Notes

ABBREVIATIONS

The following abbreviations are used in the notes and in the essay on early treatises and bibliography:

JCIW  Journal of the United States Association of Charcoal Iron Workers
JFI  Journal of the Franklin Institute
JHMS  Journal of the Historical Metallurgy Society
JISI  Journal of the Iron and Steel Institute
TAIME  Transactions of the American Institute of Mining Engineers

CHAPTER 1

1. Definitions are given in the glossary.
4. Through the nineteenth century the term steel had a connotation of quality that its makers valued. When a new group of entrepreneurs began making large quantities of low-carbon steel in Bessemer converters in 1866, metallurgists and ironmasters disagreed over the way the term steel should be used in the trade. Gradually, they reconstructed the meaning to include low-carbon as well as high-carbon alloys. Alexander Holley asserted that any iron


10. The Chinese used cast iron extensively well before Europeans did, and the extent to which cast iron technology was transferred to Europe continues to interest archaeometallurgists. See Donald B. Wagner, Iron and Steel in Ancient China (Leiden: E. J. Brill), 1993.

11. On the history of the introduction of the blast furnace in Europe see Tylecote, Early History of Metallurgy in Europe, chap. 9.


23. George Brush’s appointment stipulated that “none of the funds belonging to the Academical Department be used to support this professorship.” Loomis Havermeyer and Samuel W. Dudley, *The Engineering Heritage at Yale 1852–1957* (n.d.), p. 29.


**Chapter 2**


4. Visitors can see traces of ore-boat waterways at the Nassawango furnace site in Maryland.


18. When miners exhausted the rich ores in the mid-twentieth century they turned to the lower grade taconite and had to build separators. Soon environmentalists began to challenge their techniques for disposal of tailings, and the fate of wastes from milling iron ore became an issue for the first time. Robert V. Bartlett, *The Reserve Mining Controversy* (Bloomington: Indiana University Press, 1980).

19. Iron smelters never came close to the theoretical minimum energy needed to make iron. Even a modern smelting works uses 3.8 times the theoretical minimum. Nevertheless, this is the lowest smelting-energy use among the common metals; the ratio is 71 times for copper. P. F. Chapman and F. Roberts, *Metal Resources and Energy* (London: Butterworth's, 1983), p. 114.

20. Additionally, one slave ran the helve hammer, two maintained stockpiles, three hauled wood, and three drove wagons. There were also a shopman, two cooks, a boatman, a houseboy, and four supernumeraries. Lester J. Cappon, “History of the Southern Iron Industry to the Close of the Civil War” (MS, 1928, National Museum of American History, Washington, D.C.), p. 153.


70. Sheppard, Coal by Day, p. 5.


73. A 66-pound tilt hammer with a lift of 0.6 feet making 313 strokes per minute required 20 horsepower; a 154-pound hammer with a lift of 1.5 feet making 224 strokes per minute required 35 horsepower.


CHAPTER 3


5. Mulholland, History, p. 57. Archaeologists have not been able to investigate the site because it is covered with highway fill.


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33. In ideal uniformity, every successive item of a given object was identical to all others and, therefore, interchangeable with them. Manufacturers had better success achieving dimensional uniformity than uniformity of physical properties. R. B. Gordon, “Who Turned the Mechanical Ideal into Mechanical Reality,” *Technology and Culture* 29 (1988): 744–78.


39. J. J. Albright, letter to F. De Camp, 28 February 1839, De Camp Papers, box 1, folder 10, letter 11, Morristown Public Library, New Jersey. I thank Brian Morrell for finding this document.


46. Ransom, *Vanishing Ironworks*, pp. 140–50. The No. 1 furnace
is ruinous; the present owners of No. 2 have sponsored archaeological excavations and preservation of the stack.


50. Only remnants of the Juniata industry can be found today: the ironmaster’s house, a barn, and several worker’s houses survive at John Royer’s Cove Forge. In 1831 Henry S. Spang had 150 hands working at his Mount Etna forge and furnace. Built in 1807, this was the first ironworks in what is now Blair County; a succession of proprietors ran it until 1875. The workers’ boardinghouse, along with other community buildings, survives; however, the furnace is ruinous and the forge gone. Swank, *All Ages*, pp. 204–12; Gray Fitzsimons, ed., *Blair County and Cambria County, Pennsylvania: An Inventory of Industrial Sites* (Washington, D.C.: National Park Service, 1990); Jon D. Inners, “Mount Etna Furnace Plantation, Blair County,” *Pennsylvania Geology* 17 (1986): 2–6. The state restored the stone stack of Greenwood furnace in the 1930s, and today it forms part—along with the surviving buildings of the associated community, mines, and former coal lands—of the Greenwood Furnaces National Historic District, near Huntington. Paul T. Fagler, “Greenwood Furnace, Huntington County, Pa.: The Rise and Fall of the Juniata Iron Industry,” *Canal History and Technology Proceedings* 12 (1993): 163–95.


