European ironmasters had adopted blast furnace smelting so that they could make cast iron products, such as cannon and hollow ware. If an ironmaker had surplus pig, or if the market for castings were slack and the price of wrought iron high, he would want to convert his pig into bar iron. Charles Pettit, one of the owners of the Batsto furnace in New Jersey, noted in 1781 that “in carrying on the furnace, tho’ we run as much as we can on guns and other castings, pigs will necessarily accumulate, which we must sell at an undervalue if we sell them there [at the furnace] & they will not bear land carriage to market. Thus a double advantage offers by having a forge to work them [the pigs] up on the Spot.”¹ Smiths, who could neither shape nor join scrap pieces of cast iron, could have a finer convert them into bar iron. Some ironmasters touted trade-in value to sell their cast iron products: Connecticut makers of potash pots advised potential customers in 1771 that worn-out pots would have a high scrap value since finers knew the Salisbury cast iron to be particularly well suited for conversion to bar.²

FINING IRON

Seventeenth-century colonists brought the fining process to America. A finer melted pig iron in a small hearth containing a charcoal fire blown with a strong air blast. The air oxidized the carbon and silicon in the pig.³ As did a bloomer, a finer made a loup, a mass of solid iron particles and liquid slag, in the bottom of his hearth. He hammered the loup to consolidate the metal and expel the slag. Artisans could make equally good (or
bad) iron by the direct (bloomery) or indirect (blast furnace and finery) process.

The similarity of bloomery and finery hearths can cause confusion in their identification. Either process might have been carried out at an establishment described as a “forge” on a map or in a document, or the “forge” could have been a smithy. Additionally, an ironmaster could easily convert a bloomery into a finery (or the reverse). An eighteenth-century proprietor might start his works as a bloomery and later, as he gained access to more capital, build a blast furnace and convert his bloomery into a finery, while still calling it a forge. In 1731 a forge cost from £300 to £600 to build, and each hearth required the services of at least two skilled artisans.4

Because metallurgical chemists did not give fining much attention before ironmasters abandoned the process, we lack analytical studies of it. However, the fining reactions would have been similar to those in puddling, which metallurgical chemists did study in the nineteenth century. As the molten drops of pig iron passed in front of the tuyere, the air blast oxidized first the silicon in it and then some of the carbon. The metal solidified and accumulated on the bottom of the hearth in a bath of iron-rich slag that continued to oxidize any remaining carbon. The slag also removed part of the phosphorus in the metal. If the finer used low-sulfur pig, the absence of sulfur in the charcoal fuel assured that the finished metal would contain little sulfur.

THE REFINERY

Ironmasters had to use charcoal fuel in their fineries because the sulfur in mineral coal contaminated the liquid iron. (A smith could use mineral coal in a forge fire because at the temperature needed to soften iron, the metal did not absorb much sulfur.) A finer might burn as much as 2 or 3 pounds of charcoal for every pound of iron he made.5 He used less fuel the less silicon and carbon the pig iron contained. Hence, finers found white iron, with its lower silicon content, cheaper to convert than gray iron. Ironmasters could make white iron in a charcoal-fired blast furnace more easily than in one fired with coal or coke because less silicon entered the metal at the lower temperature attained with charcoal fuel.

Finers who had access to coke could save charcoal by first burning silicon out of their pig in a refinery (also known as a run-out fire) before fining (Fig. 5-1). They placed three or more tuyeres along each side of a long, shallow hearth built on a brick base. Sheet iron doors gave the refiner some protection from the heat, and a brick stack collected the fumes. The refiner (often known as a run-out man) melted pigs in this hearth with a coke fire and a strong air blast. He removed 60 percent of the phosphorus and 80 percent of the silicon into the slag, while his iron picked up a small amount of sulfur from the coke. He drained off the silicon-rich slag. By using the refinery, the forge
manager saved about 10 percent of the charcoal needed for fining and got about 5 percent more fined metal. At some forges, such as Cove Forge in Pennsylvania, the refiner ran the liquid refined metal directly to the finery hearths. (This technique was adopted after the photograph in Figure 3-16 was taken.) However, at most forges he let it solidify for later fining.

