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ANCIENT IRON MAKING IN INDIA

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ABSTRACT

The discovery of Agni (i.e., fire) has been very closely related with the process of human civilization and it has been worshipped during the Vedic period or even earlier. The havankund has been described as the open air laboratory of the Vedic people and they had gained ample knowledge about the physics and chemistry of fire. The beginning of pyrotechnology could be traced to the Vedic period when man worshipped Agni for blessings of metals like gold, silver, copper, iron, tin, lead and their alloys. The archaeological evidence has confirmed that iron technology began only during the late second millennium BC and it has been proved to be of indigenous origin. The paper gives a brief review of the ancient Indian community associated with this craft, viz., Agarias and other tribes worshipping God 'Asura'. They developed their own secret technology of iron smelting to produce iron and steel of excellent quality. Their practice of charcoal iron smelting was considered to have stopped at least for the past one century but recent surveys have traced it to continue to be practiced in some parts of Madhya Pradesh, Eastern U.P. and Bihar. It has provided an opportunity to study this ancient craft, its thermo-chemistry and process control as well as the details of the furnace construction and its operation. The high level of skill in smelting sponge iron blooms and its refining to produce tonnes of iron is certified by the uniformity of composition of the corrosion resistant iron used in the manufacture of some of the heaviest ancient forgings existing in the country.

Keywords : *Ancient iron making, Agarian iron and steel making, Pyrotechnology, Bhathi, Sponge Iron, Secondary refining.*

INTRODUCTION

The discovery of fire and pyrotechnology had a multifaceted effect on the furtherance of human civilization. In Indian mythology *Agni* was worshipped as early as the Vedic periods or even earlier by the performance of *Yagna* and prayers offered to the deity *Agni*. The verses (ritchas) of the *Rg Veda* [1] begin with a prayer to *Agni* to bless mankind with all worldly pleasures. One of the major contributions of pyrotechnology was its use for the extraction of metals from their minerals. Wartime and Wartime [2] have edited and published the proceedings of a seminar on 'Early Pyrotechnology' covering the use of fire in the development of early technology.

Prakash [3] has described the *havankund* (fire altar) as the open air laboratory of the Vedic period which may have been responsible for the discovery and development of the many new uses of this thermochemical energy. It seems that the Vedic people had developed a deep understanding of the physical and chemical properties of fire and its possible use for metal extraction, for the thermomechanical processing to coin new alloys and to produce various types of utility products such as jewelry, weapons, agricultural tools, utensils and transport machines. The ritcha quoted in Fig. 1 is from Yajurveda [4] describing the performance of *yagna* and prayer to *Agni* for blessings of metals like gold, silver lead, tin, copper and iron from the *yagna kunda*. Prakash [5] has examined this possibility and presented his hypothesis that the beginning of the man made iron technology was from the *havan* kund during the Vedic period in the country with a gradual transition from the *havan kund* to the shaft smelting furnace. He [6] has also postulated the beginning of the Iron Age in India before the Copper Age supported by the nature of the iron mineral deposit and the relatively simpler technology of the reduction of iron oxides compared to copper sulphide to produce these metals. Based on the archaeological evidence found at Tadkanhalli, Attranjikhera, Khairadih and many

मं० १४] यजुर्वेदसंहितायां अष्टादशोऽध्यायः ७

अश्मा च मे मृत्तिका च मे गिरयश्च मे पर्वताश्च मे सिकताश्च मे वनस्पतयश्च मे हिरण्यं च मेऽयश्च मे श्यामं च मे लोहं च मे सीसं च मे त्रपु च मे यज्ञेन कल्पन्ताम् ॥ १३ ॥

रत्नवान् धनवान् आत्मा । भुरिगतिशक्वरी । पंचमः ॥

भा०—(अश्मा च) सब प्रकार के पाषाण, हीरे आदि, (मृत्तिका च) सब प्रकार की मिट्टियां, (गिरयः च) पर्वत, उनसे प्राप्त भोग्य पदार्थ, (सिकताः च) बालुकामय देश, (वनस्पतयः च) वनस्पतियां, (हिरण्यं च) सुवर्ण, (अयः च) लोहा, (श्यामं च) श्यामलोह, (लोहं च) लाल लोह, कान्तिसार आदि (सीसं च) सीसा और (त्रपु च) टीन, रांगा आदि ये सब धातु भी (मे यज्ञेन कल्पन्ताम्) शिल्प, रसायन, भूगर्भ विद्या आदि के प्रयोग से मुझे प्राप्त हों।

Fig. 1 : Sanskrit text on the evolution of iron and other metals as mentioned in the Yajurveda[4]

Table 1 : Various tools and implements appearing at the three stages of iron technology growth

Tool Type	Name of Tool	Early Stage	Middle Stage	Late Stage
Hunting Tools	Spare Heads	●	●	●
	Arrow Head	●	●	●
	Points	●	■	■
	Socketed tangs	●	■	■
	Blades	●	●	■
	Spare lances	■	●	■
	Dagger	■	●	●
	Sword	■	●	●
	Dlephant goad	○	●	●
	Lances	○	○	●
	Armour	○	○	●
	Helmet	○	○	●
	Horse bits	○	○	●
	Caltrop	○	○	●
Agricultural Tools	Axes	●	●	●
	Sickles	●	●	●
	Spade	○	●	■
	Ploughshare	○	●	■
	Hoe	○	●	●
	Chisel	○	●	●
	Pick	○	■	●
Household Objects	Knives	●	●	●
	Tongs	●	■	■
	Discs	○	●	■
	Rings	○	●	■
	Spoons	○	●	●
	Sieve	○	○	●
	Cauldron	○	○	●
	Bowls	○	○	●
	Dishes	○	○	●
Building Materials	Rod	●	■	■
	Pins	●	■	■
	Nails	●	●	●
	Clamps	●	●	●
	Pipes	○	●	■
	Sockets	○	●	■
	Plumb bob	○	●	■
	Chains	○	●	●
	Door hooks	○	●	■
	Door Handles	○	○	●
	Hinges	○	○	●
	Spikes	○	○	●
	Tweezers	○	○	●
	Anvils	○	○	●
	Hammers	○	○	●
	Scissors	○	○	●
	Saw	○	○	●

● Indicates definite existence; ○ indicates nonexistence;
■ indicates that confirmed data is not available

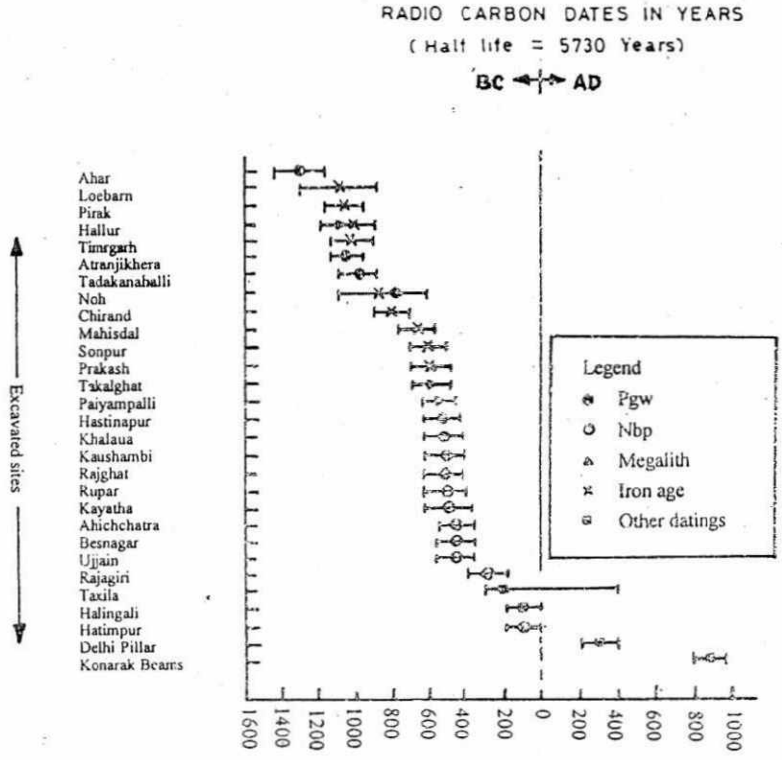

Fig. 2 : C^{14} dating of some ancient iron objects found from archaeological excavations in India.

