Adaptation of Technology to Culture and Environment: Bloomery Iron Smelting in America and Africa

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While technology always must be practiced in accord with the principles of physics and chemistry and with the natural resources available, there is usually sufficient latitude within these constraints for a given technique to be carried out in quite different ways to meet the goals of practitioners in different cultures. These goals will reflect values and preferences in the society where the technique is used. Often, these values and preferences are not explicit, and one way of discovering them is by studying the organization and practice of technology.[1] When we want to compare technological accomplishments in different cultures, or even at different times within our own culture, we need to take into account the intentions of the practitioners since these may be quite different from those that we take for granted. Techniques that were actually sophisticated adaptations to a

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[1]Anglo-American social anthropologists have, with few exceptions, failed to appreciate that technology can be an excellent source of information about systems of beliefs and values. Much of the literature in this field is in French; for prominent examples, see A.-G. Haudricourt, *La technologie, science humaine: Recherches d'histoire et d'ethnologie des techniques* (Paris, 1988); and articles in the journal *Techniques et culture*.

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given physical and cultural setting may be dismissed as "primitive" by observers from other times or other cultures who have not discovered the practitioners' objectives.

In this article we focus on a technique that has been practiced in many different cultures over a long period of time. Bloomery smelting, the reduction of iron ore directly to solid metal with charcoal to make wrought iron, was in continuous use from the early second millennium B.C. until the middle of the 20th century. Bloomeries were operated on all the inhabited continents, with the possible exception of Australia.[2] Almost from the time it was first used, iron has been a "people's metal," made for utilitarian purposes rather than as a symbol of wealth, power, or privilege. Iron metallurgy is a "sustaining technology," that is, one that is fundamental to the subsistence of the members of the societies that possess it. The study of sustaining technologies gives us a more representative sample of the interplay of cultural and technical factors in a society than does the study of techniques such as glassmaking, bronze casting, and fine ceramics, where knowledge was often restricted to a small elite and their artisans.

Bloom smelting is a difficult process to execute because specific chemical and physical conditions must be met if metallic iron is to be made. It is particularly interesting for cultural comparisons because the necessary conditions can be attained through many alternative furnace designs and smelting procedures. Examination of the methods of bloom smelting used by different peoples can reveal aspects of the smelting technology that were determined by cultural preferences rather than technical requirements and, hence, reveal beliefs about technology that could be difficult to discover in other ways.[3] These beliefs may be expressed in choices between technical alternatives in the design of the bloomery process or in actions that have social rather than metallurgical consequences. But, when interpreting aspects of a technology as expressions of cultural choice, we must first examine

[2]For the early history of bloom smelting, see R. F. Tylecote, *A History of Metallurgy* (London, 1976), chap. 5.

[3]A comprehensive worldwide review of ironworking, written jointly by a metallurgist and an anthropologist, is W. Rostoker and B. Bronson, *Pre-industrial Iron: Its Technology and Ethnology*, Archeomaterials Monograph no. 1 (Philadelphia, 1990). For regional reviews of the large archaeological and historical data, see, for Africa, Randi Haaland and Peter Shinnie, *African Iron Working, Ancient and Traditional* (Oslo, 1985); for Britain, R. F. Tylecote, *The Prehistory of Metallurgy in the British Isles* (London, 1986); and for the rest of Europe, R. F. Tylecote, *The Early History of Metallurgy in Europe* (London, 1987). T. A. Wertime and J. D. Muhly, eds., *The Coming of the Age of Iron* (New Haven, Conn., 1980), contains reviews of other regions as well, but the pace of research has been so rapid that this volume is no longer up-to-date.

the underlying natural science so that we can separate technical requirements from the discretionary factors.

Bloom smelters had to complete four successive steps to make metal. First, the iron oxide in the ore was reduced to solid, metallic iron by reaction with carbon monoxide gas released by burning charcoal. The range of temperatures and compositions of the furnace gases that would accomplish this were fixed by the principles of thermodynamics.[4] Second, the solid iron had to be separated from the earthy material (gangue) that is always present in ore by converting some or all of the gangue to liquid slag that could be drained away from the metal. This slag was made by reacting the gangue with some of the iron oxide in the ore. Third, the metal particles formed by reduction of the ore were agglomerated into the bloom (sometimes called a "loup" or "loop"), a coherent mass of iron and slag. Finally, the bloom was removed from the smelting furnace and hammered while hot to weld the iron particles together and expel enough of the slag to make sound metal. Only the fourth operation (hammering) was visible to the artisan carrying it out; the other steps involved chemical reactions and mechanical processes that were largely invisible because they went on inside the bloomery furnace. Their progress was revealed only by subtle, indirect clues. The quality of the wrought iron made depended on the skill with which the ore was selected and prepared, the furnace manipulated, and the bloom forged.

Iron ore, composed of iron oxide, can be reduced to metallic iron by carbon monoxide gas at temperatures as low as about 800°C. Since this is well below the melting temperature of iron (1,534°C), iron ore can be smelted directly to solid metal. In a bloomery, the combustion of the charcoal generated both the necessary heat and the carbon monoxide reducing agent. The lowest possible melting point of slag formed by reaction of iron oxide with gangue minerals, such as quartz, is about 1,200°C; this was, therefore, the lowest temperature

[4]Some anthropologists have argued that Western scientific concepts fail when applied to ancient technology: D. H. Avery and P. R. Schmidt, "The Use of Preheated Air in Ancient and Recent African Smelting Furnaces: A Reply to Rehder," *Journal of Field Archaeology* 13 (1986): 354–57. Fortunately, most archaeometallurgists agree that the principles of thermodynamics are both universal and useful in gaining a deeper understanding of the accomplishments of metallurgical artisans in the past. It is helpful to remember that, even in the most advanced industrial nations, complex metallurgical processes are carried out by persons having no working knowledge of thermodynamics. It is usually assumed that thermodynamic equilibrium is attained when these rules are applied to bloom smelting. Chemical and thermal conditions change rapidly inside a bloomery furnace, and there is now abundant evidence that equilibrium is often not attained while iron is being made. Hence, the application of these thermodynamic constraints is not as easy as was once thought.

at which a bloomery could be operated. At this temperature, which was low compared to those in blast furnaces, nearly all the impurities in the ore remained in the slag, and very pure iron could be made.

Although the principles on which a bloomery operated are simple, carrying them out in practice was not simple. One difficulty was that the temperature of 1,200°C needed to melt the slag was most easily attained by burning the charcoal with plenty of air. But a strong air flow through the hearth decreased the proportion of carbon monoxide relative to carbon dioxide in the furnace and so decreased the capacity of the furnace gases to reduce the ore. A balance had to be struck between the need to achieve high temperature and the need to attain a reducing atmosphere. Another source of difficulty was that, once slag began to form, the ore might begin to dissolve in it before being reduced to metal; the iron so lost might be recovered subsequently from the slag by appropriate manipulation of the furnace, but this was not easy to achieve. Finally, the iron particles formed by reduction of the ore had to be aggregated into a bloom that was sufficiently coherent that it could be removed from the hearth and hammered into sound metal.

Many alternative bloomery designs were possible, ranging from small bowl hearths dug as pits in the ground and blown with a single bellows to large shaft furnaces operating by induced draft. A great variety of bloomeries has been found by archaeologists in different parts of the world. There was scope for the exercise of much creativity in developing bloomery designs suited to local needs. Once a hearth design that would provide for adequate thermal efficiency and the necessary flow of air, ore, and fuel had been worked out, the skill of the bloom smelter was exercised in the selection and preparation of the ore and fuel and in the manipulation of the furnace to reduce the ore and agglomerate the reduced particles of metal into a bloom by separating them from the slag. Bloomeries were operated without the aid of instruments and with only the most subtle of clues as to what is happening inside at any given time.[5] The quality of the iron produced depended on both the operation of the furnace and the skill with which the bloom was subsequently forged to expel the slag it

[5]Much fieldwork has been done on the physical configuration of bloomeries, but there have been only a few studies of what is required to achieve a successful smelting operation. Two particularly important papers are E. J. Wynne and R. F. Tylecote, "An Experimental Investigation into Primitive Iron Smelting Technique," *Journal of the Iron and Steel Institute* 190 (1958): 339–48; and R. F. Tylecote, J. N. Austin, and A. E. Wraith, "The Mechanism of the Bloomery Process in Shaft Furnaces," *Journal of the Iron and Steel Institute* 209 (1971): 342–63.

contained. These technical requirements had to be met in a way that was economically useful within the community that supported the bloomers and within the constraints imposed by the availability of natural and human resources.