As late as the 1880s some forgemasters still found the principle of the refinery obscure. The president of the Charcoal Iron Workers Association asked his colleagues, “Do we understand run-outs? If so, why is their operation vested in certain families,
and the details of their operation magnified and made mysterious?" This specialist group of artisans received higher wages than finers: in 1885 run-out men were paid $3.50 a day, while finers made $2.50, and hammermen, $2.40.\(^8\) This differential may have reflected the particularly unpleasant working conditions around a refinery as well as any special knowledge the refiner may have had.

**WALLOON PROCESS**

Ironmakers called the original form of fining the Walloon process after its place of origin. The Saugus Iron Works National Historical Site has a reproduction of a seventeenth-century Walloon finery forge (Fig. 5-2). The archaeological excavations at Valley Forge, Pennsylvania, show that the eighteenth-century finers there also used the Walloon process.\(^9\)

A finer using the Walloon process passed a long pig through the opening at one side of the hearth with a downward inclination so that its end was in the charcoal fire just above the tuyere, which entered through the adjacent side. He needed a strong air blast to make his charcoal fire hot enough to melt the iron. At Saugus, two water-powered bellows pumped air into the tuyere. The finer melted the end of the pig in the oxidizing flame that formed immediately in front of the tuyere, and lifted the metal that accumulated in the bottom of the hearth into the air blast repeatedly, until he was convinced that all the silicon and carbon were oxidized. He then worked the accumulated metal into a loup, which he lifted from the hearth and took to a nearby helve hammer. With hammer blows he consolidated the iron and expelled as much slag as he could. During the hammering, he reheated the loup from time to time in a separate chafery fire to keep the slag remaining in the iron molten. By 1725 finers typically had water-powered cast iron hammers weighing 500–600 pounds.\(^10\)

In the mid-nineteenth century, ironmasters were building much larger finery forges than those at Saugus and Valley Forge. The finers at the Maramec Iron Works in Missouri worked in a frame building 80 by 45 feet containing eight hearths. Two finers and several helpers made eight heats at each hearth in their work day of twelve to fourteen hours. They used cast iron-lined forge hearths 6 feet long, 2.5 feet wide, and 4 feet high with a 3-inch-thick bottom plate. The finers started with 280 pounds of pig iron to make a 250-pound loup. When they pulled the loup from the hearth, they divided it into two parts. Helvemen consolidated each half-loup in turn under a 3-ton hammer. Next, knobblers working in a separate building hammered the loups into rough bars. Laborers took the bars to a third shop, where chafermen made the finished bars. In the 1830s and 1840s, a Maramec finer received $10 for each ton of iron he made, and paid his apprentice $3.50 from this amount. He could fine about 5 tons of iron per week and was the highest paid nonsupervisory worker.\(^11\)
This reconstruction of a Walloon-type finery hearth at the Saugus Iron Works National Historic Site shows the shallow iron hearth and the single tuyere blown by a pair of bellows. The finer melted the end of the pig inserted through the side of the hearth and oxidized the silicon and carbon in it with the intense flame immediately in front of the tuyere.

Piecework pay created a difficulty for the forge proprietor, however. The quality of bar iron depended on the care taken by the finer, helveman, knobbler, and chafer. The forge manager could test for excess carbon or slag only when the iron was finished, and then not very reliably, by breaking the bars and examining the fractures. Purchasers of Maramec boiler iron in the 1850s began complaining about badly hammered blooms. To control quality, the forge proprietor had each bloom numbered and kept a record of who made it. After he docked the pay of a few hands for making bad iron, customers' complaints diminished.\textsuperscript{12}

**LANCASHIRE (CHARCOAL HEARTH) PROCESS**

Later in the nineteenth century, American finers used the Lancashire process, developed in Sweden by artisans from Britain, to make iron more nearly free of carbon and slag than they could make by the Walloon method. American writers describing its use in the United States called it the "charcoal hearth process."\textsuperscript{13} In 1880 a typical eastern forge, the Seidel brothers' Perry Forge

