

An experimental study of iron-smelting techniques used in the South African Iron Age

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SYNOPSIS

The main factors involved in the primitive smelting of iron (ore, charcoal, temperature, air supply, process control) were evaluated in an experimental furnace that was constructed to the pattern of an Iron Age furnace found at Melville Koppies Nature Reserve, Johannesburg. In particular, the characteristics, action, and efficiency of skin bellows were investigated to gain a better understanding of the air-supply system used.

Sixteen specimens of iron ore, slag, and metallic iron (excavated material and material produced in the experimental furnace) were submitted to analysis. The results of the analyses are reported and discussed.

SAMEVATTING

Die hoofkategorie betrokke by die primitiewe smelting van yster (erts, houtskool, temperatuur, lugtoevoer, proses-kontrolle) is geëvalueer in 'n eksperimentele oond wat gebou is volgens die model van 'n oond uit die Ystertydperk wat in die Melvillekoppiesnatuurreservaat, Johannesburg gevind is. Veral die eienskappe, werking en doeltreffendheid van velblaasbalke is ondersoek om 'n beter begrip te kry van die lugtoevoerstelsel wat gebruik is.

Sestien toetsmonsters van ystererts, slak en metaalyster (uitgegraafde materiaal en materiaal wat in die eksperimentele oond geproduseer is) is ontleed. Die resultate van die ontledings word aangegee en bespreek.

The mining of iron ore, and the smelting and forging of iron, were common features in the economy of the Bantu-speaking people before the arrival of the Europeans in South Africa. There are numerous references in the books of the early missionaries and travellers connecting Bantu-speaking people with iron production. These include Burchell¹ (1812), Campbell² (1820), Smith³ (1835), and Livingstone⁴ (1843). At some places (e.g., in Vendaland) traditional iron smelting survived up to the end of the nineteenth century⁵, and the royal smithies of the Swazi kings were still working in the twentieth century⁶.

Unfortunately, all the available reports are very general and do not include any accurate descriptions by trained and competent observers of the processes of traditional iron smelting and iron working. By the time that archaeologists and metallurgists became interested, ironmaking in South Africa was already a lost art, and an important part of African cultural history was lost with it.

Purpose and Scope of Experiments

The only way of obtaining detailed knowledge about the traditional techniques is by archaeo-metallurgical investigation and by the construction of models. These methods permit interpretation of the available archaeological material in terms of analyses, analogies, or models and so contribute to comparative studies of primitive technology and cultural history. Thus, a number of attempts to reconstruct and to work African smelting furnaces have been made in South Africa over the last fifty years^{5, 7-9}.

A study of prehistoric metal technology forms part of the experimental research programme of the Archaeological Research Unit (A.R.U.) at the University of the Witwatersrand, Johannesburg, and several analytical and experimental investigations of Iron Age

copper, tin, and iron have been described in recent papers¹⁰⁻¹². The present paper reports on the construction and operation at the A.R.U. of a model of a particular type of iron-smelting furnace: the low-shaft, bellows-blown, non-slagtapping, two-slot furnace as excavated in the central and western Transvaal. Two such furnaces have been discovered¹³ at Melville Koppies Nature Reserve, Johannesburg: a large, globular furnace (furnace A) and a smaller ellipsoid type (furnace B). The latter (Fig. 1), which in shape resembles the Buispoort furnace described by Küsel⁹, was used as the pattern for the experimental furnace. (Other related types of low-shaft, bellows-blown South African furnaces⁹ are the three-slot Venda furnaces of the northern and eastern Transvaal and the Loole-type furnaces of the Phalaborwa area, some of which have only a single tuyère opening.)

Essentials of Prehistoric Iron Smelting

The production of iron from an ore seems to be a simple reduction process: the iron oxide of the ore (Fe_2O_3) is reduced to elemental iron by the carbon monoxide (CO) produced by the burning of charcoal ($\text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2$). However, there are several difficulties in this process: one is the tendency of the reduced iron to re-oxidize at high temperatures, and another is the possibility that an excessive supply of air may produce carbon dioxide instead of carbon monoxide. This excess carburization may give undesirable properties to the iron produced. Furthermore, it may often be difficult to separate the reduced metallic iron from the slag and other impurities.

The smelting process must be regulated in such a way as to create optimum conditions for reduction, carburization, and separation. There are a number of factors that influence the process.