54. Their district was named for the projecting cliffs on the north side of the Ohio River three miles below Ironton.


57. Rowe, *Scioto County*, p. 77.


64. Frances C. Robb, “Industry in the Potomac River Valley, 1760–1860” (Ph.D. diss., West Virginia University, 1991). Traces of these initiatives survive at Weverton and at Virginius Island, now part of the Harpers Ferry National Historical Park.


68. Smith, Harpers Ferry.
76. Remains of some of these furnaces survive; others have been flooded by the dams of the Tennessee Valley Authority.
77. Bruce, Virginia Iron, p. 132.
81. Swank, All Ages, p. 291.
88. Lewis, Iron and Slaves, p. 191. Archaeologists have yet to study the remains of the early iron industry in the deep South. The stack of a blast furnace that operated until 1865 is preserved at Tannehill Historic State Park in McCalla, Alabama.
89. Kenneth D. LaFayette, Flaming Brands: Fifty Years of Ironmaking in the Upper Peninsula of Michigan (Marquette: Northern Michigan University Press, 1977; reprint, 1990); “The Use of High Tempera-

90. LaFayette, *Flaming Brands*, pp. 84–86. The proprietors abandoned the furnace in 1922 after having consumed the conveniently available wood supply.


## Chapter 4

1. An exception was discovered by David Killick, who found that in the natural-draft bloomeries used in Malawi, chemical equilibrium was not attained, and silica passed through the shaft unreacted. This allowed the African smelters to make iron from laterite soil too lean to be called ore. David Killick, “Technology in Its Social Setting: Bloomery Iron Smelting at Kasungu, Malawi, 1860–1940” (Ph.D. diss., Yale University, 1990).


5. This assumption needs to be checked by archaeological field work.


10. In the German technique, the bloomer charged fine ore at short intervals and stopped only to remove the bloom. T. Sterry Hunt, “On the Manufacture of Iron and Steel by Direct Methods,” in *Reports of Progress from 1866–69* (Ottawa: Geological Survey of Canada, 1870), pp. 269–98, see pp. 273–74. Americans often called any form of bloomery a “Catalan forge.” Properly, Catalan refers to the particular form of bloomery used in southern France and northern Spain. John Percy, *Metallurgy: Iron and Steel* (London: Murray, 1864), pp. 278–315. Fine and coarse ore were charged separately in the Catalan bloomery. It appears not to have been used in America.
14. Bloomers in New Jersey, Alabama, and South Carolina also used hot blast. Proprietors of Catalan forges in Sardinia began using a preheated air blast sometime before 1850 and reduced the consumption of charcoal from 4.4 times the weight of iron made to 2.6 times. The heat exchanger used in Sardinia was distinctly different from that used in America. Percy, *Iron and Steel*, p. 312. Gordon Pollard of the State University of New York at Plattsburgh has recently found evidence of use of hot blast in bloomeries of the Clintonville forge by 1837.

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18. Most of these experimenters worked in Africa, northern Europe, or the Nordic countries. Killick, “Relevance.”


24. Egleston, “American Bloomary.” Egleston, a professor at the Columbia School of Mines, found the American process fully developed on his visit to the Adirondacks in 1879.


34. R. B. Gordon and M. S. Raber, “An Early American Inte-


36. Gordon and Raber, “Early American.” Authors in the *JCIW* describe numerous round-hearth, charcoal-fired furnaces. It is not clear how soon these came into use.


52. This belief was based on an incomplete understanding of the metallurgy of cast iron.


57. This was done, for example, at the Pine Grove furnace in Pennsylvania. John Birkinbine, “Experiments with Coal, Coke, and Anthracite in the Pine Grove Furnace, Pa.,” *TAIME* 8 (1879–80): 168–77.


69. Robbins, *Principio*, p. 45. This issue arose at the Tredegar works in Richmond in 1847, when Joseph Anderson wanted white puddlers to teach their skills to blacks so that he could expand his works using more slave labor.