Several kinds of evidence show that a high level of technological competence was needed for successful bloom smelting. One is the frequent occurrence of both very poor and quite superior metal among archaeological specimens.[6] Attempts by persons with substantial scientific and technical experience to operate bloomeries today almost invariably fail to reproduce either the fuel efficiency or the quality of metal achieved by competent bloom smelters in the past. Attempts to reconstruct bloomery smelting with the aid of persons who were familiar with the process in their youth have similarly failed.

One reason the skills needed in bloom smelting are now unfamiliar is that they were never recorded in written instructions, in part because the individuals skilled in the art usually had no desire to record what they did, but primarily because writing would have been an inadequate means of conveying the information that smelters had gained through the sights, sounds, and smells of a bloomery in action and the feel of the materials within it (as tested by prodding the fire with iron bars). The only way we can rediscover bloom smelting techniques is through archaeological methods, such as analysis of artifacts from smelting sites or experimental reconstructions of bloomery operations.

The artifacts left from bloom smelting in the past include the remains of furnaces and auxiliary equipment, traces of the materials used and products made, and smelting wastes such as slags. Of these, slag is usually by far the most abundant, and analysis of slag collected at smelting sites is often our best source of information on the technique used there.[7]

We will compare the practice of bloom smelting carried on in the late 19th century in two distinctly different geographical and cultural settings. In the eastern Adirondack region of New York State iron

[6]The range of strength properties found in historic samples of wrought iron is shown in R. B. Gordon, "Strength and Structure of Wrought Iron," *Archeomaterials* 2 (1988): 109–37. A sample of late-17th-century bloomery iron from Virginia included among the materials tested in this research was found to be completely brittle due to its high phosphorus content.

[7]R. B. Gordon and D. J. Killick, "The Metallurgy of the American Bloomery Process," *Archeomaterials* (in press). D. J. Killick, "Technology in Its Social Setting: Bloomery Smelting at Kasungu, Malawi, 1860–1940" (Ph.D. diss., Yale University, 1990), chap. 6.

blooms were smelted from rich ore and abundant wood with scarce labor to sell on a competitive, industrial market.[8] At the same time, in Malawi, Africa, iron was made in bloomeries as part of the agricultural cycle from lean ore by persons working within a belief system that strongly influenced smelting procedures but was unfamiliar to observers from industrial nations.[9] We will show that each was well adapted to the natural resources available and to its economic and cultural context.

The research aims and methods were similar in the two studies. Both were based on field surveys to locate smelting sites, intensive field study of a sample of these sites, and laboratory examination of selected material remains (ores, slags, blooms). The Adirondack industry is beyond the span of living memory, but we have tapped the rich written record of the industry in books, newspapers, and archives. The written record of the Kasungu iron industry is sparse in comparison to that of the Adirondacks, but a few former ironworkers were still alive at the time the field work was done in 1982 and 1983. Extensive interviews with these individuals were recorded on tape, and several of them were hired in a separate but related study to construct a furnace and reproduce the smelting process.[10]

American Bloomery Process

Bloomery smelting was practiced in the eastern Adirondacks from at least as early as 1801 until December 1900. The forge operators drew on the abundant, high-quality ore, waterpower, and forest resources of the region. Many of the early forges[11] were established by the proprietors of large landholdings to add income from ironmaking to that already derived from lumbering and agriculture.[12] They hired experienced bloomery smelters to run their forges. Much of the iron

[8]R. F. Allen and others, "An Archaeological Survey of Bloomery Forges in the Adirondacks," *IA: The Journal of the Society for Industrial Archeology* 16, no. 1 (1990): 3–20.

[9]Killick, "Technology in Its Social Setting."

[10]The furnace reproduction at Kasungu was arranged and recorded by N. J. van der Merwe and D. H. Avery; see their article "Science and Magic in African Technology: Traditional Iron Smelting in Malawi," *Africa* 57 (1987): 143–72, reprinted in R. Maddin, ed., *The Beginning of the Use of Metals and Alloys* (Cambridge, Mass., 1988), pp. 245–60; and also D. H. Avery, N. J. van der Merwe, and S. Saitowitz, "The Metallurgy of the Iron Bloomery in Africa," in ibid., pp. 266–70.

[11]In the Adirondacks, a bloomery "forge" consisted of at least two bloomery hearths and a helve hammer, usually powered by the fall of water. The meaning of the term "forge" can be ambiguous since it may also refer to a finery forge or a smithy. In this article, it always means bloomery forge.

[12]Morris F. Glenn, *The Story of Three Towns* (Alexandria, Va., 1977), pp. 197, 265–77, 325–38.

they made was used locally for products such as nails or tools for farms and lumbering camps. After the Champlain canal was opened in 1823, knowledgeable entrepreneurs came to the Adirondacks to establish ironworks with the intention of selling their iron on national markets. Many of them built reputations for making metal of superior quality, and their products were often chosen for critical applications, such as suspension-bridge wire. After 1850, iron from the Adirondacks was widely used for making crucible steel because of its low phosphorus content, and by 1870 steelmakers were the principal purchasers of the bloomery iron made in northern New York. In this application, Adirondack smelters were in direct competition with importers of Scandinavian iron made in finery forges. The demand for New York bloomery iron fluctuated with changes in the rate of crucible steel production and the supply of imported iron. By 1885, many makers of crucible steel had decided that they could use iron made with mineral coal rather than charcoal, and it then became increasingly uneconomic to operate the New York bloomeries; the last forge closed in December of 1900.[13] As bloom smelting ended in the Adirondacks, the forges were stripped of their equipment and then abandoned. Most forge sites remain undisturbed, in part because of the depopulation of the associated communities.

The bloomery hearth design that was eventually adopted by the Adirondack smelters was a shallow, rectangular box made of water-cooled, cast-iron plates set in the base of a brick stack that contained the pipes of a heat exchanger for preheating the air blast (fig. 1). One tuyere, placed at the side of the hearth, directed the heated air into the charcoal fire.

Smelting began as the bloomer spread ore on the hot charcoal in the hearth. The iron mineral (magnetite) reacted with the gangue

[13]The principal documentary sources on the Adirondack bloomery iron industry are Winslow C. Watson, *The Military and Civil History of the County of Essex, New York* (Albany, N.Y., 1869); Duane H. Hurd, *History of Clinton and Franklin Counties* (Philadelphia, 1880); George Chahoon, "The Making of Iron in Northern New York Catalan Forges," *Iron Age* 16, no. 7 (1875): 7; George F. Bixby, "The History of the Iron Ore Industry on Lake Champlain," *New York Historical Association Proceedings* 10 (1911): 169–237; Joseph R. Linney, *A History of the Chateaugay Ore and Iron Company* (Albany, N.Y., 1934); Richard S. Allen, "The Iron Industry of Northern New York," *Canadian Mining and Metallurgical Bulletin* 76 (1983): 85–89; John R. Moravek, "The Iron Industry as a Geographical Force in the Adirondack-Champlain Region of New York State, 1800–1971" (Ph.D. diss., University of Tennessee at Knoxville, 1976); Philip J. Hardy, "The Iron Age Community of the J. & J. Rogers Iron Company, Au Sable Valley, New York: 1825–1900" (Ph.D. diss., Bowling Green State University, 1985). Note that it was common usage in the United States in the 19th century to refer to any bloomery forge as a "Catalan forge." Properly, the Catalan forge refers to a specific type of bloomery used in southern France and northern Spain.