*Converting Pig Iron to Wrought Iron* 129
Finers used the American Lancashire hearth shown in this drawing to convert pig to wrought iron with charcoal fuel. The hearth (C) was made of cast iron plates (E, F, G). Water circulated through the channels (I), the cast iron roof (K), and the tuyere (D). The finer preheated his pig iron on the shelf (B) and tapped excess slag from the hearth through a hole in the front plate (H). (After H. M. Howe, *The Metallurgy of Steel* [New York: Engineering and Mining Journal, 1904], p. 289)

in Marysville, Pennsylvania, had a six-tuyere refinery, six single-tuyere Lancashire finery hearths, a wood-beam helve hammer, and a steam-powered blower for the hearths. 14

The Lancashire fining hearth, made of water-cooled cast iron plates, stood about 4 feet tall with the top of the charcoal bed about 1 1/2 feet above the floor (Fig. 5-3). The hot gases from the fire flowed through a heat exchanger to preheat the air blast and were then burned under a boiler to recover their remaining thermal energy. Finery forges, like bloomeries, were smoky only when the finer added fresh charcoal to the fire. The finer built up the charcoal fire, made sure a thin coating of slag covered the bottom plate of the hearth so that the iron would not stick to it, and then turned the blast on. Throughout the process, he frequently added charcoal and then threw water on the fire to quench the flame at the top of the charcoal bed. This saved fuel and kept the heat he faced to a tolerable level. The finer placed a supply of broken pig iron on a shelf above and behind the fire to warm up while he worked the hearth. He took 275 pounds of preheated broken pigs off the shelf and placed them in the fire in front of the air blast. As the iron sank with the burning charcoal, he repeatedly lifted it into the hottest part of the fire. The pigs melted in about fifteen minutes. The droplets of molten pig metal fell through the oxidizing zone of the fire, where most of the silicon and phosphorus they contained burned out, and accumulated on the bottom plate of the hearth as a semi-solid
mass. The finer felt around inside the fire with a ringer to search out any unmelted pig.

For the next stage, which lasted about fifteen minutes, the helper joined in the finer’s work. Forcing long bars under the accumulated mass of iron, bearing down, and using the edge of the foreplate as a fulcrum, they lifted the iron a few inches above the bottom plate, cutting into it and forcing in slag as they lifted. They also forced slag into the iron sideways as they pushed it back from the tuyere. This slag (rich in iron oxide) oxidized the remaining silicon, phosphorus, and carbon. The iron stiffened as its melting temperature rose, and the finer and helper had to apply their full strength to lift it. The finer followed the progress of purification by watching the color and viscosity of the slag adhering to his bar as he withdrew it from the fire. A thin, white slag indicated that the iron had “come to nature” (was fully de-carburized), and the third stage of fining could begin.

To start the final stage of the process, the finer and helper broke up the lump of iron into smaller pieces, which they lifted to the top of the fire. This was the first time they saw the metal they had made. They remelted the now purified iron and allowed the droplets to accumulate in the bottom of the hearth undisturbed so as to be as free of included slag as possible. The finer added hammer scale (iron oxide that broke off loups during hammering) as needed to keep the accumulating loup covered with a layer of iron oxide–rich, viscous slag. The slag cover protected the loup from recarburizing by contact with the charcoal. After about fifteen minutes the finer had melted all the iron, and feeling about in the fire with a light bar, he made sure that all the iron was welded onto the loup. He then levered the loup out of the hearth for hammering (Fig. 5-4).15

From about 1720 to 1830, finers made most of the wrought iron produced in North America. Then, as ironmasters adopted puddling for the large-scale production of bar iron, finers concentrated on making charcoal-hearth iron, which they could sell at a premium over puddled iron because of its lower slag content.16 Engineers considered charcoal-hearth iron a tougher material, and they used it in critical applications, such as locomotive axles and steam engine cranks. Finers still worked forges in the eastern states in the twentieth century.17 Like the bloomsmen in the Adirondacks, finers retained a place in American iron-making by producing high-grade iron for customers who would pay premium prices for the particular product they wanted. Like bloomers, finers ran their individual hearths in forges that were generally much smaller than the rolling mills where puddlers worked. The Lucknow Forge, built near Harrisburg, Pennsylvania, in 1882, had six finery hearths and six tenement houses for the artisans; nearby rolling mills employed a thousand or more hands.18