Type and Particle Size of the Ores Used

The iron ores available in South Africa for smelting are mostly of the iron oxide type: hematite (Fe_2O_3),

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Fig. 1—Remains of iron-smelting furnace B, which was excavated at Melville Koppies Nature Reserve, Johannesburg

limonite-goethite ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), and magnetite (Fe_3O_4). The ores used for smelting should have an iron content of between 40 and 60 per cent: too low a content may give a low smelting yield of iron, and too high a content may cause difficulties in smelting.

It is seldom possible to trace the provenance of an ore used in a prehistoric smelter, but ore deposits are often found near Iron Age smelting sites; for example, goethite has been found in small outcrops on the slopes above the furnaces at Melville Koppies¹³, and banded ironstone

ore occurs at Welgegund near the Broederstroom sites (Hartbeespoort Dam)¹⁴. It is likely that the ancient iron mines of Bomvu Ridge (northern Swaziland) were the source of the ore used in the many smelting furnaces discovered in that area. The analyses of these ores are given in Table I as ores 1, 3, and 4.

Ore no. 4 was also the ore used in most of the experiments described here. It has been described¹⁵ as 'banded ironstone [containing] iron in the form of mixed oxides, namely magnetite and martite (hematite). Silica is the other chief constituent and is in very weathered form'. Experiments 22 and 24 involved a medium-grade hematite ore (ore no. 5); high-grade hematite ores as found at Thabazimbi and Sishen are not considered good material for smelting in primitive furnaces because their rather high hardness, low permeability, and low silica content do not contribute to the formation of a good 'bloom'. Material taken from the donga at the Broederstroom Early Iron Age site (ore no. 2) was used in experiment 20 but did not give a satisfactory yield.

Because the particle size of the ore fed to a smelting furnace is critical for proper reduction and for a good iron yield, all the ores used in the A.R.U. experiments were broken into pieces of between 2 and 9 mm in size. Crushing and sifting resulted in a concentration of the average iron content (see Table I).

Quality and Particle Size of the Charcoal

Charcoal, the reducing agent in the smelting process, must be carefully selected. Uniformity, hardness, burning speed, porosity, and particle size are characteristics that have a decisive influence on the outcome of the smelting.

According to Bullock⁵ the BaVenda 'felled those

TABLE I
ANALYSES OF IRON ORES FOUND NEAR SMELTING SITES OR USED IN EXPERIMENTAL FURNACE

Site		1	2	3	4		5
		Melville Koppies Nature Reserve, Johannesburg. Slate exposure above 7/63 site	Broederstroom, near Hartbeespoort Dam, Transvaal, A.R.U. site 24/73 (Donga)	Welgegund 481, near Hartbeespoort Dam, Transvaal	Swaziland Iron Ore Development Co. (Mbabane), Bomvu Ridge		South African Iron and Steel Corporation, Pretoria
Constituents	Expressed as percentage	%	%	%	Ore as supplied	Ore after sifting	Ore after sifting
Silicon	SiO_2	—	15,4	—	9,37	7,6	23,4
Aluminium	Al_2O_3	—	4,7	—	2,18	3,0	1,2
Iron, ferric	Fe_2O_3	61,2	78,5	—	—	85,7	74,5
Iron, total	Fe	42,8	54,9	55-58	52,35	59,94	52,11
Magnesium	MgO	—	0,11	—	—	0,01	0,06
Calcium	CaO	—	0,06	—	—	0,01	0,03
Sodium	Na_2O	—	0,03	—	—	0,02	0,02
Potassium	K_2O	—	0,11	—	—	0,01	0,04
Titanium	TiO_2	0,52	0,17	—	0,12	0,10	0,07
Chromium	Cr	—	0,09	—	—	0,03	0,01
Manganese	MnO	—	0,09	—	0,47	0,08	0,28
Phosphorus	P_2O_5	—	0,17	—	0,08	0,16	0,08
Analyst		Analytical Services Johannesburg	Iscor Research Lab., Pretoria	T. G. Trevor	Swaziland Iron Ore Development Co.	Iscor Research Lab., Pretoria	Iscor Research Lab., Pretoria

trees for charcoal burning which were otherwise of no use to them i.e. those which were too big as poles and useless as material for objects and those which bore no edible fruits'. However, other tribes were probably more selective in their choice of wood for charcoal burning. Küsel⁹ notes that 'the water berry (*Szygium gerrardii*), the Cape beech (*Rapanea melanophloeos*) and the wild seringa (*Burkea africana*) were used to obtain charcoal . . . These three kinds of wood give very hard charcoal which burns exceptionally slowly'.