other ancient sites in the country, it flourished during the late second millennium BC throughout the country. It has also been well established that the genesis and development of the pyrotechnology of extraction of iron was indigenous and there exists a possibility of its diffusion outwards from the country. Surprisingly not many iron objects have been reported from the Harappan period except 5 iron buttons (not analyzed) reported by Shaffer [7] from Mundigak in Afghanistan, while Chakraborty [8] has reported an iron piece, probably a nail from Lothal. Chakraborty [9] has debated the migration theory and diffusion of iron technology from central Area and he has emphasized that the Aryans were the original inhabitants of Indo-Gangetic plains. Shaffer [10,11] has also supported the views expressed by Chakraborty and denied any connection between PGW and Aryan civilization. According to many archaeologists there is a close relationship between the development of PG and N.B.Ware and the beginning of the Iron Age in India, but this has been questioned by experts.

Fig. 2 indicates the C^{14} dates of iron objects found at various excavation sites in India and it demonstrates a fast growth of the technology followed by its

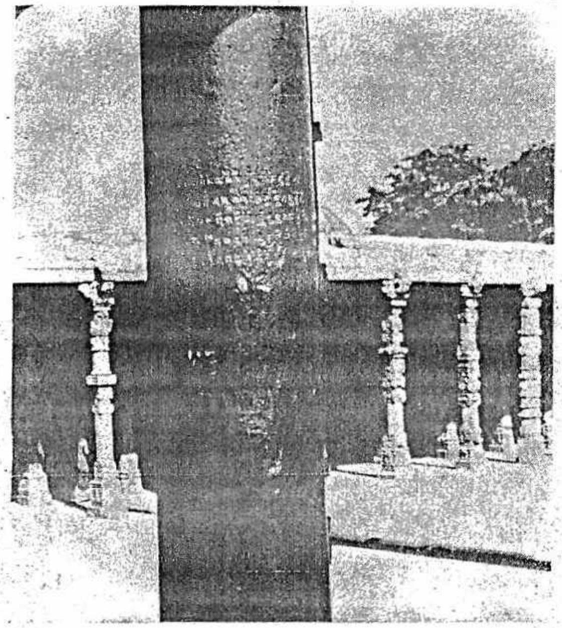

Fig. 3 : Iron Pillar at Delhi (4 c. AD)

maturity during the medieval period. Table I shows the growth pattern of the use of iron for hunting tools, agricultural tools, household objects and building material during the early, middle and late stages. The gradual growth in the

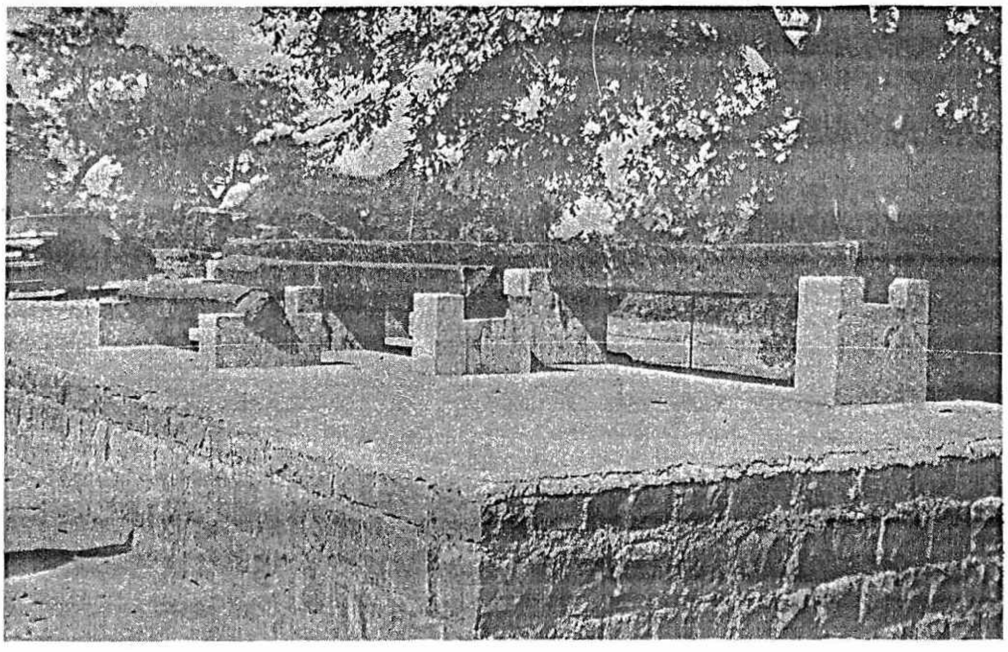

Fig. 4 : Iron pillar at Dhar (broken into four pieces, 12 c. AD).

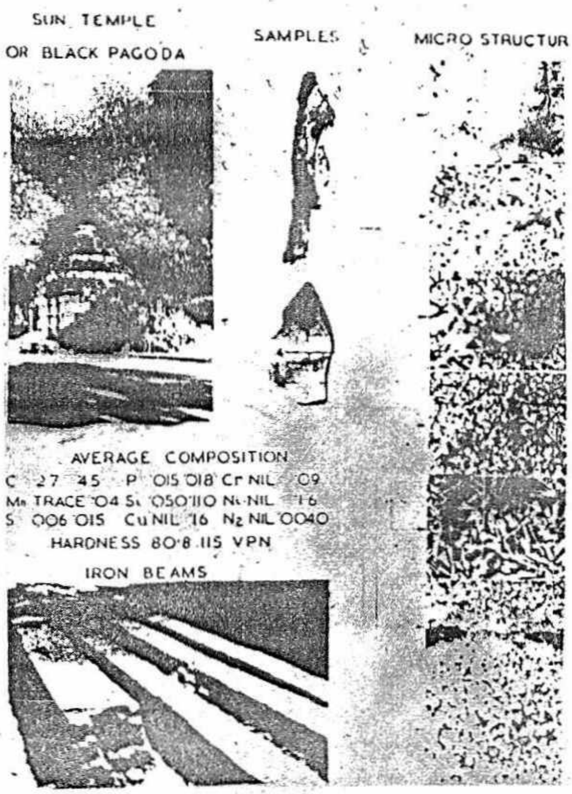

Fig. 5 : Iron beams at Konarak Temple (9 c. A.D.).

utilization pattern is an indication of the indigenous discovery of iron and its gradual spread over a long period. By the beginning of the first millennium BC the Indians had also understood the effect of carbon alloying on the strength and other

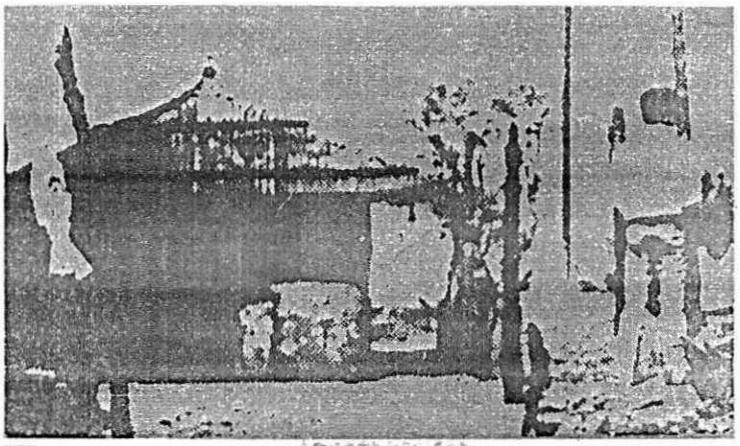

Fig. 6 : Iron pillar at Kordachari.