73. Interviews quoted in Bernard A. Drew and William F. Ed-


76. Robbins, Principio, p. 182.


CHAPTER 5


5. At nineteenth-century southern ironworks, 375 bushels of charcoal were used per ton of iron. Lester J. Cappon, History of the Southern Iron Industry to the Close of the Civil War (MS, 1928, National Museum of American History, Washington, D.C.), pp. 193–94. For charcoal that weighs 16 pounds per bushel, the ratio of weight of fuel to weight of iron is 3.0. At nineteenth-century European forges this ratio ranged between 4.5 and 1.8. Rostoker and Bronson, Pre-Industrial Iron, p. 141.


16. Some scholars have used data on the number of American rolling mills as a measure of the number of puddling works, finding that by 1856, 95 percent of American wrought iron was made by puddling. Peter Temin, Iron and Steel in Nineteenth-Century America: An Economic Inquiry (Cambridge: MIT Press, 1964), p. 100. This may be an overestimate because many mills also rolled charcoal blooms made at finery forges.


19. Rostoker and Bronson, Pre-Industrial Iron, p. 141; Crookes and Röhrig, Practical Treatise, 2:758.


37. The size of a rolling mill is specified by the distance between the centers of the rolls, which is also the approximate diameter of the rolls.


43. In an open-box pass, the grooves in the rolls do not completely enclose the work piece. In a closed-box pass, the rolls mesh together so as to form an enclosed space and force the work to assume the form of this space.


47. U.S. Patent No. 6,279, 3 April 1849.


CHAPTER 6


20. These furnaces are listed in Lesley, *Guide*.


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25. Allen, “Mount Savage.” In 1970 a visitor could see the ruins of 2 blast furnaces and 11 of the 200 or so artisans’ houses. These double houses had stone foundations with frame construction above.


27. Swank, All Ages, p. 231.

28. The name was later changed back to Paradise.


31. O. A. Rothert, History of Muhlenberg County (Louisville, 1913), pp. 220–27. In the early twentieth century the furnace stack and the sandstone enginehouse, three stories high, still stood at Paradise.


34. Camp and Francis, Making, Shaping and Treating, p. 191.


37. “Among the Nail-Makers,” Harper’s New Monthly Magazine 21:122 (1860): 145–64, see p. 157. No author’s name is given, but John R. Chapin is known to have been the writer. See the introduction to the reprint by Robert R. Goller published by the Canal Society of New Jersey in 1994.


44. A high phosphorus content may have made the task of Hasenclever’s finers difficult and may have made their product so hard. If so, his cinder iron would have lacked toughness.

**Chapter 7**

6. Tweedale, *Sheffield Steel*.
J. E. Rehder has shown that a clay cover on the item to be carburized was needed, and it now appears that carburizing was less common than previously thought. J. E. Rehder, “Ancient Carburization of Iron to Steel,” Archaeomaterials 3 (1988): 27–57.


16. John Arnold of the University of Sheffield, after analyzing samples of steel classified by a steelmaker on the basis of visual examination, observed, “The practical rule-of-thumb man had more than held his own against the invading march of the analytical chemist.” John O. Arnold, “The Microchemistry of Cementation,” JIS 54 (1898): 185–94.


21. Swank, All Ages, p. 393; Tweedale, Sheffield Steel, p. 16. Managers at the Collins Company, who started steelmaking in 1863, sent specimens to illustrate their processes to George Brush at Yale between 1866 and 1868. One sample of their cast steel contains only 0.2 percent carbon; a Sheffield melter would say it was impossible to make steel with such a low carbon content in a graphite pot. R. B. Gordon, “The Metallurgical Museum of Yale College and Nineteenth Century Ferrous Metallurgy in New England,” Journal of Metals 34:7 (1982): 26–33.


23. William Butcher, nephew of the proprietor of a Sheffield steelworks, had been brought to the United States to make ingots and steel castings for railway equipment in 1867. Butcher’s business methods led to difficulties, and within a few years the works, renamed the Midvale Steel Works, passed into the hands of others. Charles D. Wredge and R. G. Greenwood, Frederick W. Taylor, the Father of Scientific Management: Myth and Reality (Homewood, Ill.: Business One Irwin, 1991); Alexander L. Holley and L. Smith, “The Midvale Steelworks,” Engineering 23 (1877): 239.