In another report¹⁶, wood from mopane and protea trees is mentioned as good material for charcoal burning. Acacia charcoal has been used in the smelting process since time immemorial. South African acacia trees from which charcoal was made include¹⁶⁻¹⁹ *A. giraffae* (Camel-thorn, mokala), *A. nigrescens* (Knob-thorn, mokhalo), and *A. caffra* (Kaffir-thorn, um Tholo). *Terminalia sericea* (mususu), *Combretum apiculatum* (Red bush willow), and *Combretum imberbe* (leadwood, hardekool) are said^{16, 17, 19} to give a slow-burning wood that retains heat for a long time — ideal properties for a smelting fuel. The ash of leadwood also has a high lime content and could therefore form a good flux.

Unfortunately, wood or charcoal from any of these indigenous trees is now practically unobtainable in the quantities required. Only 'braai' charcoal is commercially available in South Africa. This type is made from exotic hardwoods (especially from black wattle), which are grown in plantations in Natal. This charcoal as obtained from local merchants is generally not uniform, is contaminated with half-burnt wood and occasionally even with bones, and has a high proportion of dust. Fortunately, through the assistance of Messrs Hunt Leuchars & Hepburn (H.L.H.), an improved type of Natal charcoal was obtained for the experiments. This charcoal is also made from exotic hardwoods (plantation wattle and saligna gum), but it is much more uniform and complies with a definite specification (size 4.5 to 18 mm, moisture 8 per cent, fixed carbon 76 to 84 per cent, ash (900°C) 1.1 per cent, volatiles 8 to 13 per cent). This H.L.H. charcoal still has a rather fast burning rate but otherwise proved to be suitable for the smelting experiments.

Before being used in the A.R.U. experiments, the charcoal was crushed and sifted to yield pieces of between 10 and 25 mm in size.

Bellows and Air Supply

The African smelters and smiths regarded bellows as the most important factor in their work. In many parts of Africa, the iron-smelting process was just called 'blowing the bellows', and competent smiths were referred to as 'men skilled in bellows'²⁰.

Although iron smelting ceased in Africa after the arrival of the Europeans, smithing and forging still continued and is practised even today, so that we have much information on the making of bellows for smithies. In all parts of South Africa, the bellows used for smelting and forging iron were of the skin (bag) type. (The use of drum bellows, prevalent in large areas of Africa, has been reported from Ovamboland and northern Botswana.)

Goat skins were generally employed for the bellows, but some reports mention the use of antelope skins, especially the skin of the sable antelope. Methods of how bellows were made and used are described in several publications^{1, 3, 20, 21}. There was not much variation in the way the skins were removed from the animals — the skins were always taken 'whole'. Before the arrival of the Europeans, goats were skinned alive 'to strengthen the power of the bellows'²¹. A skin bag was obtained by starting the cutting at the hindquarters and pulling the skin over to the neck. The skins were softened by scraping, pushing, and stretching, but were occasionally rubbed with treebark or cattle manure. Any stitching required was probably done by the method described by Burchell¹: holes barely large enough to admit the sinew-thread were pierced into the leather with an awl-like needle, the thread was inserted with the hand, and each stitch was fastened. The seam obtained in this way was, as Burchell states¹, 'neat and strong, far excelling all which I have seen of European sewing'. A wooden handle-valve, consisting of two slats or sticks, was then fastened with leather thongs to the hind-quarter incision of the skin bag, and a nozzle — generally a straightened antelope horn (from waterbuck, sable antelope, eland, or gemsbok) or an oxhorn — was tightly bound into the neck end.

The art of the African leather worker who could make bellows in the traditional way has now disappeared almost as completely as that of the metal smelter. However, the A.R.U. managed to obtain bellows from African craftsmen who still understood to some degree how to make karosses and to sew up skin bags according to the instructions given.

The volume of air produced by skin bellows and delivered to the smelting furnace depends on a number of factors.

(1) *Size of the bellows.* All the bellows used in the experiments were made of goat skins of similar size. The capacity of the bellows, measured by filling a bag with water, was approximately 5 litres.

(2) *Diameter of the nozzle.* All the horn nozzles used had an inner diameter of approximately 15 mm at the nozzle outlet.

(3) *Dimensions of the tuyères.* The clay tuyères used were 300 mm long and were flared at one end, having an inner diameter of 29 to 30 mm at the outlet end.

(4) *Size of the air gap at the nozzle-tuyère connection.* In the traditional process, the nozzles were held in place by wooden pegs and large stones¹, but some movement of the nozzles is unavoidable during the blowing operation of the bellows.

(5) *Pumping rate of the bellows.* In the experiments, a low-speed pumping rate of 70 to 90 double strokes per minute, or a high-speed rate of 105 to 120 double strokes per minute, was used.