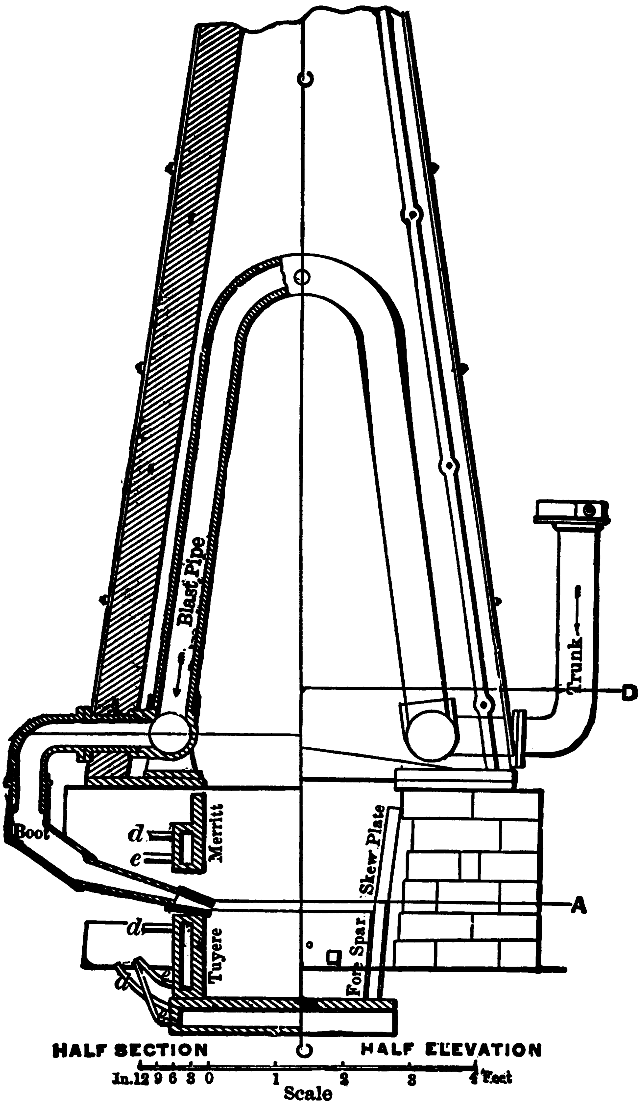

Fig. 1.—The bloomery that was in common use in the Adirondack region of New York State after about 1860 consisted of a hearth made of water-cooled cast-iron plates set in a brick stack. A heat exchanger for preheating the air blast was built into the stack above the hearth. The hearth was operated by one person, the bloomer, who placed iron ore in the hearth to be reduced by carbon monoxide generated by a charcoal fire. Slag was tapped through holes in the front of the hearth from time to time. When the iron bloom had grown so as to occupy most of the space within the hearth, it was levered out onto the floor and then taken to a helve hammer to expel the slag it contained and be hammered into a billet. (After H. M. Howe, *The Metallurgy of Steel* [New York, 1904].)

(mostly quartz) in the ore to form liquid slag that ran to the bottom of the hearth. The remaining magnetite was reduced to particles of sponge iron (fig. 2) that had to be agglomerated to form the bloom. The bloomer manipulated the placement of ore on the fire so as to build up a lip around the upper edge of the bloom to retain a pool of liquid slag that would act as a trap for all of the iron particles formed in the hearth above. Slag was formed continuously during smelting, and from time to time the bloomer tapped it out of the hearth onto the floor of the forge. After about three hours of smelting, the bloom would have filled the available space in the hearth; the bloomer then cooled it with water, lifted it with levers, and, with the aid of others, tipped it out on to the floor; the pool of slag on its top, now solidified, was knocked off. Pieces of slag from the tops of blooms have a distinctive shape and are common artifacts at forge sites. The hammerman then forged it into sound metal with the helve hammer, expelling as much of the entrained slag as possible. It could then be hammered into a billet or rolled into a square or rectangular bar.

The ore as mined typically contained about 53 percent iron. Ore separators were set up near a good supply of water with machinery to crush the ore to the size of fine sand. Enough gangue was removed by magnetic separation or washing to bring the iron content up to about 67 percent. Theoretically, a bloomery operating at peak efficiency with respect to iron recovery would use 170 pounds of this ore to produce 100 pounds of iron and 28 pounds of slag. To accomplish this, there had to be no loss of unreacted ore from the hearth, all the iron formed had to be trapped in the bloom, and the slag had to have exactly the composition of the mineral fayalite ($2FeO\ SiO_2$). These were not easy technical requirements to achieve, particularly in the small hearth of a bloomery.

Our analyses of the slag found at forge sites in the Adirondacks show that after about 1850 the bloom smelters there consistently approached the theoretical maximum recovery of iron from the ore. They also show how the very high labor productivity possible with this form of the bloomery process was achieved. The key steps were the use of finely ground, rich ore, a hearth design and smelting procedure that passed the ore through the reaction zone in the hearth very rapidly, and careful shaping of the growing bloom to form a lip that would effectively trap the reduced iron. The high industrial efficiency of the American bloomery process can be seen by comparing it with the Catalan bloomery process practiced in southern France in the mid-19th century, the final development of bloom smelting achieved in Europe. At a Catalan bloomery, 7,180 pounds of charcoal, 6,240 pounds of ore, and 109 man-hours of labor at the hearth were used

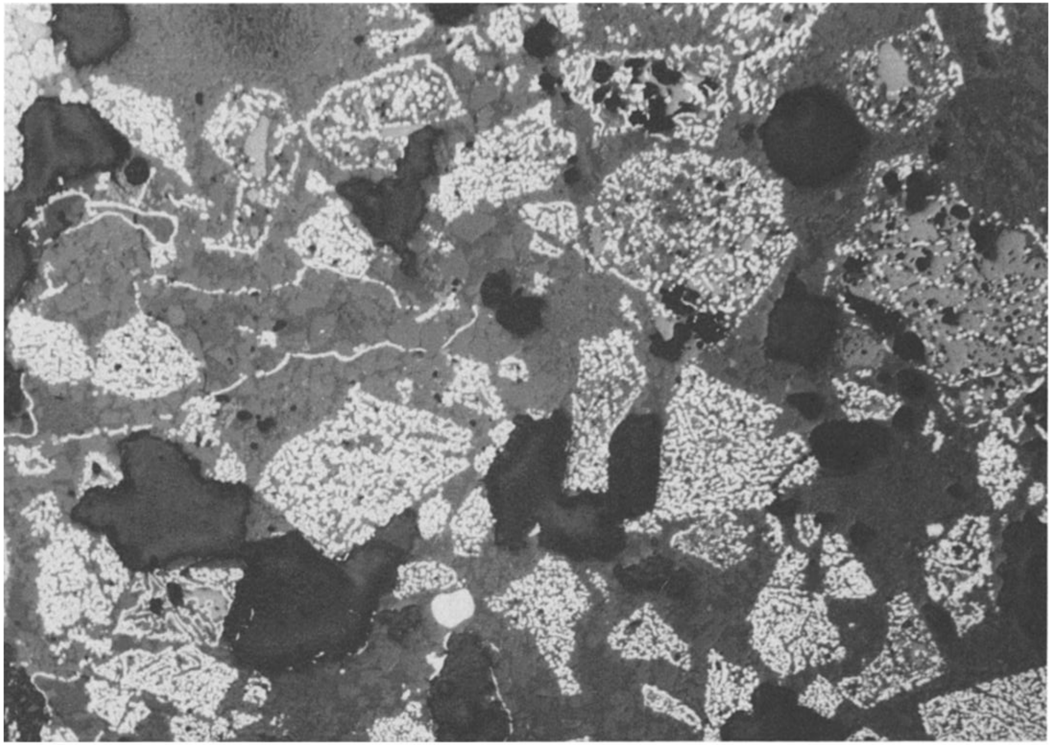

FIG. 2.—The iron mineral in the ore used at the New York bloomeries was pulverized magnetite. Carbon monoxide generated in the bloomery fire reduced the magnetite to sponge iron particles, like those seen in this micrograph, that retained the shape of their parent magnetite grains. The iron grains are surrounded by slag formed by reaction between the gangue and the iron mineral in the ore. One key to the high efficiency of the American bloomery process was rapid reduction of the iron mineral before there was significant loss to the slag. The sponge iron particles settled to the bottom of the hearth where they were consolidated into the bloom.

to make 2,000 pounds of iron. The same amount of iron was made at an American bloomery from 5,425 pounds of charcoal (24 percent less), 4,000 pounds of ore (36 percent less), and 15 man-hours of labor (86 percent less).[14]