Fig. 7 : Iron trident at Tanginath Temple (broken in 12th c.A.D.).

properties of iron and developed the production of steel, later known as 'wootz' steel throughout Asia and Europe. During the same period Indian steel was valued more than gold and during the medieval period strips of steel were being used as currency bars (Cypalinski [12] and Nosck [13]).

Some of the major achievements of Indian iron production and its fabrication have been mentioned by Yater [14] such as the making of the heaviest forgings in the

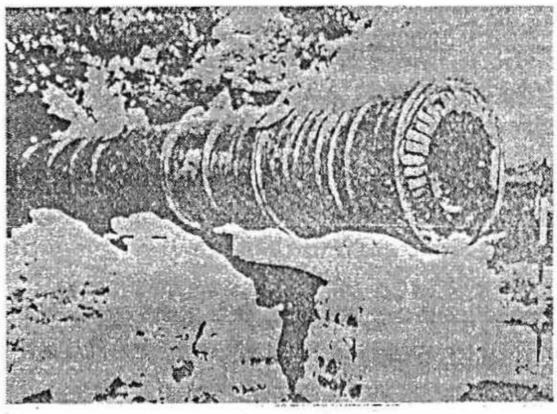

Fig. 8 : Iron gun at Tanjore.

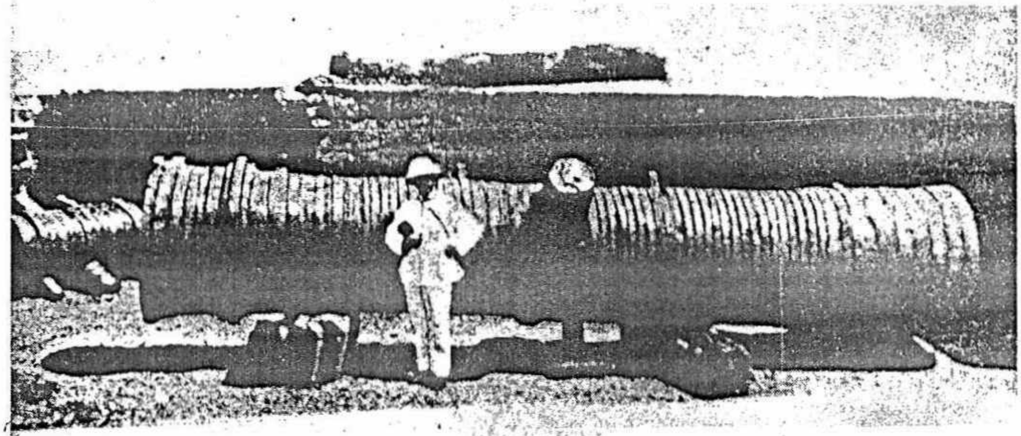

Fig. 9 : 'Landa Kesab' iron gun at Bijapur.

world. These include the famous iron pillar of Delhi weighing about 6 tonnes (4th c. AD), the iron pillar at Dhar weighing about 8 tonnes (12th c. AD), the iron beams at Konarak temple (9th c. AD), the trident on Mount Abu (14th c. AD), the iron pillar on Kordachari hill and the iron trident at the Tanginath temple (12th c. AD) shown in Figs. 3 to 7. Each of these speaks volumes about Indian iron smelting technology and craftsmanship. The Delhi iron pillar is famous not only for its craftsmanship and surface finish, but also for its corrosion resistance. Recently Bindal *et al.*, [15] studied the soundness of this pillar by ultrasonic methods and they reported it to be solid and flawless from within with a very uniform composition. The big cannon pipe at Tanjore having a length of 7500 mm (shown in Fig. 8) has been studied by Roessler [16] and he described it to be made of iron rods bound by three layers of steel rings. There is another iron gun (Landa Kesal), lying at Bijapur fort shown in Fig. 9 weighing about 50 tonnes.

'AGARIA'-THE IRON SMELTERS OF INDIA

The Agarias are one of the major tribes of India engaged in the production of iron in Central India, Eastern Uttar Pradesh, Bihar and Orissa. Their main deity is God *Asura* and there are many other *Asur* tribes spread over other parts of the country. In the 19th c. AD Verrier Elwin [17] travelled throughout India and published a book about the Agarias and their iron production technology. The Agarias worship *Lohasur* or *Kalabhairao* as their tribal God and the whole family including women were engaged in this traditional trade and the technology was maintained as a family trade secret. In the early days due to some reason they were not permitted to settle near the villages and moved from place to place and hence produced iron deep inside the jungles. Their belief in God *Lohasur* or *Kalabhairao* was so strong that when they went to Japan they prepared wall hangings of their deity shown in Fig. 10 and hung them in the *mandala* for worship before beginning the production of iron. During the British regime their trade was banned by the Government so as to promote import of iron and steel from UK and thus this ancient craft was considered to be lost. Most of the historical and technological details of this indigenous technology are available from the travel records of Voysey [18], Holland [19], Hadfield [20] and many other European visitors to India whose major objective was to use this technology to their advantage.

Fig. 10 : Wall hanging found in Mandala *from Japan showing the workshop of* Kalabhairo *and* Asura *before starting iron production.*

During the British rule many attempts were made by private and Government organizations to begin large scale production of iron and steel in India at Porto Novo, Salem, Bajpur, Kumaon, Birbhum and Raniganj etc. Indore was one of the famous centres for iron production even in the past by the name 'Amravati'. Most of these attempts failed, probably because of non-cooperation from Indian craftsmen. Hence the present description and design of the iron smelting furnaces is based on the furnaces existing during the 18th and 19th century and from their descriptions recorded by the above mentioned travellers and also in the books published by Neogi [21] and Banerjee [22]. Igaki [23] compared the corrosion resistance of iron from Japan and India, and he certified to the excellence of quality of Indian iron.

Fig. 11 : Sketch of the iron smelting furnace found at Loharpara *in Bastar. This furnace is made in one wall of a pit below the ground level.*

IRON SMELTING PROCESS AS A LIVING TECHNOLOGY

A fresh attempt to locate the members of the *Asura* community and study their iron making practice was made in 1960 by M.K. Ghose and K.N.P. Rao and they were successful in locating a few families near Jamshedpur and in Orissa. They were successful in getting three different furnaces operated at Jiragora and Chiglabecha in Orissa, and at Kamarjoda in Bihar. They also prepared a detailed log sheet of these operations. In 1963 a public demonstration of this lost craft was organized at the National Metallurgical Laboratory, Jamshedpur. In 1964 Ghose[24] published a detailed report on the working of these furnaces and their products. After this, in 1981 Prakash and Igaki [25] made a successful attempt to locate a family of the Mundia tribe at *Loharpara* in Bastar who were smelting iron in that region until recently. Fig. 12 shows a line diagram of their 'bowl-furnace' made in one face of a pit *i.e.,* below the ground level. Before operating the furnace the front wall of the furnace was prepared afresh each time.

Later on Sharma [26] took up a project to survey the border region of Eastern Madhya Pradesh and he was successful in locating an iron smelting site at Bishunpur and also made contact with two old craftsmen of the Bijia tribe who had seen the furnace operation in their childhood. After great persuasion they built a furnace shown in Fig. 12 and successfully demonstrated the operation of the furnace. At Bishunpur a training centre by the name of *Vikas Bharathi* has now been set up to train the younger generation. Prasad *et al.*[27], have published a detailed report on the performance of this furnace.

Fig.12 : Iron smelting furnace made above ground level at the Vikas Bharti Centre at Bishunpur.