24. For the Collins Company, see Colt, letter to Wood, 3 June 1873, MS 72192, Connecticut Historical Society, Hartford.

25. The late K. C. Barraclough of Sheffield supplied this information.

26. Analysis of a sample of bloomery iron made in New York in 1866 shows that it contains 0.04 percent phosphorus, comparable to “second mark” Swedish iron.


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28. For example, microprobe analysis of iron from the site of the Bellmont Forge, one of the large suppliers to the crucible steel industry in Pittsburgh, revealed zones containing more than 0.5 percent phosphorus. Additionally, iron sulfide is present in the slag inclusions. R. B. Gordon and D. J. Killick, "The Metallurgy of the American Bloomery Process," *Archeomaterials* 6 (1992): 141–67.


34. Nelson, "Comparison."

**CHAPTER 8**


9. Surficial markings on a section of a Cooper Union beam preserved at the Smithsonian Institution indicate it was rolled in a universal mill. The surviving section of Camden and Amboy rail is too deeply rusted to retain evidence of the mill on which it was made.

10. Unlike cast iron, wrought iron had approximately the same strength in tension and compression. Hence, the upper flange of an I-beam (carrying the compressive load) should have been the same size as the lower flange (carrying an equal tensile load).

11. In 1854 William Fairbairn described one-piece wrought iron I-beams as desirable for use in buildings, but not yet rolled. He sug-
gested a riveted-on top flange as a substitute. Wrought iron I-beams had been rolled in France since 1849. Jewett, “First American.”


14. Snell, “Musket Factory,” p. 36. The armory made about 10,000 muskets and rifles in 1819, and 12 pounds of scrap per musket is excessive, so there must have been an accumulated backlog of scrap to rework.


18. Tredegar Contracts, 2 July 1870, Virginia State Library and Archives, Richmond.


26. “Fall of the Pemberton Mill,” JFI69 (1860): 242–50. Francis’s statement is included in this report. Bad casting of structural members was also a problem in Britain. After the collapse of the Tay bridge in 1879, blow holes in its cast columns were found to have been filled with a mixture of beeswax and boot polish. Neil Upton, An Illustrated History of Civil Engineering (London: Heinemann, 1975), p. 115.


CHAPTER 9

5. The original bloomery at Townsend's Sterling Ironworks had been replaced by a blast furnace and forge in 1752, and by 1768 he had a substantial business exporting bar iron to England. James M. Ransom, *Vanishing Ironworks of the Ramapos* (New Brunswick: Rutgers University Press, 1966), pp. 177–84.
6. The army decided to keep the chain at West Point in case it should be needed in another war. Finally, in 1829 Colonel Boford of the ordnance department authorized its sale to the West Point Foundry as scrap. Only a few links were saved. In the 1880s John C. “Westminster” Abbey sold a large number of iron links that he claimed were from the West Point chain. Many were resold by Francis Bannerman, the famous New York dealer in surplus military equipment. A number of these links, actually from naval mooring chain, are still displayed at museums and historical sites. (An example is visible in Figure 4–4.) Diamant, *Chaining*, p. 185. We have as yet no metallurgical study of the iron in the West Point chain.
8. Louis F. Middlebrook, *Salisbury Connecticut Cannon* (Salem, Mass.: Newcomb and Gauss, 1935), pp. 14, 41. Bryant had a boring mill and apparently cast cannon solid. This technique had only been introduced in Britain in 1774, when Wilkinson patented his boring mill.

16. Johnson and Reeves had only a secondary interest in properties such as the relation of yield strength to tensile strength, elongation, reduction in area, and elasticity, which would be of primary interest to materials scientists today.

17. Peter Lagerhjelm[s], *Versuche zur Bistimmung der Dichtheit, Gleichartigkeit, Elasticität, Schmiedbarkeit und Stärke des Gewalzte und Geschmiedeten Stabeisens*, translated by J. W. Pfaff (Nuremberg: Johann Leonard Schrag, 1829). The testing machine is still at the Franklin Institute in Philadelphia.


24. David Kirkaldy, *Results of an Experimental Inquiry into the Ten­sile Strength and Other Properties of Various Kinds of Wrought-iron and Steel* (London: Hamilton, Adams, 1862). William Fairbairn, for example, failed where Johnson and Reeves had succeeded in finding the dependence of the strength of rolled plates on their orientation relative to the rolling direction (p. 19).