The indirect process of making wrought iron (smelting in a blast furnace followed by fining) wasted less ore but consumed
5-4. This finer at Ramnäs Bruk, Sweden, has just completed a loup in a Lancashire-type hearth. Liquid slag is flowing off the hot metal. He would next take the loup to a steam hammer for shingling. This picture was taken shortly before the closing of the works on 13 May 1964. (Courtesy of the Smithsonian Institution)

more fuel than bloom smelting. The additional fuel used in fining overbalanced the fuel savings achieved with the blast furnace. When European ironmasters adopted fining to get an alternative outlet for their pig iron, they found the cost of finery fuel a burden. The fuel ratio (the weight of charcoal consumed in making a unit weight of bar iron) averaged 3.1 in Europe during the eighteenth century and, in the nineteenth, 2.8 with a range of 2.0–3.0. The data in Table 5-1 show that American forge-masters kept up with developments that improved fuel economy in fining and used fuel at about the same rate as their European counterparts through the first half of the nineteenth century. By the 1870s they were far ahead of their European colleagues. They also made wrought iron with less fuel than ironmasters who used puddling furnaces: the fuel ratio at an up-to-date puddling works in 1877 was at best 1.0.

No single invention or individual made these improvements in fining efficiency. Instead, forgemasters gradually modified their hearth designs and technique. Some ran liquid iron from the blast furnace directly to their finery hearths, thereby avoiding the use of fuel to remelt the metal. Through incremental innovation, Americans advanced the fining process well beyond its development in Europe. To those who measure technological
Table 5-1 Fuel Ratio at American Finery Forges

<table>
<thead>
<tr>
<th>Date</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1746</td>
<td>3.9</td>
</tr>
<tr>
<td>1754</td>
<td>3.4</td>
</tr>
<tr>
<td>1845</td>
<td>2.7</td>
</tr>
<tr>
<td>1877-78</td>
<td>0.7</td>
</tr>
</tbody>
</table>


Note: Calculations are based on charcoal with a unit weight of 16 pounds per bushel.

In making this judgment such individuals miss a component of American industrial productivity that remained essential until the twentieth century, when steelmakers were finally able to offer metal made to rigid specifications.

**Puddling Iron**

Americans always had adequate forest resources for their charcoal iron industry. However, it took a lot of labor to cut and coal wood. Once ironmasters understood how to use mineral coal in place of charcoal for converting pig to bar iron and for smelting, they adopted the new fuel where coal was available at low cost and the demand for their iron sufficient to justify investment in new plant and equipment. When Americans adopted mineral coal to make iron, they made a transition from a widely available, renewable energy resource (wood) that anyone could harvest to a fuel that, though abundant, could be supplied only by specialist workers in mining districts. Coal miners followed a dangerous trade and lived in communities distant from the ironworks. Americans’ substitution of coal for wood brought about changes in the environment and distanced consumers from the environmental and social costs of getting fuel.

Ironmasters could not make wrought iron with mineral coal in either a bloomery or a finery because the fuel, in direct contact with the metal, contaminated it with sulfur. British ironmasters learned how to use coal through fifty years of experimentation. Some used clay pots while others, including Henry Cort, adopted reverberatory furnaces to keep the fuel separated from the iron. Cort succeeded in making good-quality wrought iron with bituminous coal in 1783. People in the iron trade called his technique “puddling,” and after others had developed it into a
reliable method, British ironworks managers adopted it in place of fining.\textsuperscript{21}

In the original form of the process, the puddler melted pig iron on the hearth of the furnace and then used the air that passed through the furnace with the flame from the firebox to oxidize the silicon and carbon in the metal. As the puddler purified the iron, it began to solidify, and he had to exert his full strength to manipulate it. He divided the decarburized metal into several "puddle balls," lumps of solid iron and liquid slag that he pulled from the furnace and hammered or squeezed to consolidate and force out the excess slag, just as bloomers or finers did with their loups. Puddlers sometimes used a refinery to reduce the silicon content of their pig metal and thereby speed the subsequent puddling.