During the study of the Bishunpur furnace the author came to know of the operation of many other furnaces by the Agarias in the Surguja and Mandla districts of Madhya Pradesh. In 1993-94 a project was taken up by Sunil Sahasrabudhey of Institute of Gandhian Studies, Varanasi, who appointed a team to survey the Sonbhadra, Wadruffnager, Mandla and Surguja districs to locate the settlements of the Agarias and their iron production technique. It was a surprise to find that inside the deep forests of these areas about 100 kg. of iron was being produced until about 20 years back, and that some ancient furnaces continued to be operated to meet the local demand. Arun Mishra and his team [28] prepared a detailed sociological and techno-economic study of these people and their craft as a part of the First National Congress on Traditional Sciences and Technologies organized at Indian Institute of Technology (IIT), Mumbai. One of the families from Wadruffnagar was persuaded to demonstrate their skill by constructing a furnace (shown in Fig. 13) and to operate it at the Swadeshi Vigyan Karyashala organized in 1993 at the Gandhian Institute for Studies, Varanasi and later on at IIT Mumbai in the National Congress, 1993-94. Another group of Agarias from Balaghat demonstrated the operation of their furnace shown in Fig. 14 at the Second National Congress of Traditional Sciences and Technologies of India organized in 1995-96 at Anna University, Chennai. At both places they were particular about bringing their iron ore (limonite) and charcoal from their area to operate the furnace successfully. The furnace from Wardruffnagar was smaller in size than that from Balaghat and it

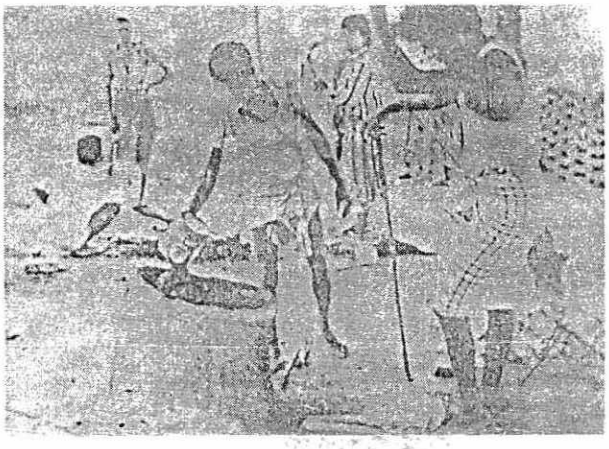

Fig. 13 : Iron smelting furnace used for iron smelting at Wardruffnagar.

Fig. 14 : Iron smelting furnace from Balaghat constructed and operated at the Second National Congress on Traditional Sciences and Technologies, Chennai (1995-96).

could produce only 2 to 3 kg iron per heat as compared to 5 to 6 kg from the other furnace. Operation of similar furnaces by tribal craftsmen has also been reported from other parts of the country.

IRON SMELTING PROCESS

The traditional iron smelting practice consists of the following six steps.

i) Collection of raw material and its preparation.

ii) Construction of the furnace and tuyere pipe.

iii) Making and fixing of air bellows.

iv) Ignition and furnace operation.

v) Removal of slag and handling of hot sponge iron.

vi) Secondary refining of the iron bloom.

Women took an active part in all activities including the furnace operation as well as other specific jobs allotted to them. The furnace was generally constructed near the site of the iron ore deposit in the forest, or sometimes in the back yard of the house. The whole operation was controlled by the head of the family and his wife and the technology was maintained as a secret passed on from generation to generation. The younger generation provided a helping hand from a very young age and they were trained in all the skills of the trade. By the age of 17 to 20 years they were permitted to marry and also to prepare their own furnace for metal extraction and refining.

Collection of Raw Materials and their Preparation

Iron Ore

Most of the furnaces used weathered limonite ($2Fe_2O_3$, $3H_2O$) containing 30 to 40% Fe as the ore because it has high reducibility and it could be easily mined. Generally the ore body was dug to a depth of 2 to 3 m but at certain places open pit digging of up to 5 to 6 m has been reported. In the Malabar region horizontal tunnels of inclined shafts of up to 50 to 100 m length have been found. Sometimes in order to break the hard ore bed, the practice of fire setting or *Dahankhanan* was

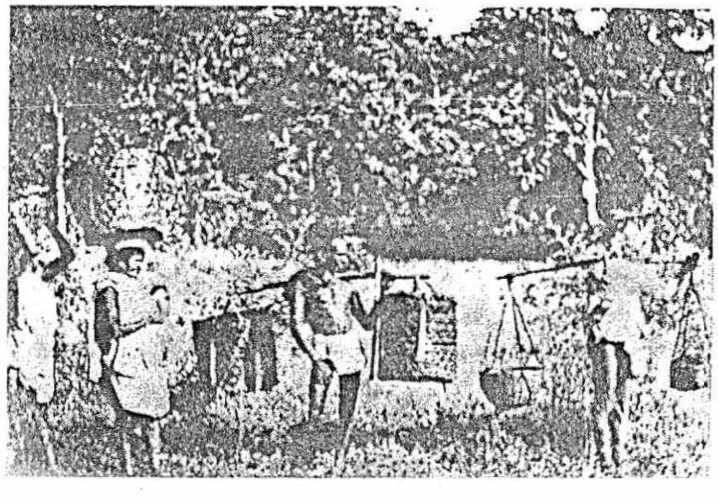

Fig. 15 : Agaria man bringing iron ore in tokna *from the forest.*

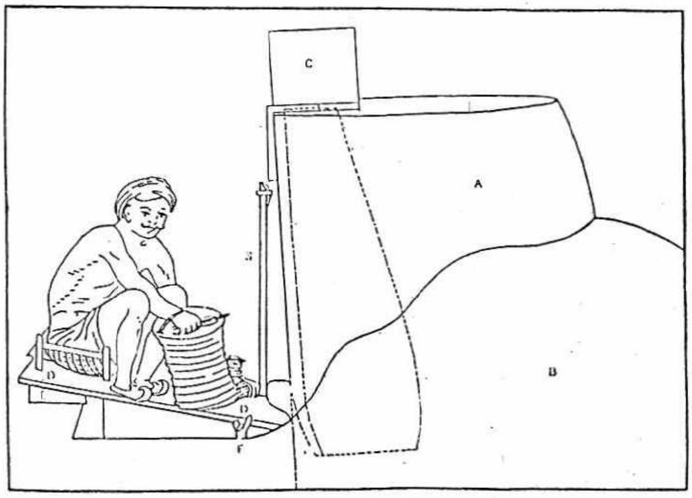

Fig. 16 : Iron smelting furnace from Assam (medieval period).

used. The mixed ore was brought in tokna or baskets, as shown in Fig. (15), to the working site and there it was generally dried and broken into pieces of a size of 5-6 mm. Sometimes, these were also heated to remove the excess moisture and to make the breaking easier. The fine pieces were collected and mixed with clay used for making the furnace.

In some areas like Salem and Assam where magnetite sand is found in the river bed, it was separated from the clay and SiO_2 by washing or panning and then used for the extraction of iron. The furnace used for smelting magnetite had a different design as described by Mohamud [29] (see Fig. 16). In Salem, magnetite sand was also smelted in crucibles to produce steel directly.

Charcoal

For making charcoal, women and children went to the forest to collect dry food and green branches of teak, sal and bamboo *etc.*, which were two to three years old. As per the traditional practice they never cut the whole green tree. The wood charcoal was prepared near a river or some water source either by firing the wood in an open heap and then water quenching it at a suitable stage, or by burying the wood inside a pit and then when the wood became charred, it was quenched and the pit was covered with green leaves and sand to prevent the access of air. The charcoal was collected the next day when the fire had been extinguished. Charcoal pieces of 30 to 50 mm size were used in the furnace and the smaller pieces were used to heat the forge hearth used for secondary refining. Very fine coal dust was mixed with clay and sand and used for preparing the furnace bottom and for closing the mouth in the front wall of the furnace.