31. A close-fitting, hot ring placed over the breech contracted as it cooled, forcing the staves together.

33. The report on the Peacemaker iron by the Franklin Institute committee is printed in Robert Mallet, *On the Physical Conditions Involved in the Construction of Artillery* (London: Longman, 1856), p. 239.

34. Wade found the samples from the Peacemaker stronger than the committee did in its tests. We now know that Wade's specimen design made iron appear stronger and less ductile than it really was. Wade's report, dated 24 February 1844, is reproduced in U.S. Army, Ordnance Department, *Reports of Experiments on the Strength and Other Properties of Metals for Cannon* (Philadelphia: H. C. Baird, 1856).

35. Wade and the committee both found that the strength of the iron used for the cannon increased by 30 percent when hammered in a forge, a good indication that it had high ductility and toughness. The shrunk-on rings applied compressive stress to the welds of the iron bars in the cannon barrel. The welded-on rings used in the Peacemaker did not.

36. According to naval historian Edward L. Beach, an order issued after the explosion on the *Princeton* required all naval gunners to load their pieces with half the standard charge of powder. The order remained in effect early in 1862 when the *Monitor* engaged the *Merrimack*. The *Monitor*’s balls failed to penetrate the *Merrimack*’s armor. With full powder charges in its guns, the *Monitor* would have sunk the *Merrimack* with a few shots. E. L. Beach, *The United States Navy: A 200-Year History* (Boston: Houghton-Mifflin, 1986), p. 292.


40. E. G. Garrison and R. J. Anuszkiewicz, “An Historical and Archaeological Evaluation of the *CSS Georgia*,” *Historical Archaeology* 21 (1987): 74–100. These authors reported elongation; the reduction in area was estimated using the relation between these measures of ductility found in other irons.

41. Holley’s data taken on American chain-cable iron submitted to the U.S. Navy for trial (samples selected by the manufacturers rather than random samples) in 1877 would cluster around points
6–8 if plotted in Figure 9-4. Alexander L. Holley, “The Strength of Wrought Iron as Affected by Its Composition and Its Reduction in Rolling,” TAIIME 6 (1877–78): 101–24.

42. Kirkaldy, Experimental Inquiry.

43. The Lukens rolling mill on the Brandywine River had been rolling boiler plate since 1824 and was managed after 1825 by Rebecca Lukens.


50. Poor specimen design made Wade’s test data on wrought iron less reliable than those obtained earlier by Johnson and Reeves. Like them, Wade did not consider ductility an important property. He evaluated iron only in terms of its tensile strength and consequently found no quantitative test that could replace artisans’ judgments based on the appearance of fracture surfaces.


52. James C. Booth (1810–88) received a bachelor of arts degree from the University of Pennsylvania and studied at the Rensselaer Polytechnic Institute. He taught chemistry in a private laboratory in Philadelphia beginning in 1836, was professor of chemistry at the Franklin Institute 1836–45, and was on the faculty of the University of Pennsylvania 1851–55. He was state geologist for Delaware and a member of the First Pennsylvania Geological Survey. He became melter and refiner at the Philadelphia mint in 1849.

53. Campbell Morfit (1820–97) studied at Columbian College (now George Washington University). He worked at James C. Booth’s private chemical laboratory in Philadelphia and later in a chemical factory in the same city, which he eventually acquired. He became professor of applied chemistry at the University of Maryland in 1854 and left in 1858 to return to industrial work. Morfit made enough money as an entrepreneur to be able to offer an industrial chemistry laboratory to the University of Maryland. The university, uninterested in industrial chemistry, rejected the offer. Morfit went to England in 1861 rather than choose a side in the Civil War.

54. U.S. Army, Ordnance Department, Reports of Experiments, reports of July 1851 and August 1852.
55. For example, Booth and Morfit found that hot-blast iron contained more combined carbon (which we now identify as cementite) and silicon than cold-blast iron. We now explain the higher strength of the cold-blast iron in terms of the effect of blast temperature on the silicon content of the iron and the effect of silicon on graphitization. J. B. Pearse reviewed the Ordnance Department research in 1875. J. B. Pearse, “Iron and Carbon, Mechanically and Chemically Considered.” TAI ME 4 (1875–76): 157–78.

56. Rodman’s report of 30 November 1851 to Colonel Craig shows his command of analysis of internal stresses. U.S. Army, Ordnance Department, Reports of Experiments.