In the experiments, factors (1), (2), and (3) could be kept constant. However, to achieve a constant pumping rate is difficult, since pumping for long periods is tiring work and needs a team of well-trained bellows workers who have learnt to time the up and down strokes of the bellows and to co-ordinate the closing and opening of the handle valves by clenching and unclenching of the

TABLE II

COMPARISON OF BELLOWS AND BLOWERS

Test method: Velometer. Pumping-rate of bellows: 105 to 120 double strokes per minute

Type	Zulu bellows		Tswana bellows		Venda bellows		Electric blower
	Made to the pattern of bellows exhibited in the Africana Museum, Johannesburg. Made by African leather worker, Johannesburg		Made to the pattern of traditional 'whole skin' bellows by an African farm worker. Farm Brits District		Loan of bellows by courtesy of Mr E. O. Hanisch, National Cultural History Museum, Pretoria. Bellows made by BaVenda tribesmen		Domestic Dryer Classic 450 W
Nozzle type	Impala horn		Ox horn		Waterbuck horn		—
Measurements taken	At nozzle outlet	At tuyère outlet	At nozzle outlet	At tuyère outlet	At nozzle outlet	At tuyère outlet	At tuyère outlet
Surface port area, mm ²	175	706	176	706	178	706	706
Air velocity, m/s	24	8	10	3	13	6	9
Air volume delivered, l/min	252	339	106	127	139	254	381

hands. It is also difficult to adjust and to maintain a constant gap at the loose nozzle-tuyère connection.

These technical considerations, combined with economics, led to the use of electrical blowers rather than skin bellows for the experiments, the volume of air delivered by the electric blower being controlled by gate valves. So that the results obtained with electric blowers could be correlated with skin-bellows operation, the A.R.U. team co-operated with the Mechanical Laboratory of the South African Bureau of Standards in determining the volume of air supplied to the smelting furnace by the two types of blowers. The results of the tests undertaken are given in Table II. It is realized that the volumes of air provided by the bellows and the blowers are not strictly comparable since test conditions (such as the pumping rates for the bellows and the air gaps at the tuyère connection) varied slightly during the tests. However, repeated tests showed that, for practical purposes, there is a reasonable correlation between the blowing capacity of the electric blower and that of the skin bellows.

The following conclusions can be drawn from the tests on the two types of blowers.

- The capacity of the electric blower was about $1\frac{1}{2}$ to $3\frac{1}{2}$ times higher than that of single bellows. Therefore, one electric blower can be used instead of one or two pairs of bellows to supply the same or a higher volume of air to the furnace. This correlation was confirmed by the results of two test runs in the experimental furnace. Temperatures of 1150 to 1250°C (measured by thermocouple-potentiometer) were obtained by use of a pair of bellows operated at approximately 120 double strokes per minute.
- The efficiency of the bellows used (expressed as the ratio of volume of delivered air to the theoretical capacity of the bellows) is low, ranging from 15 to 50 per cent.
- An interesting fact that became evident from the tests was the difference in air velocities measured at the blower or bellows outlets and at the outlets of the tuyères into which the blower or the bellows horns led. Air velocities at the tuyère outlets were from

20 to 80 per cent higher. It appears that the loose fitting of the horn (or blower) ends into the flared opening of the tuyère causes an air gap into which outside air is sucked during blowing and that a venturi effect develops. The air regime established in this way is complex. Small changes in the relative position of the horn and of the tuyère inlet have a considerable influence on the air volume delivered into the furnace²².

It is possible that the use of electric blowers instead of bellows may create conditions in the air-flow system that are not present in the traditional process. To reproduce in some way the effect of the up and down movement of the bellows, a timing regulation switch was installed into the cable leading to the electric blower, thus actuating an on-off cycle of air blowing. However, this modification did not appear to have any pronounced effect.

Temperatures

It appears from the results of smelting experiments, as well as from the metallographic investigation of iron pieces found at archaeological sites, that primitive iron smelting and forging were conducted at temperatures reaching but not exceeding 1150 to 1200°C. Such temperatures are obtainable in well-insulated medium-sized furnaces when efficient bellows and a suitable type of charcoal (and of course strong and experienced workers) are employed. Somewhat lower temperatures may still give satisfactory results if the time of operation is prolonged.

Composition of the Gas

The composition of the gas in the furnace is decisive for a good yield of iron as well as for a good-quality iron. For a constant bed depth and thermal regime, the CO:CO₂ ratio controls the carbon content of the iron and the iron content of the slag, and the CO:CO₂ ratio is decided by the fuel to ore ratio²³.