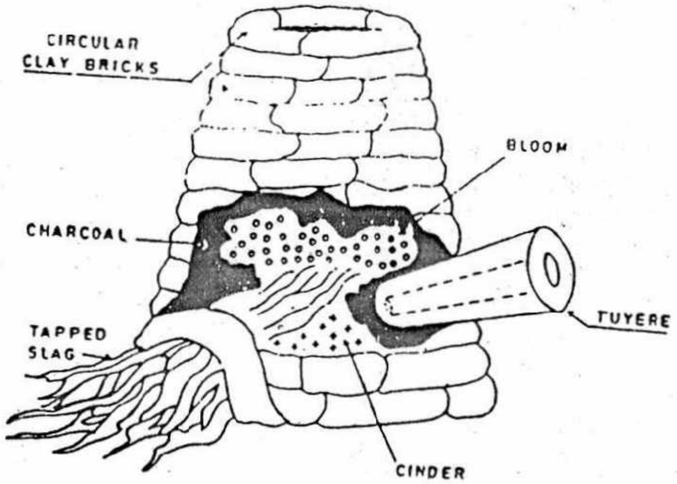

Fig. 17 : Ancient iron smelting furnace made of china clay bricks from the excavation site of Naikund (700 B.C.).

Construction of Furnace and Tuyere Pipe

Study of the published literature has shown that while the furnaces like those of Bastar (see Fig. 11) and Ghatgaon were constructed below the ground level by digging a deep pit, others were made above the ground level or on a raised platform. One such furnace from Naikund dating back to 700 BC is shown in Fig. 17 while Fig. 18 shows a furnace from Bihar. Fig. 19 shows a photo of the

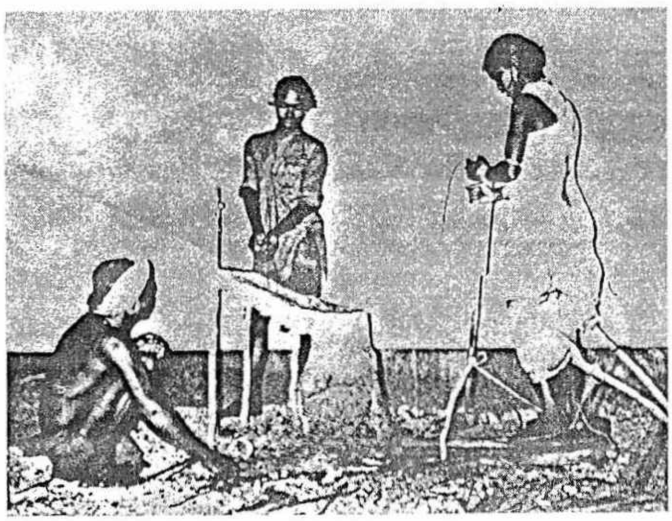

Fig. 18 : Iron smelting furnace from Bihar. It shows a women operating the air bellows.

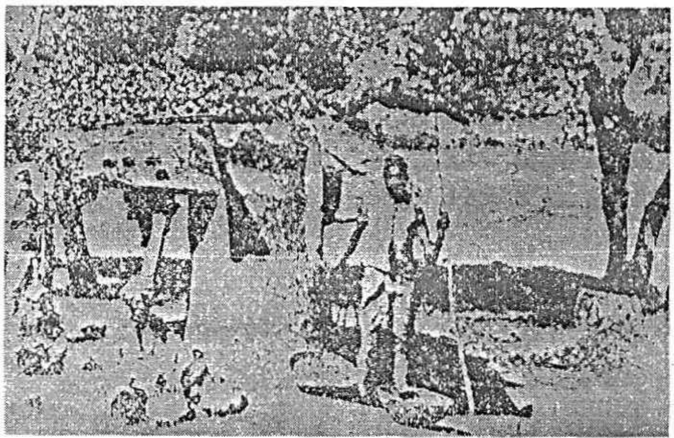

Fig. 19 : Iron smelting furnace Kothi *from Nagpur.*

Nagpur furnace known as 'kothi' having a capacity of 40 kg. of iron per heat. Some furnaces were constructed partially below the ground level, like the Jiragora furnace, whose line diagram is shown in Fig. 20.

The production capacity of these furnaces varied from 2 to 10 kg per heat and in some cases even up to 250 kg per day as in the case of the twin hearth Malabar furnace described by Buchanan [30]. Prakash [31] has studied the design parameters of about 10 furnaces as reported in Tables 2 and 3 and compared it with those

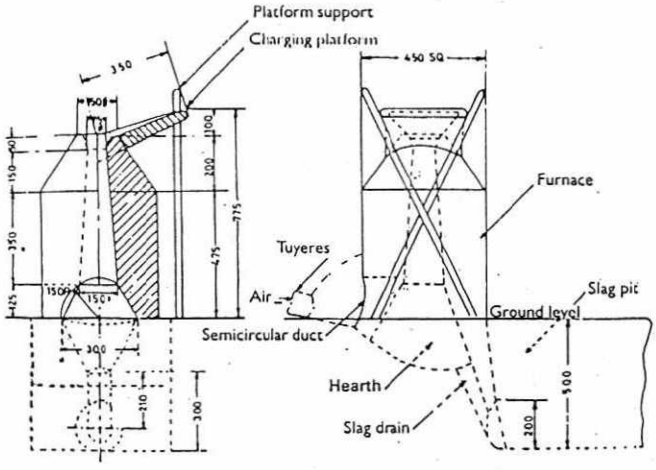

Fig. 20 : Line diagram of the Jiragora furnace operated in 1963.

Table 2 : Technical details of ancient iron furnaces

Sl. No	Location of Furnace	Shape	Cross Section Max. cm	Cross Section Mouth cm	Height (cm)	No. of bellows	Capacity (kg)	Remarks
1.	Madhya Pradesh	Circular	O.D. 107 I.D. 43	O.D. 56 I.D. 12	137	two	16	Made above ground level
2.	Madhya Pradesh	Rectangular	122 x 76	—	122	two	214	Two furnaces made into a pit of 122 x 305 x 91 cm smelted 380 kg of ore in 3 hrs. made from clay bricks
3.	Nagpur	Square	56 x 56	51 x 25	92 to 122	two	5	—
4.	Rajdoha	Circular	O.D. 107 I.D. 46	O.D. 56 I.D. 13	132	two	18	One heat took 6 hrs. and consumed 80 kg of charcoal
5.	Nalanda Valley	Rectangular	56 x 81	51 x 25	90 to 122	two	5	Charge consisted of 25 kg of ore, 25 kg of charcoal
6.	Salem	Circular	61	31	90 to 153	two	—	A chimney was fitted over the mouth
7.	Mandla	Circular	O.D. 78	O.D. 16	76	—	—	—
8.	Chiglabecha (Korapur)	Circular	I.D. 30	I.D. 15	95	two	—	Hearth of furnace below ground level
9.	Jitagora(Koraput)	Circular	I.D. 25	I.D. 7.5	57.5	two	—	Below ground level
10.	Kamarjoda (Joda, Bihar)	Circular	I.D. 30	I.D. 7.5	67.5	two	—	Above ground level
11.	Bastar	Circular	I.D. 24	I.D. 20	80	two	—	Furnace made below ground level in one face of a square pit (200 x 200 cm)

Table 3 : Technical analysis of the design of ancient and modern furnaces (calculated from the data given in Table I)