Adirondack bloomery hearths were usually run continuously from 12:01 A.M. on Monday morning until midnight Saturday. Each bloom smelter made 350–400 pounds of iron every three hours of a twelve-hour shift. To obtain a good yield of high-quality iron, close control of the temperature of the hearth and the timing of additions of ore and charcoal were needed. To judge what was happening within the hearth, the bloomer observed the color of the flame, the color and fluidity of the slag, the feel of the bloom as tested with a long iron bar, and the sounds made by the fire in the hearth. There were no analytical instruments. The shape of the bloom, which had to be held within narrow limits to make it an effective trap for the reduced iron, was controlled by the dexterity with which the ore was distributed over the surface of the hearth. To achieve the best fuel economy, it was necessary, according to one authority, "to keep the ore up to the capacity of the fire; but to do so requires an active and intelligent bloomsman. There is a very great difference in the capacity of the men in this respect."[15]

The technical aspects of the operation of a bloomery hearth during smelting were totally under the control of the bloomer, who worked as an individual at the hearth. However, the bloomer could not complete the process alone. A bloom weighing 350–400 pounds was too heavy for one person to lift from the hearth, and the forging of the bloom into a billet was done by a specialist hammer operator. Getting the bloom out of the hearth was typically a group effort of the bloomer, two hammermen, and the bloomer from the neighboring hearth when all went well; if it did not, bloomsmen from other hearths in the forge would join the group. Once out of the hearth, the bloom was wheeled to the helve hammer on a cart to be forged into a billet. Manipulating the hot bloom on the hammer anvil was heavy labor, and at the larger forges there were two operators for the hammer; they changed off after working each bloom. The smooth operation of the forge depended on blooms becoming available for forging at regular intervals. Each bloomer had to regulate the pace of smelting so as to have a bloom ready at the appropriate time and be prepared to help out at other hearths when needed. Consequently, a substantial

[14]Gordon and Killick.

[15]Thomas Egleston, "The American Bloomery Process for Making Iron Direct from the Ore," *Transactions of the American Institute of Mining Engineers* 8 (1879–80): 515–50.

amount of informal organization was needed for the smooth functioning of the forge.

An article in the *Elizabethtown Post* for October 6, 1864, shows the pride and competitiveness of Adirondack bloomers. The paper reported that working at three fires in a single tour (12 hours) on August 20, hammerman John S. Kinney and bloomers C. Bulls, L. Carreau, and D. Benson used ore from the Old Bed and Burt mines to make five loups to the tour, amounting to 2 tons, 4 hundredweight, 3 quarters, 2 pounds gross weight, an average per fire of 1,671 pounds. "If any forge in the county can beat it, the Valley Forge boys will try again."[16]

To discuss the significance of the American bloomery process, we need to know the goals toward which the practitioners were working, and, to find these, we have to examine the context in which smelting was carried out. The natural resources available, the markets for bloomery iron, the prevailing state of metallurgical knowledge, and the social setting in the forge communities were all components of this context.

The Adirondack region had abundant resources of low-phosphorus iron ore, wood suitable for making charcoal, and waterpower sites. The operators of American bloomery forges utilized these abundant, high-grade natural resources to minimize the labor per unit of iron made. The natural resource base provided a necessary condition for their economic success. The distribution of natural resources also influenced the communities in which smelting was carried out. Nearly all the forges used waterpower to operate helve hammers that weighed up to 5 tons and so were necessarily placed at substantial water privileges. They had to be located within reach of ore and fuel through the existing transportation system of wagons (in summer) and sleds (in winter). Because forge operators needed contiguous forest acreage, and their water privileges were well separated, they placed forges over a large area. Since many forges were not within established towns, the proprietors often had to build small communities as well. The waterpower available at each site set an upper limit to the number of hearths that could be included in any one forge. The largest, at Clintonville, had twenty hearths in a 60 × 330-foot stone building; the smallest ones had two hearths.

[16]If figured in terms of long measure, 2 tons, 4 hundredweight, 3 quarters, and 2 pounds divided by three is 1,671 pounds. Both long and short measure seem to have been used in the Adirondack region, and now it is often difficult to discover what the convention was at a particular time and place.

Bloomery smelting with European methods was one of the first industries undertaken by colonists in America, but the historical and archaeological evidence of its subsequent development is incomplete. The bloomery hearths used for smelting magnetite ore in northern New Jersey late in the 18th century appear to have been derived from German bloomeries rather than the Catalan forge of southern France, even though American bloomeries were often called Catalan forges.[17] The Adirondack bloomery was similar to those in New Jersey but with the hearth made larger in area and shallower to increase the rate of reduction of the ore. We have not found the names of the innovators who developed the American bloomery process; we believe that many individuals, who exchanged information freely with each other, made incremental improvements in the process used earlier in New Jersey. We infer that the objective toward which they were striving was to minimize the labor needed to operate the forge. Minimizing the use of labor at the bloomery hearth also meant achieving the most efficient possible use of ore and charcoal since the preparation of these materials was labor intensive. Adirondack bloomery smelters adopted an important innovation in the 1840s when they fitted apparatus to preheat the air blast with waste heat from the hearth. This reduced the fuel used per unit of iron made by about 30 percent.[18] The hot-blast bloomery appears to have been an American invention because the only other known use of hot blast in bloom smelting was on Catalan forges in Sardinia.[19] The heat exchanger used in Sardinia was distinctly different from the American design.

Magnetic separation of the iron mineral from the gangue to improve the grade of the ore was also adopted at many Adirondack ironworks. Among the innovators were Allen Penfield and Timothy Taft; they established a forge near Crown Point in 1828, and, within a few years, their iron had been recognized as superior.[20] In 1831 they supplied Joseph Henry with iron for his experiments on electromagnetism, and thereafter Penfield interested himself both in Henry's research and in Samuel Browning's experiments on the beneficiation of iron ore with a magnetic separator. When they built a separator at

[17] A technical description of the bloomeries used to smelt the rich magnetite ores in northern New Jersey late in the 18th century was written in 1783 by the Swedish traveler Samuel G. Hermelin, *Report about the Mines in the United States of America,* trans. Amandus Johnson (Philadelphia, 1931).

[18] T. Sterry Hunt, "Iron and Iron Ores," *Reports of Progress* (Geological Survey of Canada, Ottawa, 1869), pp. 245–394; see p. 278.

[19] John Percy, *Iron and Steel* (London, 1864), p. 312.

[20] Watson, p. 468.

Ironville, they found that the permanent magnets needed frequent remagnetization to function effectively. Penfield arranged with Henry to build an electromagnet for this purpose.[21]

With the innovations made in the years up to 1850, American artisans had pushed the bloomery close to the limit of efficiency set by the physics and chemistry of the process. Although they continued to experiment with other methods of direct reduction, the process used in the Adirondacks did not change much thereafter. The Adirondack bloomery was well adapted to producing for the market in high-quality wrought iron. Since the individual bloomery hearths were small, they could be started up or shut down easily as market conditions changed, as they frequently did. The capital investment needed was much less than for a blast furnace plant. Some bloomery iron was used locally in the early decades of the 19th century, but the national importance of this industry was in supplying high-grade wrought iron at premium prices for specialized uses. The bloomery forges were well adapted to producing a high-value product subject to large price fluctuations.

The operators of Adirondack bloomery forges depended on the skills of several kinds of artisans. There was a division of labor among bloomers, hammermen, and charcoal burners. Less specialized tasks included hauling ore, charcoal, and iron; felling timber; mucking ore in the mines; and operating the ore separator. As entrepreneurs built larger and more numerous forges, the peer group in which the bloomers worked became larger, both within the workplace and in the region. Forges were concentrated along the rivers that were the most suitable sources of waterpower and were typically 5 miles or more apart. Communications in the region were sufficiently good for the accomplishments at any one forge to be known promptly at the others, but each forge still had to depend on the expertise of its own staff and could not easily call in specialist help to resolve operating problems that might arise. Individual bloomers and hammermen could achieve reputations for their skill (or ineptitude) among their peers, and improved methods of working discovered by one bloomer were soon widely known. Conditions were thus favorable for technological improvement through incremental learning and the adoption of the many "little kinks and devices" that are a key component of attaining maturity in manufacturing technology.[22]

[21]Richard S. Allen, *Separation and Inspiration, Concerning the First Industrial Application of Electricity in America in the Crown Point Iron Works,* Penfield Foundation, Historical Publication no. 1 (Crown Point, N.Y., 1967).