In the experiments undertaken by the A.R.U., the ratio of fuel to ore was generally high (4:1 to 6:1) since the burning speed of the charcoal used was high and

consequently excessively large quantities of fuel were required.

Construction of Furnace

The constructional features of the smelting furnace (shape, dimensions, construction material, insulation characteristics, etc.) are also important for the smelting process. Details of the construction of the A.R.U. experimental furnace are given later in this paper.

Tuyères

The numbers, dimensions, and positions of the tuyères are important factors in the operation of a smelting furnace: the size of the tuyères influences the blast pressure; the flared entrance section of the tuyère receiving the bellows nozzles affects the air volume; the tuyère angle and the width of the firebed between the tuyère outlets (in a two-tuyère furnace) have a bearing on the critical CO:CO₂ ratio and the reduction-oxidation balance. These and related aspects of the primitive iron-smelting process have been discussed thoroughly in a number of papers published by Tylecote and his co-workers²³⁻²⁶.

The A.R.U. model furnace incorporates a feature that one of the authors (R.S.) had observed in smelting furnaces excavated at Uitkomst and Melville Koppies. It appears that the tuyères there were placed at a slight angle to the left of the longer axis, whereas they are usually aimed radially towards the centre of the furnace. Such a lateral deflection of the air stream could create a turbulent circular movement of warm air round the central fire and consequently a better heat distribution in the furnace¹⁰. To provide a suitable active reduction zone, the tuyères were directed downwards at an angle of approximately 35° from the horizontal.

Control of Smelting Process

The amount of air injected into the furnace was known from the results of the flowmeter tests evaluating the capacity of skin bellows and of electric blowers. In some batches of the present project, temperatures in the interior of the furnace were measured by a thermocouple (NiCr/NiAl) connected to a Cambridge potentiometer. The temperatures noted were compared with the corresponding temperature radiation colour observed through the tuyères or through a glass window covering a hole bored through the furnace wall. The colours observed in the glowing interior were also matched with those developed in a temperature-controlled muffle furnace; for example, a cherry-red glow corresponded to a temperature of about 850°C, and a bright orange to a temperature of 1000 to 1100°C. Other 'sensorial' tests used for controlling the smelting process were observation of the colour of the flames playing on the top of the fire-bed — blue luminous flames indicating a satisfactory reducing atmosphere — and the 'feel' of the heated furnace walls for the heat distribution in the furnace. It is difficult to describe such observations accurately but they can be well interpreted after a number of firings, and there is no doubt that the Iron Age metal workers developed an ability to interpret such signs and symptoms — which may have included smells and

sounds — to a fine art. In this way, an experienced smith could judge the various stages of the process, and could give his helpers orders to work the bellows at the right speed and to add ore or charcoal at the proper times, thus maintaining the required conditions in the furnace. The statement by Tylecote²³ that 'it would not take long for an early smelter to appreciate this and make adjustments for any changes in the working of the furnace' should apply also to the working of an experimental furnace.

Construction of Experimental Furnace

The B furnace found¹³ at Melville Koppies (now partly cracked and falling to pieces) had a major axis of 45 cm, a minor axis of 24,5 cm, and a height of about 40 cm (measured from the furnace bottom to the wall rim). The bowl below the tuyère level was about 20 cm deep, and the thickness of the walls varied from 5 to 10 cm (see Fig. 1). Some dimensions of the experimental furnace were scaled down: the major axis at tuyère level measured 35 cm, and the minor axis 20 cm (inside measurements). The height of the furnace was increased to 65 cm since it was thought that the top portion of B furnace had disappeared before it was excavated.

The furnace was erected on an open piece of ground on the campus of the University of the Witwatersrand (Fig. 2). A bowl about 15 cm deep was dug into the ground and clay lined. Over it a shaft 51 cm high was erected on a brick base using a mixture of clay and red soil. Tuyère slots were cut in at opposite sides of the shaft. The dimensions of the structure are evident from the drawing (Fig. 3). Before the experiments were started, the furnace was dried out by a wood fire.

Experimental Smelting Operations

The iron-smelting process includes a number of operational factors that have not yet been mentioned. These include the time of firing, the sequence of charging the furnace with ore and fuel, and the methods of discharging bloom and slag. The experimental programme therefore included thirty experiments to evaluate the influence of temperature, the time of operation, and the types and quantities of ore and charcoal charged so that a suitable set of conditions could be selected. Since a detailed tabulation of the batch records would require too much space, only a short summary of the observations is given here.