Sl. No.	Location of the furnace	Furnace Cross Section	d: D Ratio	H/D/2 Ratio	Stack angle $\theta°$	Furnace Volume (V_1) $V_1 = \frac{HD^2 H (m^3)}{P}$	V_2 = cm³/kg of iron (k= 0.5)	Remark
1.	Madhya Pradesh	Circular	0.28	6.37	81.1	0.13	7916	Direct Reduction
2.	Rajdoha	Circular	0.28	5.77	80.1	0.14	7758	
3.	Salem	Circular	0.51	3.97	75.9	0.22	—	
4.	Mandla	Circular	0.21	2	64	0.23	—	
5.	Chiglabecha (Koraput)	Circular	0.5	6.3	81	0.04	—	
6.	Jitagora	Circular	0.3	4.6	77.8	0.02	6654	
7.	Kamarjoda (Joda, Bihar)	Circular	0.25	4.5	77.5	0.03	30150	
8.	Bastar	Circular	0.83	6.6	81.4	0.23	—	
9.	Madhya Pradesh	Rectangular	—	—	—	0.57	5285	Value of K should be different
10.	Nagpur	Square	0.4	9.76	84.1	0.16	31987	
11.	Nalanda Valley	Rectangular	0.26	9.76	84.1	0.24	48535	
12.	Modern Indian Blast Furnace	Circular	0.7 to 0.77	7	81.9	760	358	Indirect reduction Ref. [32]

D- maximum diameter (Bosh), d- throat diameter, H - furnace height, $\theta°$ - stack angle, P - production kg/heat,
K - constant (0.5) for soft ore, V_1 - useful volume, V_2 - volume cm3/kg or iron.

published by Bashforth [32] of a 1000 tonnes per day furnace, using empirical equations. The study of these tables shows that these furnaces were made according to certain design concepts which are still valid. Some of these similarities are the throat to bosh diameter, bosh angle and also height to diameter ratio.

Most of these furnaces were constructed above the ground level and they had either circular or rectangular cross-sections. The 100 to 150 mm thick furnace wall was constructed from locally available alumina-rich clay and sometimes it was mixed with a small percentage of iron ore fines. The taper of the furnace was supported by three to four sticks fixed along with the wall. When the furnace wall was partially dry, a 300 mm high man hole was made at the bottom of the furnace wall and the furnace wall was checked for cracks from drying and other flaws and was given a final finish. The bottom of the furnace was shaped like a bowl and a hole was made on one side for tapping out the slag. Unlike the modern furnaces, since the reduced spongy iron bloom was in solid form, the slag hole was made at the base of the furnace *i.e.,* below the iron bloom. At the mouth of the furnace generally a slanting platform of bamboo sticks covered with clay was made to put the charge and slide it into the furnace.

The clay tuyere used for blowing air was prepared from the same clay. It had a shape like a trumpet having 25 mm dia. at the smaller end, and about 160 mm on the other end, and a length of about 250 to 300 mm. It had a wall thickness of 10 mm and it was generally used in baked condition lasting for one heat only.

The final preparation of the furnace was done by first layering the furnace bottom with *Kudon* or paddy chaff and clay mixed with charcoal powder. Then the front wall was built to a height of about 80 mm and the tuyere was placed in position with its smaller end protruding beyond the furnace wall. Then the man hole in front was closed using the same mixture of clay and charcoal.

Making and Fixing the Air Bellows

A pair of air bellows (*bhathi*) was used to blow air in the furnace. The body of these foot operated air bellows was generally made in the form of a wooden trough having a cavity of about 300 mm diameter and a height of ~150 mm. Near the bottom of this, a hole of ~ 35 mm was made in the side wall to fix a bamboo pipe having 12 to 15 mm diameter hole and 500 to 600 mm length. The other end of this bamboo pipe was inserted in the larger end of the clay tuyere and it carried air to the furnace when the air bellows were operated. The top of the wooden trough was covered with a moist piece of raw hide having a flap valve fitted in a hole in the centre. This hide was bound tightly around the circumference of the trough. The moist hide was kept taut by fixing a string in the central hole and tying it at the upper end to a green bamboo piece whose other end was secured by fixing in the ground at an angle shown in Fig. 18. This bamboo piece acted like a spring when the bellows were pressed by foot.

Generally a big piece of stone was put on the bamboo pipes to keep them secured in place. A man stood with one foot on each bellow and balanced himself with the help of one or two sticks while he pressed the bellows alternately to supply air to the furnace. The amount of air blown in the furnace was regulated by controlling the rate of foot strokes applied on the bellows. This in turn controlled the rate of combustion of charcoal and the thermochemistry of the furnace operation.

The Ignition and Operation of the Furnace

Before firing the furnace, the Agarias and other *Asur* tribes performed pooja by offering a cock and a bottle of wine to their deity *Lohasur* and *Agiasur* and performed *havan* with prayers for the successful operation of the furnace and for blessings of iron of good quality. Then they charged some firewood pieces in the furnace which was already prepared. Over this, charcoal was filled to the top of the furnace and the firewood was ignited by inserting a small piece of burning charcoal picked from the havan. When the firewood was kindled the bellows were put into the tuyere mouth and air was blown at a slow rate. Slowly the rate of blowing air was increased till a flame of about 600 mm tall appeared at the top of the furnace. Then iron ore and charcoal in the ratio 1 : 2 to 1: 4 were charged in the furnace in alternate layers. Thus the iron smelting was begun.

Joshi [33] has published English translations of the tribal folk songs and prayers sung at the performance of the pooja to please the *Lohasur' Baba.* Twelve Agaria brothers and fourteen Kansasur brothers were required for help during the successful operation of the furnace and to produce iron by the interaction of mother earth (iron ore) and *Babspathi Maharaj* (charcoal). The religious beliefs in these deities was so strong that when the Indian iron smelters went to Japan during the Buddhist period they prepared a wall hanging of *Kalabhairao* and *Lohasur* (shown in Fig. 10) and hung it in the *Mandala i.e.,* the place of operation of the furnace and also performed pooja before starting the furnace.

The furnace operators were well aware of the poisonous effect of CO gas and they ignited the gas at the top of the furnace as soon as it started coming out. In order to detect any leakage of the gas generally a burning oil lamp was put near the furnace so that it could burn the gas and also give a warning from the changes in the brightness of the flame. As the charging of alternate layers of ore and charcoal proceeded, the rate of operation of the bellows was controlled by observing the colour and height of the flame, thus providing a strong reducing atmosphere at the correct temperature inside the furnace. The temperature inside, in front of the tuyere, was checked through the tuyere hole and also recorded by a thermocouple to be 1450°C to 1550°C.

One heat of the furnace generally requires 10 to 15 kg. of ore and 35 to 40 kg of charcoal while flux was not added to the charge to adjust the properties of the slag. After completing the charging of the stipulated amount of ore and charcoal, a few more charges of only charcoal were made for superheating the sponge. The slag hole, *hagan*, was generally kept open and the fluid slag ($2FeOSiO_2$) began flowing out after about an hour. This was continuously removed to keep the slag hole open. The fluidity and quantity of the slag, as well as its colour (black) after solidification, indicated the success of the reduction reaction in the furnace. After about 4 to 5 hours, when all the iron ore had been reduced, the rate of blowing air was increased to raise the temperature of the sponge iron and the slag. If at any time molten metal came out along with the slag it was considered to be a bad omen because this indicated carbon pick-up by iron beyond 2% and the production of white cast iron which was very brittle and hence useless. The belief continued till a process was developed in Mysore to convert it into steel by decarburization process.

Handling of Hot Sponge Iron

After all the iron ore was consumed and sufficient slag had been removed, the air bellows were removed and the mouth of the furnace (man hole) was opened and the remaining part of the clay tuyere was also removed. The remaining hot charcoal was pulled out with the help of a stick and quenched. With the same stick the hot sponge iron having a temperature of 1250°C to 1300°C was dislodged and pulled out with the help of a long tong. This was carried and placed on a granite stone anvil and hammered to squeeze out the molten slag and to consolidate the iron into a solid mass. Sometimes the large block of hot sponge iron was cut into smaller bits by striking it with a piece of ore. Further refining and forging of the iron was done during the secondary operation.