[22]Patrick M. Malone, "Little Kinks and Devices at Springfield Armory," *IA: The Journal of the Society for Industrial Archeology* 14, no. 1 (1988): 59–76.

The Adirondack ironmaking communities were small villages, gritty with ore and charcoal dust, striving to make a product for a national market that was subject to large fluctuations in demand.[23] Smelters worked twelve-hour days five-and-a-half days a week when business was brisk. Communities and workplaces were businesslike but were placed in rural settings. Some were company towns in which workers were paid in scrip rather than cash. Most could offer little alternative work at a comparable level of technological sophistication when the iron trade was slack. The residents of some of them, such as Ausable Forks, turned to papermaking after the demise of bloomery smelting, but others were abandoned and are difficult even to locate today.

The work of bloom smelting was carried out by skilled artisans who specialized in particular tasks but worked in groups where participation in other tasks was frequently needed. There was a spirit of competition between these groups that led to occasional bursts of high production for display of prowess. The bloomer worked independently while smelting but at times depended on the help of others. The work involved elements of independence, creativity, and cooperation that were not circumscribed by rigid job descriptions and are not easily described in terms of a division of responsibilities and privileges between "managers" and "workers," even though the largest forges had upward of 900 employees. Technical information was freely exchanged among the participants, and they continued to experiment until they achieved the maximum industrial efficiency possible with the basic smelting technique and the natural resources available. They applied the results of scientific research where this was found useful. In these ways, the Adirondack bloomery smelters reflected 19th-century American beliefs about the use of natural and intellectual resources and of labor in industry.

Bloom Smelting in Kasungu, Malawi

At the same time that the thud of the helve hammer was heard in the green valleys of the Adirondacks, bloomery iron smelting was in progress half a world away in the vast, dusty woodlands of eastern Africa. Bloomery smelting technology was first brought to this region in the second or third century A.D. and persisted until the first quarter of the 20th, when competition from cheap European manufactures drove indigenous iron smelting to extinction. In the Kasungu District of central Malawi, bloom smelting was abandoned about 1930. The

[23]The competition came from alternative materials rather than from other Adirondack forges. High-quality bar iron could be purchased from Sweden and Norway, while late in the 19th century, the electric furnace gradually supplanted the crucible steel process and made it possible to use cheaper starting materials than bloomery iron.

technology and social organization of iron production at Kasungu have recently been reconstructed through interviews with former ironworkers, archaeological excavation of smelting sites, archival research, and laboratory analyses of material remains.[24]

Both the physical and the cultural environments at Kasungu were markedly different from those of the bloom smelts in the Adirondacks. The Kasungu region has been tectonically stable since the Miocene and, consequently, has been eroded down to a nearly flat plain. The drainage lines have become choked with sediment, and rivers now flow only in the four months of the annual rainy season. The bedrock lies deep beneath a mantle of infertile sand, on which grows the characteristic *Brachystegia* savannah woodland of central and southeastern Africa. The lack of relief in this landscape ruled out irrigation agriculture, so the inhabitants were dependent on rainfall for the cultivation of their staple finger millet (*Eleusine coracana* Stapf.), the cereal of last resort in poor soils.

Adequate yields of millet were obtained by an ingenious system of ash-bed swidden agriculture that exploited the ability of deep-rooted trees to draw mineral nutrients up from the water table below the leached sands. Trees were felled or pollarded over an area ten to twenty times the size of that to be sown. The wood was then carried to the garden site, stacked, and burned to form an ash bed. Sorghum and millets were grown on this for three or four years before weed infestation and declining yields dictated the abandonment of the plot to a fallow of twenty to forty years. The sustainable carrying capacity of these lands under this system of agriculture was a mere five persons per square mile.[25]

Iron axes were required to fell trees, which in this biome are almost all hardwoods. Iron hoe blades were also needed to till the heavy black clays of the choked river valleys, in which beans, maize, manioc, and a wide variety of minor crops were grown once the annual flood waters subsided. Iron tools were used for many other tasks, including spear- and arrowheads for hunting and warfare; adzes and drills for woodworking; needles and bodkins for leatherworking and basketry; and hammers, tongs, and chisels for the forge; as well as in knives, razors, fishhooks, and small items of jewelry. Iron was not used to any significant extent in transportation or construction.

Although the range of items made of iron was large, the amount of iron required was modest, as the largest items on this list (hoe blades

[24]Killick (n. 7 above).

[25]The classic study of this system of agriculture is William Allan, *The African Husbandman* (London, 1965).

and hammers) weighed at most 6 pounds. The annual consumption of iron per capita at Kasungu in the first quarter of this century cannot be accurately estimated, but probably did not exceed 2 pounds. This level of demand could easily be satisfied by the seasonal production of part-time ironworkers. Iron was smelted in the dry weather between the end of the harvest in July and the onset of the rains in December. Blacksmithing was done on demand throughout the year.

The Kasungu District contains nothing that an economic geologist would classify as an iron ore, but low-grade deposits of iron oxide lie underfoot almost anywhere in the region in the form of laterite. Laterites are subsoil horizons enriched in iron oxide and are found in many tropical regions that have low relief, high rainfall, and a long dry season. Most laterites in the Kasungu region contain too little iron oxide to be usefully smelted, but deposits of higher grade are found in the former river valleys. Since these valleys were also the only sources of water in the dry season, smelting furnaces were invariably built along their margins.

The design and dimensions of the bloomeries were very variable indeed, but all were shaft furnaces with six or more tuyeres and were fitted with an opening for drawing off slag. The most common design had a shaft 8–10 feet tall, divided internally into upper and lower chambers (fig. 3). The shaft was a monolithic clay construction made of puddled earth mined from the huge termite mounds that stud the valley margins.[26] Air was supplied at the base through long ceramic tuyeres. Charcoal fuel and laterite ore were charged from the top and the bloom was extracted through a large arched opening at tuyere level that was sealed with rocks and daub during the smelt. A furnace might last a decade or more with occasional replastering of the interior of the shaft.

The tall furnaces were operated by natural draft alone, no bellows or other blowing apparatus being used. Iron smelting by natural draft was a technology almost entirely confined to Africa in historic times; the only recorded exception was noted in Burma in the mid-19th century. Tall, natural-draft furnaces were more common than the forced-draft furnaces (i.e., those blown by bellows) in the dry savannah woodlands of Africa. On other African biomes, such as the grasslands, the equatorial rainforest, and the deserts, the balance was

[26]Termite soils were often used for refractory ceramics in Africa. For a comparative study of the performance of these and other refractories, see S. Terry Childs, "Clays to Artifacts: Resource Selection in African Early Iron Age Iron-making Technologies," in *Pottery Technology: Ideas and Approaches*, ed. G. Bronitsky (Boulder, Colo., 1989), pp. 139–64.