In a number of experiments, the influence of the top temperature on the yield and quality of the iron was evaluated. It was thought that low top temperatures (900 to 1000°C) maintained for a reasonable time would favour the reduction-oxidation balance. However, that was not found to be the case. The best results were obtained by use of fairly high temperatures (1100 to 1250°C) for short periods, especially at the end of the firing, provided a reducing atmosphere was maintained at all times. During the run, large clay sherds were placed loosely over the furnace top to protect the firebed from wind.

Unsatisfactory results were obtained when the operational time (time elapsed from start up to discharge) was less than 5 hours. On the other hand, prolonging the



Fig. 2—Experimental iron-smelting furnace built at the A.R.U., University of the Witwatersrand (the 70 cm long iron tongs in the foreground are made after the pattern of a pair of tongs found in an ethnographic context in the northern Transvaal)

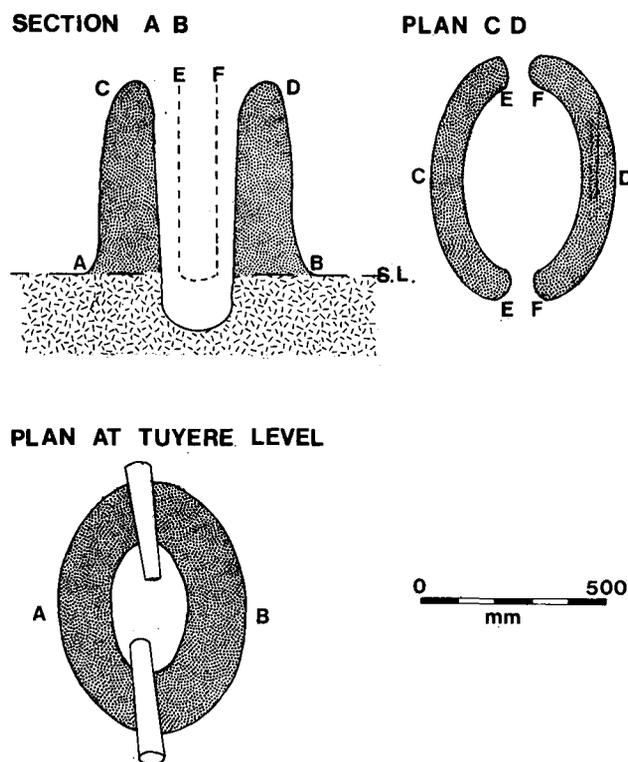


Fig. 3—Section and floor plan of the experimental iron-smelting furnace

process to more than 8 hours did not appear to bring any improvements.

Medium-grade hematite appears to be a suitable ore when it is crushed to a uniformly small particle size. Although a slow-burning charcoal made from indigenous wood would have been preferable, the graded H.L.H. charcoal prepared from locally available exotic plantation hardwoods appeared to be acceptable, even when relatively large amounts were required for the smelting process. It seems that special flux materials were seldom used in the primitive African smelting process. Generally, the addition of some iron silicate slag formed in previous batches provided some fluxing characteristics. In one experiment, 10 per cent lime (calculated on the ore charge) was added, but no pronounced improvement was observed.

By a process of elimination, a method of smelting was finally evolved that gave satisfactory results.

Batch 26

A detailed account is given below of the experiment on Batch 26, which consisted of 3500 g of iron ore supplied by the Swaziland Iron Ore Development Co. (8 mm in size and dust-free), 1500 g of sintered bloom (slag recovered from Batch 25), and 14 600 g of H.L.H. charcoal (4 to 18 mm in size and dust-free).

The tuyères were placed in position and both slots sealed with clay. After the sintered bloom had been placed at the bottom of the furnace, a small fire was started from pieces of wood and dry leaves. The charcoal recovered from Batch 25 was then added and the blowing started. When the firebed showed a red glow (approximately 40 minutes after starting), the first ore portion (approximately 150 grams) was placed onto the centre of the firebed and immediately covered with a charcoal layer. This procedure was repeated at intervals of approximately 10 minutes until all the ore had been added (4 hours after starting). The temperature during the charging was first kept at about 900 to 1000°C, but was then allowed to rise to between 1200 and 1250°C 6 hours 40 minutes after starting. All the time, sufficient air was blown into the furnace to keep the top of the firebed at a red glow and the flames playing over the firebed at a luminous blue colour. Charcoal was added regularly to keep the firebed at the required height (approximately 45 cm above tuyère level).