After the remaining charcoal had been pulled out and quenched in water the furnace was left to cool. The next day it was examined for erosion of the wall and the hearth bottom was cleaned. This was followed by repairing the wall with a clay mixture, preparing the bottom and fixing a new tuyere pipe before closing the mouth and finally re-starting the smelting operation. Thus each furnace was used

Fig. 21 : Photograph of the iron smelting site at Stara Stupnia in the Holy Cross mountains.

several times after suitable repairing and probably this is the reason why only one or two furnaces have been found at each excavation site in India, whereas in Europe a cluster of large number of furnace bottom remains have been found placed very close to each other as shown in Fig. 21.

Secondary Refining of the Iron Bloom

The iron produced by the smelting furnace still contained a large amount of slag inclusions and iron oxide and hence it needed to be refined. This was carried out by reheating the bloom to over 1000°C in a forge hearth as shown in Fig. 22. During this process, some silica sand is sprinkled on the hot iron to facilitate formation of fluid slag, which flows out through a hole made in the side of the forge hearth wall.

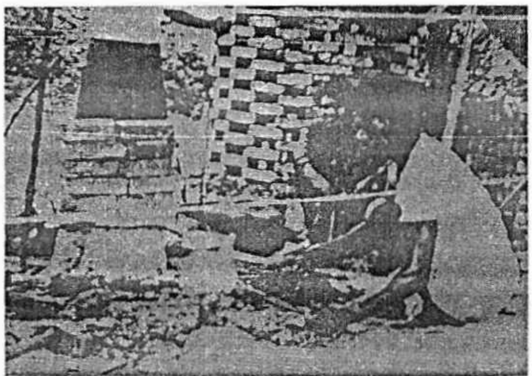

Fig. 22 : Forge hearth furnace of Agaria from Wardruffnagar, constructed for secondary refining of iron bloom.

Table 4 : Chemical analysis of iron sponge, refined iron and slag in percentage from Bishunpur

Constituent	Sponge Iron	Refined Iron	Slag
Fe (T)	54.99	96.25	50.64
Fe(M)	22.53	94.21	3.7-52.87
C	—	0.16	0.21
Mn	—	0.057-0.043	—
P	—	0.02	—
S	37.31	0.007-0.2	0.033
FeO	4.90	1.55-0.013	59.12
Fe_2O_3	—	1.18	4.53
SiO_2	—	0.30	11.82
Al_2O_3	—	3.034	9.71
CaO	—	Trace	7.84
MgO	—	Trace	1.92
P_2O_5	—	—	1.99
Alkali	—	—	0.765

The piece of hot sponge iron is taken out and forged to reduce its slag inclusions and porosity. The process is repeated until the bloom has become solid and free of almost all the slag. Then this was forged into bars of 15x14 mm thickness and 150 to 200 mm length and sold to the *Lohars* for shaping them into utility products. Table 4 gives the chemical composition of iron blooms, refined iron and slag produced at Bishunpur. Before deciding the use to which the bar could be put it was tested and examined for its ductility and fracture to determine its 'C' content and possible use. The rods were classified into Kanta Loha, Tikshna Loha and Munda Loha depending upon the increase in 'C' Content. There were further classified into subgroups as shown in Fig. 23 taken from *Rasa Ratna Samucca* [34] (8th-12th c.A.D.). The large forgings like the iron pillars were made by forge welding these rods by heating them into piles and forging with the help of heavy iron hammers. A glimpse of this operation is found in the account book prepared for expenses incurred during the manufacture of the iron beams of Konarak, published by Bonner and Sharma [35].

Thermo-chemistry and Process Control

In order to understand the thermo-chemistry and the effect of operating parameters, Prakash [36] examined the theoretical considerations for the reduction

Kinds of Iron (Loha)		Properties
Kanta Loha (Soft Iron)	Bhramaka	Very soft magnetic iron
	Chumbaka	Mildly mangetic, stricks to iron pieces
	Karsaka	It can attract iron objects
	Dravaka	Very strong magnetic iron
	Romaka	Permanent magnet, develops strong magnetic field around it. it may be Ek Mukh, or Sarva Mukh
Tikshna Loha (Carbon Steel)	Khara	Develops good cutting edge breaks on bending
	Sara	Softer iron and its has fibrous fracture
	Hrnnala	Hard and tough has fibrous fracture
	Travaratta	Develops good cutting edge
	Vajra	Has good hardening and tempering property has bluish colour and hard cutting edge
	Kala	Developes hard cutting edge after blue tempering
Munda Loha (Cast Iron)	Mrdu	Soft brittle iron may be grey cast iron. Has low melting point.
	Kunda	Mottled grey iron
	Kadara	White cast iron

Fig. 23 : Classification of iron and its properties as given in Rasa Ratna Samucca *(800-1200 AD)*

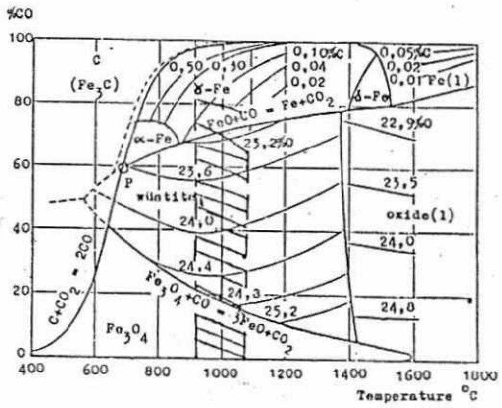

Fig. 24 : Fe-C-O equilibrium diagram at one atmosphere showing the operating temperature (hatched) of the bloomery furnaces.

Table 5 : Material Balance for Ironmaking from Jiragora (M.K. Ghosh).

Furnace trial results show 24kg of ore/30kg of charcoal. Time of reduction and smelting - 6 hours. Reduction efficiency 36.2%

Material	Analysis %	Calculation	Metal Fe(kg)	Theoretical Composition	Actual Composition (basis 21kg)	Gases (kg)	Remarks
Ore-24kg							Metal Composition
Fe(Fe_2O_3)	63.4	24x0.634x0.302	5.5	9.7	9.66	2.357	C- 0.4%
SiO_2	2.44	24x0.0244.0.021	0.01	0.565	5.68	1.387	Si-0.2%
P_2O_5	0.01	—	0.0004			0.114	Fe - rest
Al_2O_3	1.66	—	—	0.446	1.41	0.026	Slag Composition
CaO + MgO	0.5	—	—	0.12	1.29		SiO_2- 27.08%
MnO	0.9	—	—	0.20	0.21	0.888	Al_2O_3- 6.72%
Lol	3.7						Fe - 46%
Total			5.5104	11.031			MnO - 1.026%
							Cao - 5.0%
Oxygen in iron as FeO				2.77			MgO - 1.16% SO2 - 0.075% O2 - 12.98%
Charcoal - 30 kg							5.54 kg of iron will be associated with 21 kg
F.C	75.8		0.022			22.718	slag Theoretical slag wt.
Ash	3.2			0.96			= 14.76 kg hence SiO_2 +
V.M.	21.0					6.3	Al_2O_3 added as flux = 6.24kg. Theoretical char coal for reduction = 16kg

Table 6 : Heat balance of ironmaking furnace at Jiragora (M.K. Ghosh)[10]

Heat Input	K Cal	Heat Output	K Cal.
Heat generated by combustion $CO/CO_2 = 4$	81, 011. 5	Heat for heating ore to 1000°C	4, 920.00
		Heat for endotherimic reduction	5, 451.87
		Heat content of metal at 1200°C	1, 385.00
Total	81, 011.5	Heat content of slag at 1200°C	6, 300.00
		Heat in outgoing gases	48, 026.28
		Heat lost by conduction and radiation by difference	14, 928.22
		% Radiation loss = 18.5%	81, 011.5

