but it would not be of great value owing to variations in the composition and the degree of reduction of different ore particles, and owing to the slow cooling of the charge in the furnace after solidification.

It is evident from the microanalyses that, during the formation of primary wustite, CaO, K_2O, and Al_2O_3 were rejected almost completely into the remaining liquid and formed a complex liquid that solidified by a eutectic reaction. The temperature of this reaction is not known but is estimated to be below 1000 °C owing to the influence of the alkali oxides.

During a heating cycle, the sequence of events outlined above would be reversed. The processes would take place much more quickly because of the more favourable kinetics of the new phase relationships.

It is evident from Fig. 10 that the formation of wustite particles in a fayalite matrix can also take place in the solid state. The formation of metal at the edges of reacted ore particles indicates that reduction by carbon monoxide becomes difficult once the fayalite matrix forms, which results in a reduction in the porosity of the ore.

Preheating and High-temperature Techniques

A problem much discussed recently by archaeo-metallurgists is the preheating of the air blown from bellows into the combustion chamber of traditional bloomery furnaces.

Preheating appears to have played a role in the iron-smelting of the Hayas (Tanzania), studied by Avery and Schmidt[14,15]. Their metallurgical and ethnographic studies, followed by thermodynamic and experimental work, led them to the conclusion that the air blown from the bellows to the tuyères was there heated by the gases of the hot combustion zone of the furnace flowing round the tuyère walls. They suggested that the preheating could be in the range 500 to 600 °C, which would permit reducing temperatures of up to 1700 °C in the furnace, resulting in the production of medium- to high-carbon steel by a complex process much in advance of early European metallurgical practice[14,15].

One does not, of course, expect to find close analogies between the sophisticated smelting technologies used in East and West Africa and the much simpler ones used in South African low-shaft bloomery furnaces of the Iron Age. Also, the shapes and dimensions of the furnaces, the numbers and types of bellows, the operational procedures, and the raw materials used in West and East Africa are too different from those in Southern Africa to allow easy comparisons. However, a study of preheating effects in the operation of South African bloomery furnaces would be an interesting exercise, and the experiments described in this paper offered such an opportunity.

The temperature along the length of the tuyère passage was measured by the insertion of a thermocouple into the opening of the tuyère outlet and the moving of the thermocouple from there to various positions inside the tuyère. Enough time was allowed for the thermocouple to reach equilibrium condition at each location. Fig. 11 shows the results of these measurements. Apparently, there is only a slight curvature in the shape of the heating graph, indicating a nearly uniform temperature rise along the length of the tuyère interior.

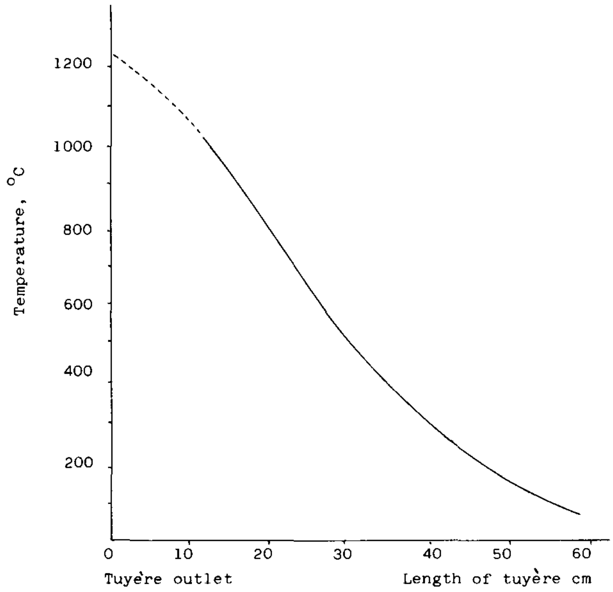


Fig. 11—Temperature distribution in the tuyère

From the volumetric air-flow rate and air velocity[1], the heat capacity of the air, the dimensions of the tuyère, and the temperature difference between the tuyère inlet and the outlet, a reasonably good approximation of the degree of air preheating can be obtained. According to such a calculation under ideal conditions in an experimental furnace of the Tswana type, maximum air preheating of 150 to 160 °C could be obtained; however, in practice the preheating effect would probably not be more than 80 to 100 °C. In view of the many contributing factors to the heat economy of the low-shaft bloomery furnaces, this is a relatively low figure, indicating that preheating seems to have played only a minor role in South African furnaces.

Avery and Schmidt[15] suggest another possible source of preheating: '. . . in the Low-veld area of the Transvaal, the Phalabora and Venda furnaces have tall slots into which the tuyères fit. This would have caused charcoal to fall out, forming a pile of burning charcoal over the tuyère and possibly providing a preheat to these furnaces'. However, it is debatable whether a small amount of charcoal glowing at a relatively low temperature could transfer much heat to the tuyère section outside the furnace wall. It is likely, too, that cold (ambient) air flowing into the furnace chamber through an open (unsealed) tuyère slot would lower the furnace temperature considerably.

In any society, innovations are an answer to challenges or needs, but, in most regions of Africa south of the Limpopo, few radical technological changes such as those required in a high-temperature steel-making process seem to have occurred during the Iron Age (*ca* 3rd to 19th century AD). The traditional African bloomery-smelting process was adapted to the requirements of apparently fairly static societies and, of course, to the raw materials available, especially to the generally scarce wood sources of the interior. A relatively simple smelting technology seems to have been sufficient for the needs of the South African subsistence farmer.

Conclusions

(1) Operational temperatures between 1280 and 1350 °C were required for satisfactory separation of the iron from the bloom conglomerate in the experimental furnaces.

(2) The use of phase diagrams of the $FeO-SiO_2$-anorthite type for the determination of operational furnace temperatures is limited.

(3) The determination of liquidus temperatures (melting points) for the smelting slags investigated by hot-stage microscopic technique showed melting points in the range 1440 to 1490 °C, confirming the findings of previous studies.

(4) The liquidus temperature of the charge is estimated to have been about 1250 °C or lower.

(5) Under the conditions of the smelting experiments conducted, no significant preheating of the air flowing through the tuyères into the furnace combustion chamber was observed.

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