59. Through the nineteenth century engineers needed more reliable iron than artisans could make by their craft methods. Metallurgists devised adequate quality control methods in the early decades of the twentieth century. It would be a mistake to describe these as simply devices to give managers more control over workers.


65. H. M. Howe was obliged to explain the subject as late as 1894. H. M. Howe, “The Crystallization of Iron,” Engineering and Mining Journal 58 (November 1894): 484–85.


71. C. B. Richards, “Experiments on the Strength of Bar-Iron and Boiler Plate,” Transactions of the American Society of Civil Engineers 2 (1874): 339–48. Richards’s data show that a specimen of the form used by Wade is 25 percent stronger than one made with adequate length. The importance of specimen design in measuring the
properties of wrought iron can be explained by twentieth-century research on the plasticity of composite materials. In a material containing voids or inclusions not well bonded to the matrix (like wrought iron), hydrostatic tension developed because of the shape of the specimen reduces ductility. Hydrostatic tension develops because of plastic flow at sharp or re-entrant edges of the specimen. This makes a test bar in the form of a plate (such as those used by Johnson and Reeves) less ductile than a round bar of the same iron.


76. Tredegar Iron Works, Contract Book for 1868 (Virginia State Library and Archives, Richmond).

CHAPTER 10


6. When printed copies were issued by the Patent Office at a later date, the title on the patent drawing was altered to read “Manufacture of Iron & Steel.”

7. McHugh, Holley, p. 125.

8. Cambria had puddling furnaces for making large quantities
of wrought iron to be rolled into rail. Morrell may have wanted run-
out metal made by Kelly's process for the puddling furnaces, but
it is more likely that having heard of Bessemer's announcement,
he was interested in pneumatic steel. If so, he was asking Kelly to
undertake the same development process carried out over three
years by the numerous chemists and engineers who got the pneu-
matic process working in Sheffield for Bessemer.

9. Bessemer completed his initial experiments with the pneu-
matic converter in August 1856 and began selling rights to his
process. All the buyers found they could not make sound steel
by following Bessemer's specification. Professional metallurgists in
Britain helped Bessemer by finding that he had, by chance, used
low-phosphorus pig in his initial experiments. The pneumatic pro-
cess, unlike puddling, did not remove phosphorus, and most British
pig had a high phosphorus content. Bessemer eventually found a
source of low-phosphorus pig in northwestern England. His sec-
ond problem was overoxidation of the steel at the end of the blow.
Mushet solved this problem by showing that the steel could be de-
oxidized with spiegeleisen. Bessemer used Mushet's discovery after
the patent lapsed in 1859. His third difficulty was low temperature
at the end of the blow, resulting in poor separation of the metal
and slag. Göransson solved this by enlarging the tuyere openings
in the converter (contrary to Bessemer's advice). Barraclough, Steel-
making: 1850–1900, chap. 3.


11. The converter is now at the Smithsonian Institution. Exami-
nation of the residues in it show that steel was not made with it. R. B.
769–79.

12. Kelly's reference to run-out fires in his letter to Swank makes
it clear that by finery (in his description of Union Forge) he meant
refinery fires. There are discrepancies about dates in this letter that
suggest it was written from memory, without notes. For example,
Kelly says that he suspended his experiments in 1847 to give full
attention to building the Suwanee blast furnace that is reported by
Lesley to have been completed in 1846. Swank, All Ages, p. 397.

13. The Kellys used charcoal fuel in their Suwanee blast furnace
and therefore would have made pig with a lower silicon content
than that from the coke or anthracite furnaces used at the larger
ironworks. When the Swedes developed the Bessemer process for
converting charcoal-smelted pig, they found that the lack of silicon
made the metal "blow cold" in the converter: not enough heat was
released by oxidation of silicon to keep the charge fluid. Swedish
steelmakers solved this problem by blending the ores they smelted
to get pig with a sufficiently high manganese content to make up
for the deficiency in silicon. Barraclough, Steelmaking: 1850–1900,
p. 100. Kelly would certainly have encountered the same problem
had he attempted to make steel at Eddyville.