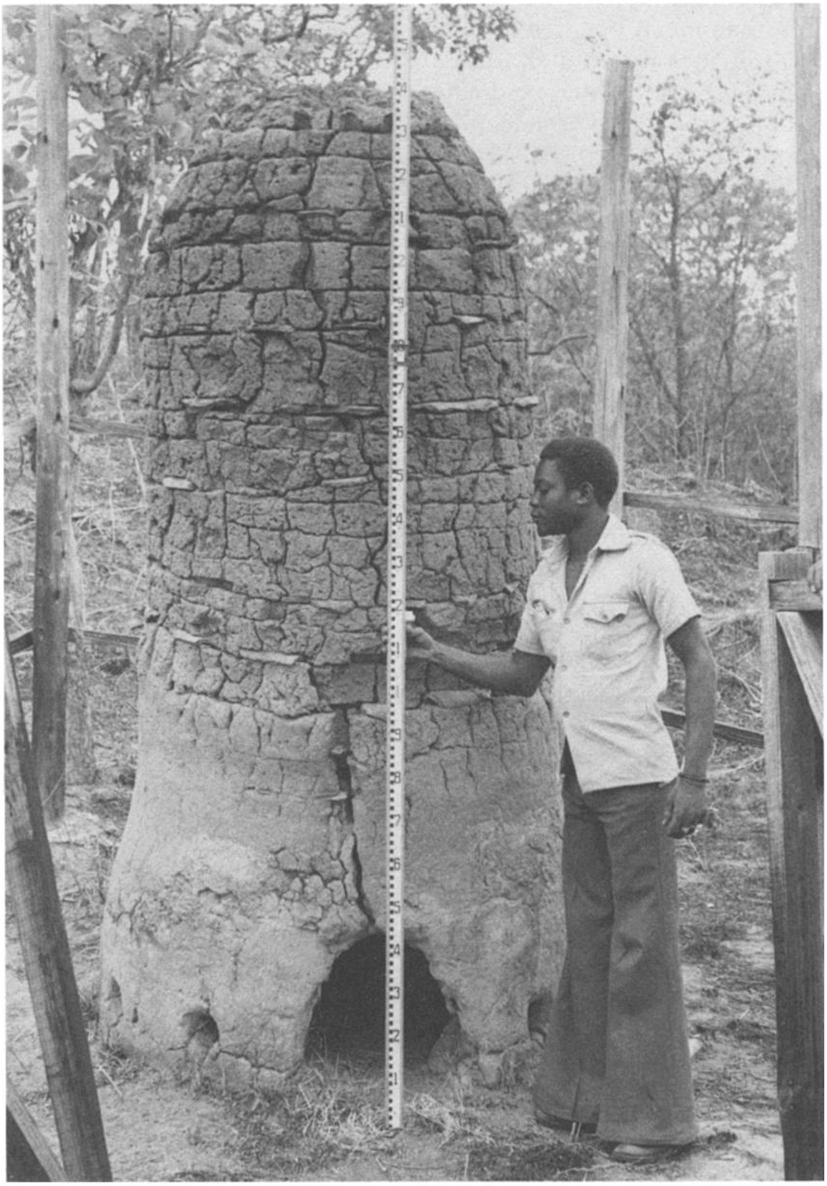

FIG. 3.—Bloomery furnace near Kasungu, Malawi. The stack is made of baked clay taken from termite mounds and is sufficiently high to permit the furnace to attain smelting temperature by natural draft rather than with an air blast provided by pumping bellows. The small holes around the base are for the insertion of tuyeres; the bloom was removed through the large opening when smelting was finished. The flat plates inserted in the upper part of the furnace are broken pieces of old tuyeres.

reversed, with forced-draft furnaces being much more numerous than those blown by natural draft.[27] The rate at which air is drawn into natural-draft furnaces is necessarily much lower than that obtained from forced draft.[28] Since the productivity of bloomery furnaces is proportional, within certain limits, to the rate at which air is supplied, it takes much longer to produce a bloom of given size in natural-draft than in forced-draft furnaces, even when the latter are manually blown. At Kasungu the large natural-draft furnaces took four or five days to produce a bloom of 45–70 pounds. This quantity of bloom could be produced in less than half the time in a manually blown bloomery furnace of similar size.

Much of the heat produced by combustion in a smelting furnace is uselessly dissipated by radiation and convection from the stack. Since these losses are proportional to time (stack temperature being much the same in forced- and natural-draft furnaces of similar size), one might expect that natural-draft furnaces would be relatively wasteful of fuel. This was confirmed in a demonstration of the smelting process by former ironworkers at Kasungu in 1982. A natural-draft furnace of similar dimensions to that illustrated in figure 3 consumed 3,200 pounds of charcoal in 114 hours (twenty-four of which were for preheating the furnace) to reduce a charge of 165 pounds of laterite ore. The fuel-to-ore ratio of 19.4 is the highest recorded for a bloomery furnace. Hand-blown forced-draft bloomeries can be operated successfully with ratios as low as 1:1, though ratios around 5:1 were probably more common.[29] (In the American bloomery, the ratio was 1.3:1.)

[27]On the distribution of the various types of furnaces in Africa, see Walter Cline, *Mining and Metallurgy in Negro Africa* (Menasha, Wisc., 1937); and D. J. Killick, "A Little-Known Extractive Process: Iron Smelting in Natural Draft Furnaces," *JOM: Journal of the Minerals, Metals, and Materials Society* 43, no. 4 (1991): 62–64. The Burmese exception was described by Percy, pp. 270–73. The natural-draft furnaces employed in Kasungu appear to be representative examples of a widely used African furnace type. This particular region was chosen for study because David Killick, N. J. van der Merwe, and D. H. Avery knew that some of the former ironworkers of the region were still alive. This afforded an opportunity to obtain oral testimony about the smelting process and its social context and also to induce the former ironworkers to reenact the processes of building a furnace and smelting iron.

[28]For technical background, see J. F. Rehder, "Natural Draft Furnaces," *Archeomaterials* 2 (1987): 47–58, and "Pressure Drop in Air Flow through Beds of Charcoal," ibid. 4 (1989): 106–9.

[29]The figures for charcoal consumption at Kasungu are from van der Merwe and Avery (n. 10 above), p. 155. Comparative data are from Tylecote, Austin, and Wraith (n. 5 above), and Rostoker and Bronson (n. 3 above), table 14.3a. This table presents the data as kilograms of charcoal per 100 kilograms of iron produced; the highest consumption cited is 1,727 kilograms. If a potential yield of 30 kilograms is assumed for

The actual mechanism of the smelting process can be reconstructed by laboratory studies of material residues of the process. Samples taken from ore piles on former furnace sites contain only 20–30 percent iron, which poses an interesting problem. The generally accepted models of the bloomery process suppose that all the silicate and aluminosilicate gangue minerals in the ore react with a portion of the iron oxide in the ore to form liquid slag that will drain away from the solid metal bloom. Since bloomery slags contain about 55 percent iron, it follows that the ore should contain at least this much iron if any metal is to be obtained.[30] How did the Kasungu ironworkers manage to produce iron blooms from ores containing only half this amount?

The answer was provided by close examination of slag piles in the field and by petrographic study of thin sections of samples taken from these. This showed that the condition of thermodynamic equilibrium usually assumed in analyses of the bloomery process was not achieved in the Kasungu bloomeries. Many of the large quartz grains in the ore had not been consumed; the iron oxide with which they should in theory have reacted was thereby made available for reduction to metallic iron.[31] This means that the ore was effectively of much higher grade than is implied by its bulk chemical composition.

Former ironworkers at Kasungu do not explain the process in these terms, but they are very clearly aware of the influence of the grain size of the gangue on the outcome of the smelt. When asked to select the best iron ores from a range of hand specimens of laterite, they invariably picked out samples in which visible nodules of iron oxide are interspersed with large quartz grains and rejected specimens in which the iron oxide and gangue minerals are too fine-grained to be resolved by the unaided eye. The fine-grained specimens would probably not yield any metallic iron when smelted, as the reaction between the gangue and the iron oxide would proceed to completion. This would consume all the available iron oxide, so the smelt would produce slag but no metal.

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the Kasungu furnace, the charcoal consumption would be 10,700 kilograms per 100 kilograms of iron.

[30]A recent statement of this position is Rostoker and Bronson, p. 92.

[31]This is a good illustration of the pitfalls that may be encountered when the standard concepts and techniques of modern industry are applied unthinkingly to the products of preindustrial technologies. The latter are usually much less homogeneous than modern materials, as reactions have rarely proceeded to completion. Methods that assume the attainment of equilibrium, such as the use of phase diagrams to infer the melting point of slags from their bulk chemical composition, will produce entirely erroneous results in cases where equilibrium is not achieved.

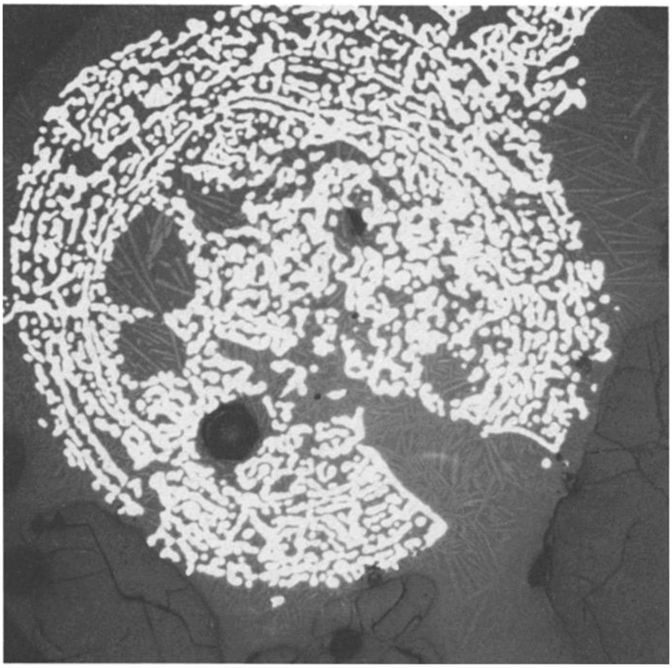

FIG. 4—A nodule of iron mineral from lateritic soil reduced to sponge iron in a shaft bloomery in the Kasungu District of Malawi. This particle of sponge iron had reached a sufficient depth in the furnace to be surrounded by liquid slag that has subsequently solidified (light gray with bright needles). The slag contains grains of unreacted gangue minerals (dark grains containing cracks). The success of the Malawi bloomery depended on incomplete reaction of the gangue with the iron mineral in the furnace; had this reaction been allowed to go to completion, no iron would have been produced from the low-grade ores that were the only source of iron in this region.