Firing was stopped 7 hours 20 minutes after starting. The tuyère holes were sealed with clay, and the charge was allowed to burn down for a further 30 minutes. Then the seal of the front slot was broken and the still-glowing coal bed raked out. At the bottom of the furnace were large pieces of bloom mixed with half-burnt charcoal, slag, ash, lumps of sintered metal, and fragments of spongy crude iron, still glowing red. The hot mass, which adhered strongly to the clay bottom of the furnace, was levered off with an iron bar and taken out with long iron tongs. The pieces of malleable spongy iron were immediately separated from the other material and hammered to flat pieces.

The final recovery from Batch 26 was approximately 600 g of crude iron, 170 g of vesicular slag, and 2330 g of sintered bloom. The calculated fuel-to-ore ratio for this

TABLE III

ANALYSES OF SLAG FOUND AT SMELTING SITES OR PRODUCED IN EXPERIMENTAL FURNACE

Site		1	2	3	4	5	6	7
		Melville Koppies Nature Reserve, Johannesburg				Smelting slag from experimental furnace		
A.R.U. Reference		Site 7/63 — Upper Furnace A		Site 28/64 — Lower Furnace B		Exp. 21	Exp. 24	Exp. 26
		0-8 cm B.S.	Base	0-15 cm B.S.	22 cm below rim			
Constituent	Expressed as %	%	%	%	%	%	%	%
Silicon	SiO ₂	24,00	25,28	20,68	21,76	31,3	27,6	24,5
Aluminium	Al ₂ O ₃	6,89	6,94	5,36	5,16	5,6	1,5	5,3
Iron, ferric	Fe ₂ O ₃	12,64	13,38	4,88	11,64	8,4	1,0	7,1
Iron, ferrous	FeO	45,91	44,66	63,76	56,28	51,5	63,1	60,0
Magnesium	MgO	1,38	0,96	1,89	0,52	0,6	0,29	0,37
Calcium	CaO	3,84	1,92	1,44	1,47	1,24	3,77	1,04
Sodium	Na ₂ O	0,37	0,32	0,32	0,39	0,17	0,02	0,13
Potassium	K ₂ O	0,75	0,79	0,57	0,77	0,64	0,82	0,99
Titanium	TiO ₂	0,40	0,38	0,26	0,31	0,31	0,03	0,17
Phosphorus	P ₂ O ₅	0,14	0,03	0,19	0,00	0,22	2,52	0,37
Chromium	Cr	<0,01	<0,01	0,00	0,00	0,07	0,01	0,05
Manganese	MnO	1,75	3,3	0,07	0,12	0,25	0,32	0,16
Analyst		National Institute for Metallurgy, Johannesburg				Iscor Research Laboratories, Pretoria		

batch was 4,2:1, and the yield (the ratio of iron in the recovered material to iron in the ore charged) was 26,5 per cent; the resulting crude iron contained 92,5 per cent iron from a charge containing 59,94 iron.

Yield in the Experimental Process

As could be expected from the variations in the experimental conditions, the yield varied widely (from 9,8 to 26,5 per cent). Even the results of batches in which the operational conditions were fairly uniform varied considerably, probably because of the inherent complexity of the Iron Age iron-smelting process, a complexity partly due to the large numbers of operational factors, partly to accidental changes such as fluctuations in temperatures, airflow, etc., and partly due to environmental influences such as rain, strong winds, etc. It is likely that the smelting procedures of the ancient metal workers varied a great deal too. Measured by modern industrial standards, the general efficiency of the African Iron Age smelters was low^{25, 26}. The low yields in the traditional smelting process, combined with the high labour requirements (up to 100 man hours for a single smelt), were probably responsible for the fast disappearance of African iron smelting once imported cheap implements produced by modern methods became available.

The composition of prehistoric iron-smelting slags is remarkably constant¹². Typical of the slags produced in Iron Age smelting furnaces are the slags found in the Melville Koppies furnaces A and B, which date from the eleventh century A.D. and the nineteenth century A.D. respectively (nos. 1 to 4 of Table III). A comparison of these slags with the slags produced in the experimental furnace (nos. 5 to 7) shows fairly close agreement, especially of the values for silica, iron oxides, and lime. The main anomaly is the high phosphorus content (2,5 per cent P₂O₅) in the slag from experiment 24, for

which bone material in the charcoal used may be responsible.

The total iron content of the crude iron recovered from three experimental batches ranged from 92,5 to 97,4 per cent. Three pieces of forged iron from separate batches (Table IV) contained from 91,7 to 95,9 per cent metallic iron. Such values are considered to be typical for Iron Age products.