14. For the social reconstruction of patents, see C. C. Cooper,


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20. It remains unclear if others had successfully transferred steel puddling to America. A reporter’s account of his visit to Corning, Winslow, and Company in Troy, New York, could be interpreted as a description of steel puddling. Scientific American, 7 September 1861, p. 149. The Burgess Steel and Iron Company of Portsmouth, Ohio, appears to have operated a version of the process in the 1870s. F. H. Rowe, History of the Iron and Steel Industry in Scioto County, Ohio (Columbus: Ohio State Archaeological and Historical Society, 1938), pp. 32–34.
22. In the basic open hearth process, phosphorus was eliminated before carbon; in the basic Bessemer (Thomas-Gilchrist) process it was removed after carbon in the afterblow. Pig iron with more than 2 percent phosphorus was needed to maintain the temperature of the melt in the basic Bessemer converter. Basic open hearth furnaces could operate on the lower phosphorus pig that was abundant in United States, and Americans did not make much use of the basic Bessemer process. Barraclough, Steelmaking: 1850–1900, chap. 7.
24. McHugh, Holley, p. 195. The remains of this furnace still stand, unmarked, a few miles west of Ironville, New York.


30. For iron and steel production and price data, see Swank, *All Ages*, pp. 440, 514.

**CHAPTER 11**


5. Parks Canada metallurgists found that artifacts made about 1760 were heterogeneous, with carbon contents ranging up to 0.7 percent and slag inclusions rich in manganese and phosphorus, as would be expected for iron made from bog ore. They interpreted the presence of high concentrations of both MnO and CaO as evidence that the artisans used the indirect process rather than a bloomery. M. Fiset and others, “Objects from the ‘Forges of St. Maurice’: Metallographic and Chemical Study,” *CIM Bulletin* 77:863 (1984): 115–21. Twelve specimens of cast iron from the site analyzed by Unglik included gray, white, and mottled iron with a high phosphorus content. Henry Unglik, “Metallurgical Investigations of Cast Irons from Les Forges du Saint-Maurice Ironworks, Quebec, Canada,” *JHMS* 21 (1987): 1–7.


8. E. N. Hartley, *Ironworks on the Saugus* (Norman: University of

9. For a description of the geography of the Saugus venture, see Gordon and Malone, Texture of Industry, pp. 68–74.


17. Peter Hasenclever, The Remarkable Case of Peter Hasendever (London, 1773; reprint, Ringwood: New Jersey Highlands Historical Society, 1970), pp. 6–7. Members of the New Jersey Highlands Historical Society located the site of the Charlotteburg middle forge, finding the remains of four hearths and two hammers within the perimeter of the forge building along with iron artifacts. Stone-lined raceways along each side of the building carried water to the wheels. According to a 1769 description, the forge had a capacity of 350 tons per year. Edward Lenik, “Excavations at Charlotteburg Middle Forge,” Bulletin of the New Jersey Academy of Science 10:2 (1965); reprint, Bulletin of the Archeological Society of New Jersey (Spring/Summer 1974): 7–10. The New Jersey archaeologists also located the Lower Longwood forge, a bloomery operated from 1796 to sometime before 1880 on the west bank of the Rockaway River about a mile below the outlet of Longwood Lake. Edward Lenik, “The
Rediscovery of Lower Longwood Forge,” *Bulletin of the Archeological Society of New Jersey* 26 (1970): 12–21. We have a good idea of the layout of a nineteenth-century New Jersey bloomery from George Sellmer’s study of Windham forge on the Pequannock River (Figs. 3-11, 4-1). It was built in 1790, rebuilt in 1849, and closed in the 1880s.


26. Tredegar continued to make chilled iron car wheels until, in the twentieth century, railroads required all wheels to be made of steel. The demand for charcoal iron for car wheels enabled several rural Virginia blast furnaces to remain in blast through the 1880s. “Charcoal Iron Industries in South-Western Virginia,” *JCIW* 5 (1884): 100–107. Although coke delivered by the C and O Canal was used at the Potomac furnace on the Potomac River across from Point of Rocks, Maryland, in 1848, no coke-fired furnaces were operated in Virginia after the start of the Civil War. James M. Swank, *History of the Manufacture of Iron in All Ages*, 2nd ed. (Philadelphia: American Iron and Steel Association, 1891), p. 371.


APPENDIX A


3. The phase diagram shows the ranges of temperature and compositions within which the different constituents can exist in equilibrium with one another. Equilibrium may not necessarily be attained in any given sample of iron.

4. To a first approximation, the iron-carbon diagram also describes alloys such as cast iron (which contains silicon, phosphorus, and sulfur) and steels alloyed with small amounts of manganese, nickel, or chromium.

5. Ferrite has a body-centered cubic crystal structure; austenite is face-centered cubic.


APPENDIX B


4. James M. Swank, History of the Manufacture of Iron in All Ages,