Laterite ores are very permeable and could therefore be smelted without the elaborate pretreatment required for dense ores like the magnetites of the Adirondacks. The mechanism of the process at Kasungu was simple solid-state reduction, in which the iron oxide nodules were fully reduced to concentric shells of metallic iron (fig. 4) below the free-running temperature of the slags. As the burden in the furnace dropped into the hotter zones near the tuyeres, the slag liquified and drained to the base of the furnace, from which it was tapped. The iron shells welded together on contact to form a bloom. To this point the metal was carbon-free, but the long time spent in contact with hot charcoal in the base of the furnace enabled the bloom to pick up carbon by solid-state diffusion.

Some of the bloom samples recovered are eutectoid steel (i.e., they contain 0.8 percent carbon).

Subsequent stages of the process appear to have been very variable. Some smelters said they obtained compact blooms in the furnace. While it was impossible to obtain accurate data on yields, by extrapolation from portions of blooms seen in the field the maximum yield appears to have been 70–80 pounds. Others had not been able to form coherent blooms in the primary smelting furnace and used a secondary, bellows-driven furnace to consolidate the many small scraps of bloom from the smelting furnace into a single compact mass. The blooms were reheated in a low, bellows-driven furnace and forged into billets with heavy, two-handed hammerstones. The billets were later cut up and worked into tools at the forge, which was usually no more than a fire pit excavated in the soil and shaded by an open-sided thatched roof. The smith worked in a seated or squatting position, using an assortment of suitably shaped rocks as anvils.

Iron tools excavated from 19th-century village sites in this region display excellent symmetry and great delicacy of line, both of which are evidence of a high level of manual dexterity on the part of the smiths who made them. From a metallurgical perspective, however, they are of mediocre quality. The carbon content is very variable within individual artifacts and many contain excessive amounts of entrapped slag. It is clear that no attempt was made to homogenize the metal before forging it to its final shape. None of the cutting edges had been improved by welding on a steel bit, and only two of the fifteen edges examined had been hardened by quenching.[32] Although these tools were adequate for their designated tasks, they were not as hard or as durable as they might have been. They would therefore have required more frequent repair or replacement than properly homogenized and hardened tools.

The inhabitants of central Malawi saw the smelting process in a very different light from their counterparts in the Adirondacks. Although former ironworkers at Kasungu clearly recognize the importance of proper furnace design and the correct choice of materials, these were not thought sufficient to ensure success in iron smelting. Success or failure was more often believed to be determined by two other factors, both of which lie in the ideological rather than the material realm.

[32]One of the most curious features of the history of metallurgy in Africa is the scarcity of evidence for the intentional heat treatment (quenching and tempering) of steel. This was certainly not for lack of hardenable steel, since African metallurgists appear to have routinely produced high-carbon steel directly in the bloomery furnace since the early first millennium A.D.

These beliefs had a profound effect on the organization of iron production.

The first factor was the role of the spirits of ancestors (*mizimu*). In this society the *mizimu* were very much a part of everyday life, and their approval was thought essential to the success of most productive ventures, including agriculture, hunting, and trading expeditions. Their shrines are still tended today in most rural hamlets in the Kasungu District. Before each smelt the master smelter (and owner of the furnace) would place offerings of food and beer in his shrine while calling on the *mizimu* to support the work of their descendants.

Once the smelt was under way, great care was taken to avoid offending the *mizimu,* lest they should withdraw their support and thereby cause the smelt to fail. For this reason the furnaces were built at some distance from the villages and the smelting crew sequestered there for the duration of the smelt. This enabled the master smelter to monitor their behavior. The most onerous constraint on the crew was an absolute ban on sexual intercourse for the duration of the smelt. A second restriction that was rigidly enforced was that no woman between the ages of menarche and menopause was allowed to approach the furnace enclosure.

Why should menstruation or sexual intercourse be thought to endanger an iron-smelting operation? Menstrual blood is regarded in this society as polluting and defiling and thus as a potential affront to the *mizimu*. Any woman with the potential to menstruate was therefore kept away from the furnace, but prepubescent girls and barren or postmenopausal women might approach it. Sexual intercourse in this society is thought under certain well-defined circumstances to bring misfortune on those engaging in it, on innocent third parties, or on any economic or ritual enterprise in which they might be engaged. Sexual abstinence was required during many important economic and ritual activities, of which iron smelting was one. This constraint applied to both the participant and his wife or wives; the anthropologist Max Marwick noted that, "Should the husband be engaged in any hazardous enterprise, such as hunting, distilling *kacaso,* smelting iron, or, in modern times, mining, his wife must refrain from adultery lest she ruin the enterprise and endanger him."[33] The seclusion of the ironworkers for a period of up to two months was a means of ensuring their celibacy and thereby keeping the *mizimu* in a cooperative frame of mind. Their wives could not, however, be quarantined during this period, as they had to maintain the household while their spouses were absent. When

[33]Max Marwick, *Sorcery in Its Social Setting: A Study of the Northern Rhodesian Cewa* (Manchester, 1965) p. 67. *Kacaso* is a potent spirit distilled from fermented sugarcane.

the smelting process failed inexplicably, as it did from time to time, accusations of infidelity would often be directed at the wives.[34]

The second reason why iron smelting was believed to fail without apparent material cause was through malicious acts of sorcery. In this society every misfortune was thought to have a definite social cause, so sorcery was often invoked to explain incidents that even perfectly secular Westerners tend to call acts of God. Sorcerers were credited with the power to inflict illness, death, or financial ruin on their victims; to make crops uproot themselves in the fields; or to cause a smelting operation to abort. In precolonial times anyone accused of sorcery might be forced to imbibe an infusion of the bark of the ordeal tree (*Erythrophleum suaveolens*), which contains toxic alkaloids. If the accused immediately vomited up the liquid their innocence was demonstrated; if they did not they stood convicted and might be put to death if the poison did not itself kill them.[35]

Sorcery was therefore an extremely serious matter, and master smelters took elaborate precautions against it by preparing medicines to counteract the spells of the sorcerer. These were made from a variety of plant and animal substances. In the only instance where the composition of the antisorcery medicine was studied in depth, twenty-seven separate items were required; none of these have any conceivable metallurgical function.[36] The composition and the preparation of the medicine were specific to each ironmaster and would be imparted to his apprentices only on payment of a large fee. This was always paid, as it was believed that any attempt to smelt without a proven antisorcery medicine would result in certain failure.

Bloomery smelting at Kasungu was extraordinarily wasteful of fuel, labor, and time when compared to the lean efficiency of the Adiron-

[34] For further details, see Killick, "Technology in Its Social Setting," chap. 4. In many African societies the formation of the bloom in the furnace was explained by analogy to the gestation of a human fetus in the womb. In some cases the furnace was actually built in female form. More commonly the ironworkers became the symbolic husbands of the furnace for the duration of the smelt. Any sexual contact with their actual spouses during this period was therefore tantamount to adultery. Since adultery is a particularly heinous offense in these societies, even symbolic adultery might offend the ancestors and imperil the smelt. A particularly compelling analysis of the symbolism invoked in African iron smelting is given in the videocassette *The Blooms of Banjeli: Technology and Gender in West African Ironmaking,* by Carlyn Saltman, Candice Goucher, and Eugenia Herbert (Somerville, Mass.: Documentary Educational Resources, 1986). See also the film *The Tree of Iron,* by Peter O'Niell, Frank Muhly, and Winnie Lambrecht (Gainesville, Fla.: University of Florida, Center for African Studies, 1988). This metaphor was not explicit in the Kasungu region, though the use of anatomical terms for some parts of the furnace suggests that it was implicit.