Forging

The forging of iron is generally believed to be a relatively simple process, but its experimental simulation turned out to be rather difficult. The reduced iron taken hot from the furnace bottom was mainly in the shape of small spongy fragments that were malleable and easily hammered to thin flat plates, but much iron was also recovered as finely divided matter or in small nuggets and lumps that had to be reheated and hammered free from slag. It proved difficult to weld the fragments and small particles together.

It appears that the metal workers of the Early Iron Age understood how to compact and forge-weld small iron pieces, as the metallographic examination of iron pieces excavated at Broederstroom showed¹². Two techniques known from Nigeria²⁵ were applied in the A.R.U. experiments to forge together small pieces taken from the smelting furnace. In one experiment, iron lumps and nuggets were pressed together and covered with a clay envelope, and the cylinder so formed was heated in a forge fire to about white heat for half an hour, and then cooled down and broken up with a hammer. A conglomerate had formed, which was reheated, but the pieces had not joined properly and broke apart after hammering. In another experiment, the iron particles were compacted in a short clay tuyère, which was then sealed at both ends with clay and heated as previously described. No homogeneous product was obtained. Finally iron particles were collected and pressed together

TABLE IV
ANALYSES OF THE CRUDE AND FORGED IRON PRODUCED IN EXPERIMENTS

Type of iron produced	1	2	3	4	5	6
	Forged	Crude	Crude	Forged	Crude	Forged
Experimental batch no.	B1	B21	B24	B24	B26	B26
Iron, total (%)	98,13	93,5	97,4	95,6	92,5	97,2
Iron, metal (%)	95,88	83,6	88,6	91,7	79,1	95,0
Al (%)	—	0,4	0,04	0,04	0,35	0,11
P (%)	—	0,014	0,23	0,14	0,04	0,04
Si (%)	—	1,02	0,20	0,31	1,02	0,22
Analyst	National Institute for Metallurgy, Johannesburg	Iscor Research Laboratories, Pretoria				



Fig. 4—Slag and crude iron produced in the experimental furnace, together with arrowheads and a razor forged from crude iron

in a clay crucible, which was placed on the white-hot firebed of a forge hearth, covered with clay sherds, heated strongly for about an hour, and then taken out of the fire. The malleable iron in the crucible was compacted with an iron bar and the crucible returned to the fire. This procedure was repeated. Then the crucible was removed from the fire, allowed to cool, and broken up with a hammer. A solid, well-consolidated block of iron, weighing 99 g, was recovered. The surface structure of this block resembled the cylindrical iron ingot 24/73Aj discovered at the Early Iron Age site Broederstroom¹².

Attempts to manufacture large iron bars or blocks as used in the making of the typical large hoes and adzes of the Iron Age people were unsuccessful. Much ex-

perience is apparently needed to master the primitive forging process. The easiest way to obtain formed iron pieces is to handpick the larger fragments of malleable spongy iron found in the smelted mass at the furnace bottom and to hammer them to thin flat plates. Such plates can be welded together by hammering when reheated and taken out red-hot from the fire. From this material a few small arrowheads and razors could be shaped (see Fig. 4).

The forge furnace (smithy hearth) used in the experiments is shown in Fig. 5. This forge was modelled on the pattern of a bellows-blown Zulu furnace exhibited in the Africana Museum of the Johannesburg Public Library.



Fig. 5—Experimental forge used for the demonstration of iron forging at Melville Koppies Nature Reserve, Johannesburg

Conclusions

- (1) The evaluation, in an experimental furnace, of the raw materials used in the prehistoric smelting process, of the airflow system, of the temperatures, and of the gas composition showed that these factors can vary considerably from one production batch to another. The only efficient control that can be exercised in an Iron Age process is continuous observation and adjustment. Success or failure of the prehistoric smelting process depended largely on the aptitude, training, and experience of the operators.
- (2) In the operation of an experimental smelting furnace, the materials and appliances of the Iron Age smelters could be reproduced only imperfectly. However, it was possible, by the use of modified techniques, to obtain a satisfactory yield of high-grade iron similar to prehistoric iron.
- (3) Attempts to forge formed pieces from the iron smelted in the experimental furnace resulted in the production of some smaller objects (iron blocks, arrowheads, razors), but the more complicated forge-welding techniques that the African smiths used when making large implements could not be reproduced.
- (4) It appears from the results of the analyses, tests, and experiments that, in the African Iron Age, the smelting and forging of iron were complex processes, and it is much to the credit of the smelters of that time that they could turn out, with the simple means available to them, relatively uniform, high-grade products in quantities sufficient for their needs.

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