Theoretical Flame Temperature = 1,938°C

Blowing Rate : Air blown in 6 hrs. = 203 m^3
Air blowing rate = 564 litres/min
No. of strokes for blower size
(280 mm dia, 100 mm ht.) = 87/min
Note : Maximium capacity of worker = 300 strokes/min

of iron oxide inside the furnace using the Fe-O-C equilibrium diagram shown in Fig. 24. In this figure the shaded area shows the range of temperatures at which the ancient furnace should have been operated to obtain effective reduction of iron oxide to produce iron blooms containing low carbon. In this range FeO could be theoretically reduced at a CO/CO_2 ratio of 80: 20. Taking this CO/CO_2 ratio the overall reduction can be written as:

$$2C + O_2 \rightarrow 2\,CO \qquad \ldots \quad 1$$

$$Fe_2O_3 + X\,CO \rightarrow 2\,Fe + 3\,CO_2 + (X\text{-}3) \qquad \ldots \quad 2$$

$$\text{and } CO/CO_2 = (X\text{-}3)/3 = 4$$

$$\textit{i.e.},\ Fe_2O_3 + 9\,CO \rightarrow 2Fe + 3CO_2 + 6\,CO \qquad \ldots \quad 3$$

These reduction reactions, being exothermic, should be able to provide sufficient heat to maintain the furnace temperature and also provide heat for the formation of fayalite-based ($2FeOSiO_2$) liquid slag. Bloomgren and Tholander [37] have studied the constitution of iron smelting slag in low shaft furnaces and concluded that fayalite-based slag having a melting point of 1250° could be formed easily and that it will prevent carbon pick-up by the reduced iron by virtue of the higher oxidation potential present in the furnace.

Table 7 : Comparison of operating parameters of Jiragora and Bishunpur iron making furnaces

Operation	Time	Materials charged		Blowing Rate	Remark
		Ore	Coal		
JIRAGORA FURNACE					
Furnace Preheating	1 hr		8 kg	Faster than 87 strokes/min	See Table I
Reduction stage	4 hrs		14 kg	87 strokes/min	Sequence of ore and coal chargin
Consolidated stage	1 hr		8 kg	Vigorous blowing	Not available
Total Opeating time	6 hrs				
Total Material charged and metal produced		24 kg	30 kg		5.6 kg of iron
BISHUNPUR FURNACE					
Furnace Preheating	1.25 hrs	2.5 kg	3.25 kg	40-5- strokes/min	Fce.Temp. 550°C
Reduction stage	4 hrs	8 kg	16 kg	60-70 strokes/min	950°C
Consolidation stage	0.5 hrs	1 kg	2 kg	110 strokes/min	1500°C
Total operating time	5.75				
Total material charged and metal produce		11.25kg			2.5 kg of iron

Utilizing these parameters and the operational log sheet of the Jiragora furnace (shown in Fig. 25) published by Ghosh [24], the material and heat balances were calculated by Ghose [24] as reported on Tables 5 and 6.

From the study of these tables the following could be concluded:

i) The furnace charge balance was good enough to produce low 'C' wrought iron.

ii) The fayalite rich slag required addition of SiO_2 and Al_2O_3 flux in this furnace toproduce the slag of the recorded composition and quantity.

iii) As shown in Table 6 the air supplied in the furnace by the two bellows operated at 87 strobes per minute was sufficient to generate a theoretical flame temperatureof 1900°C. The measured temperature in front of the tuyere inside the furnace has been recorded to be 1459°C to 1500°C.

Based on these calculations, Prakash [36] predicted the operating rate of the blower for the whole operation of the Jiragora furnace as shown in Table 7, and

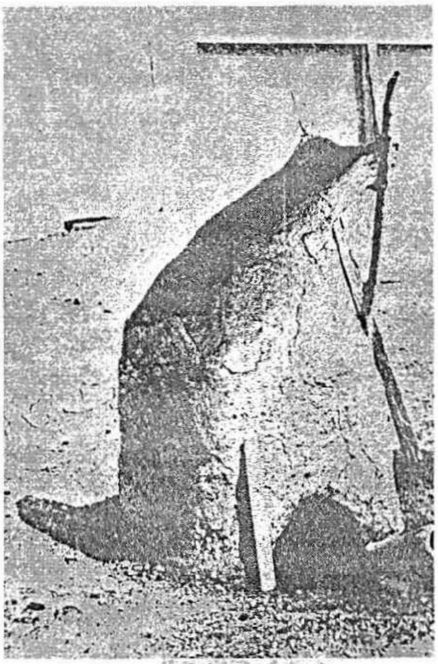

Fig. 25 : Photograph of Jiragora furnace and the clay tuyere placed in front of the bottom opening (man hole).

compared it with the operating rate of the bellows recorded during the operation of the Bishunpur furnace and they were found to be comparable. This was further confirmed while the furnaces were being operated at Varanasi and Chennai. At these two places the possibility of replacement of the costly sal wood charcoal with the inferior grade available in the local market was also tried and found to be successful with some modification in the wind blowing rate. At the conference

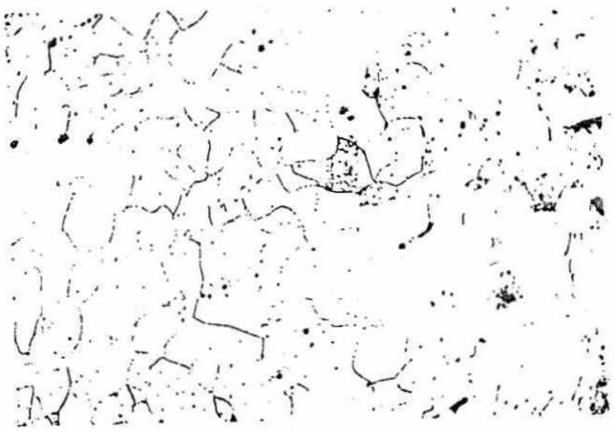

Fig. 26 : Microstructure of refined boomery iron showing uniforms grains of ferrite and some slag inclusions (Mag X 100).

Table 8 : Chemical composition of iron produced by ancient Indian furnaces

Source	C%	Si%	Mn%	P%	S%	Others
Delhi Iron Pillar	0.23	0.066		0.18	Traces	N_2 = 0.0065%
Bhubaneshwar Iron Beams	0.27 to 0.45	0.05 to 0.11	Trace to 0.04	0.015 to 0.018	0.006 to 0.015	Cr - 0.9% Ni - 1.6%
Bastar Iron Axe (100 years old)	0.25 to 0.45					Other elements in traces
Smelting iron from Jabalpur (recent)	0.59	110 ppm	40 ppm			Cu - 340 ppm Ni - 353 ppm Others in traces
Smelted iron from Bishunpur (recent)	0.016 to 0.043		0.057	0.02 to 0.2	0.007 to 0.013	

held at Chennai, on the last day from sal wood was replaced with the locally available charcoal from casuarina wood and after successful operation of the furnace the yield of iron was found to be doubled. The rate of air blowing was controlled by observing the colour and length of the CO flame burning at the top of the furnace and the temperature inside was estimated by visual observation of the charge in front of the tuyere and also the fluidity of the slag. It was considered undesirable, and a bad omen, if molten metal flowed out along with the slag. Table 8 gives the chemical composition of some ancient iron objects and of iron produced by the Jabalpur and Bishunpur furnaces. Fig. (26) shows the microstructure of a piece of ancient iron showing uniform ferrite grains and some slag inclusions.

The accuracy of the ancient master craftman's judgement may be assessed from the fact that for the production of 8 tonnes of the corrosion resistant iron required for forging the iron pillar of Delhi, either a furnace of the Nagpur type *kothi* (see Fig.19) having a production capacity of 40 kg of iron per heat would have had to have been operated 200 times, or as many as 200 furnaces would have had to have been operated simultaneously. The soundness and structural homogeneity of the Delhi iron pillar has been tested by Bindal *et al.* [15] This and other heavy forgings mentioned in this paper are living testimony to the skill of the ancient iron smelters and black smiths.

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