[35] Marwick.

[36] van der Merwe and Avery.

dack bloomeries.[37] Since industrial societies tend to equate efficiency with proficiency, bloomeries like those at Kasungu are usually characterized as "primitive" in comparison to an "advanced" process like the one used in the Adirondacks. We do not think that this is a fair judgment, however, for it ignores the environmental, demographic, and social differences between the two situations.

The low productivity of the Kasungu bloomeries does not necessarily imply a lack of proficiency on the part of the furnace masters. In fact, it took a great deal of skill in prospecting, furnace design, and charging practice to produce any iron at all from low-grade ores in natural-draft furnaces, which are inherently difficult to control.[38] Nor is it obvious how they might have improved the productivity of the process with the means at their disposal. The laterite ores are not easily beneficiated by crushing, washing, and roasting since this reduces much of the iron oxide to dust that is washed away with the gangue. Nor would an increase in the size of the furnace have increased productivity since the limiting factor was the rate of air supply. Even had they possessed means for converting rotary motion into reciprocating linear motion, which they did not, the local climate and landforms would have made it impossible to harness waterpower to drive bellows or trip-hammers.

[37]In the 1920s the cash price at Kasungu of an iron hoe imported from Europe or South Africa was about half that of a hoe made from locally smelted bloomery iron; see Killick, "Technology in Its Social Setting," p. 96. This is almost certainly an underestimate of the real cost of local bloomery iron, since the master smelter received substantial labor subsidies from unpaid apprentices and relatives. Van der Merwe and Avery made a detailed record of the labor expended in a reconstruction of iron smelting by natural draft by the Phoka of northern Malawi, and calculate that at the prevailing wage rate ($1.50 per day for smelters, $0.70 for porters), a single hoe would be worth $250, 100 times the current price of an imported hoe. This figure needs qualification. All the cost of building the furnace was set against a single run of the furnace, whereas in traditional practice the furnace would have been used for many smelts. Second, the peculiar location of this furnace required that 14,300 pounds of wet clay be carried 2,000 feet up an escarpment. At Kasungu, by contrast, the furnaces were built within a few yards of the clay source. For both of these reasons the costs calculated for the Phoka experiment greatly overestimate the real costs of traditional iron production.

[38]Two lines of evidence support this assertion. The first is that Western experimentalists (many of whom are experienced industrial metallurgists) have experienced great difficulty in smelting iron by natural draft. See R. F. Tylecote and J. F. Merkel, "Experimental Smelting Techniques: Achievements and Future," in *Furnaces and Smelting Technology in Antiquity*, ed. P. T. Craddock and M. J. Hughes, British Museum Occasional Paper no. 48 (London, 1985), pp. 3–20. The second is the high failure rate noted in recent demonstrations of natural-draft smelting in Africa by former practitioners of this technology. The requisite skills are evidently subtle and are quickly forgotten.

The one way in which they might have increased productivity would have been to use forced-draft rather than natural-draft furnaces. It is therefore germane to ask why the Kasungu ironworkers, like so many others in the savannah woodlands of east, central, and west Africa, chose to smelt iron by natural draft. Two possible reasons occur to us. The first is that with natural draft very little manpower was needed in the smelting process itself, there being no bellows to pump. If sufficient charcoal was made during the lull in the agricultural cycle from June to October, then smelting by natural draft could continue through October and November, when all male labor was fully employed in cutting timber for new swidden gardens. The second is that in a society where the fear of sorcery is endemic, one might, if one were a furnace owner, want to limit the number of casual employees lest they learn the composition of the antisorcery preparation. Such knowledge might be sold to a potential malefactor, who would find ways to nullify it.

But there is no evidence that the inhabitants of Kasungu needed a more efficient iron-smelting technology, given the low level of demand for iron. When the British explorer David Livingstone passed through this area in the mid-19th century, he noted that although iron smelting was a part-time occupation, only every third or fourth hamlet had a smelting furnace. Iron was nevertheless in plentiful supply, and Livingstone was frequently accosted by smiths trying to sell him their surplus stock. There is also evidence from oral history of a thriving trade in ironware from the Kasungu region to the Luangwa valley in present Zambia at this time.[39] Natural-draft smelting was therefore more than adequate for the level of demand. Nor was the prodigious appetite of natural-draft furnaces for charcoal a major consideration in the Kasungu region, where the furnaces were widely dispersed and the supply of charcoal ample.

Conclusion

The differences in the organization of iron production in these two regions stem in large part from their very different social settings. Bloom smelting in the Adirondacks was relentlessly market-driven. Competitive pressures from entrepreneurs using alternative methods of making iron and free exchange of information among the bloomers stimulated rapid technical innovation in this industry in the early decades of the 19th century. The less productive variants of the

[39]D. and C. Livingstone, *Narrative of an Expedition to the Zambezi and Its Tributaries* (London, 1865), pp. 561–62; H. Waller, ed., *The Last Journals of David Livingstone,* 2 vols. (London, 1874), 1:131–51. The oral traditions are discussed in Killick, "Technology in Its Social Setting," chap. 3.

process were quickly weeded out by market forces, so that by the 1860s all forges in the region were employing essentially identical techniques. The most important of these innovations were the shallow water-cooled hearth, preheated blast, and exacting beneficiation of the ore. The Adirondack forges had then reached the limit of innovation; the bloomery process simply could not be made more productive. From then on the Adirondack smelters could only watch helplessly as improvements in iron- and steelmaking steadily eroded the market for the more expensive bloomery iron. The last forge in the region closed in 1900.

In central Africa, by contrast, there were no strong selective pressures to increase the productivity of iron smelting. The existing technology, inefficient though it was, was more than equal to the level of demand. Iron smelting was not market-driven; nor was there the clear-cut separation between economic and spiritual realms that is characteristic of industry in the North Atlantic nations. Iron-smelting technology was embedded in social belief and was thought to be subject to the same supernatural forces that influenced all other economic and social activity.

These beliefs had definite practical consequences. The need to avoid offending the ancestors influenced both the location of smelting furnaces and the composition of the workforce. The general fear of sorcery in this society was also influential. As the master smelter alone knew the composition of the antisorcery medicines, he was the "owner" of the furnace and had undisputed control of all aspects of the smelting process. He received a disproportionate share of the product and was able to extract both labor and a substantial fee from any apprentice who wished to learn the antisorcery medicines. Furthermore, the remarkable variations in furnace design found in the Kasungu District in the early 20th century are taken as evidence that mutual fear of sorcery inhibited lateral communication between smelters and so slowed the diffusion of the best techniques.

Both the Adirondack and the Malawi bloomery industries were sensitive to changes in the economic contexts in which they operated. In New York, the development of electric-furnace steelmaking technology eliminated the need to make high-grade steels by the crucible process and reduced the demand for bloomery iron. In Africa, steel suitable for making hoes became available at low cost from discarded machinery of European origin.

Artifacts are a key part of the interpretation of bloom smelting because this process depends on chemical reactions and physical processes that go on within a furnace where they cannot be seen. Even if the smelting processes could be seen, neither the American nor the

African bloom smelter would have had a vocabulary that could convey their understanding of the process they carried out either to each other or to us. Artifacts from smelting, however, carry a record of the process that can be read in the laboratory with the aid of the physical and chemical principles that govern smelting. But laboratory analysis of the artifacts is only one of a series of equally important steps essential to the interpretation of the material evidence. The laboratory evidence should be used in the light of the associated contexts of resources, geographical setting, and culture. When so examined, it shows that, in the African and American examples studied here, quite different choices were made about the way that smelting was carried out. While these choices were bounded by the physical and chemical constraints, they also reflect adaptation to the local natural resources, economy, and cultural preferences.

In the past, interpretation of African smelting skills has been impeded by the preoccupation of observers with the magic and ritual that accompanied smelting and obscured to Western eyes the physical and chemical processes that were selected to use the particular natural and economic resources available to the ironworkers. In the United States, interpretation had been obscured by the sparse written record and the uncritical acceptance of earlier judgments that American bloomery smelting was a primitive technology and the focus of some historians on the quantity of metal produced rather than its quality. For these reasons, important technological developments made by Africans and by Americans have been overlooked.