Ironmasters using Cort's process thought at first that they only needed a cheap and heat-resistant hearth bottom, and they made one with sand. As puddlers heated the pig, the iron oxide on its surface reacted with the sand to make iron-rich slag similar to that in a bloomery or a finery. They lost almost half their iron in this slag. In 1818 S. B. Rogers of Nantyglo, Wales, tried an iron oxide bottom in a puddling furnace and found that it greatly reduced the iron loss. At about the same time Joseph Hall of Tipton, Staffordshire, added some of the iron oxide that broke off hot metal in rolling mills (mill scale) to the charge in a puddling furnace. The violence of the ensuing reaction surprised him: he had found that mill scale greatly accelerated oxidation of the silicon and carbon in the molten iron. The mill scale reacted with the sand adhering to the pigs and the silicon in the iron to form a slag that rapidly oxidized the carbon in the molten pig. Because the reaction with the carbon was rapid enough to cause the slag to appear to boil, puddlers called this form of the process pig boiling or, because of the tendency of the slag to flow out of the furnace, wet puddling.\textsuperscript{22} They then described the old process (oxidizing by air) as dry puddling.\textsuperscript{23} Ironmasters who took up the new technique introduced by Rogers and Hall found they could dispense with the refinery because the mill scale quickly removed silicon during puddling.

Pennsylvanians attempted to replace fining with coal-fired puddling as early as 1817. Isaac Meason fitted his rolling mill in Plumstock with a refinery and two puddling furnaces. Meason followed British practice, firing his puddling furnaces with bituminous coal and using coke in his refinery. An English cokemaker who had arrived in the Pittsburgh area in 1813 may have aided him.\textsuperscript{24} Reminiscences recorded fifty years later are our only record of Meason’s experiment. They are silent on his success. Nevertheless, other ironmasters soon acquired the necessary skills: a partnership of four built a rolling mill with puddling furnaces (presumably coal-fired) in Pittsburgh in 1819. By 1826 the city had four mills with puddling furnaces, and ironmasters
were setting up similar works in towns down the Ohio River, such as Covington, Kentucky.\textsuperscript{25}

At first, puddling-works proprietors bought pig iron made in charcoal-fired blast furnaces. Later, they substituted an increasing proportion of metal from coal-fired furnaces and reserved the charcoal pig for special applications where they could sell the product at a premium price. They designated this metal—smelted in blast furnaces with charcoal fuel and converted to wrought iron with mineral coal—“best charcoal iron.” Although some proprietors built integrated works with their own blast furnaces, most bought pig on the open market.

PUDDLING WITH ANTHRACITE

In Virginia and the western parts of Pennsylvania and Maryland, ironmasters had at hand the long-flame, bituminous coal they needed to use British puddling techniques. Outside the area around Richmond, Virginia, ironmasters in the East, where demand for wrought iron was greatest, could not easily get bituminous coal. Some forge proprietors in areas lacking access to coal attempted to reduce their fuel costs by replacing their fireboxes, which were heavy consumers of charcoal, with wood-fired puddling furnaces. Wood worked well because it produced the long flame needed to carry heat from the firebox to the hearth.\textsuperscript{26}

The managers of the Adirondack works tried one at Tahawus in 1846.\textsuperscript{27} As late as 1866 artisans at the Hunt-Canfield forge in Huntsville, Connecticut, fired their puddling furnace with pine and hemlock.\textsuperscript{28}

British ironmasters had sixty years’ experience with bituminous coal by 1820 and had little need to use anthracite. They always fired their reverberatory furnaces with long-flame coal and believed that anthracite could not be used for puddling iron because it burned with a short flame.\textsuperscript{29} Hence, Pennsylvanians could not draw on British experience when they began to adapt puddling furnaces to anthracite fuel.

When blacksmiths had experimented with anthracite in their forge fires late in the eighteenth century, they had found no need to change their basic equipment or technique.\textsuperscript{30} Manufacturers with forge shops gradually adopted this fuel: in 1829 the Collins Company in Connecticut replaced charcoal with anthracite in its axeworks forge fires, even though teamsters had to haul the coal fifteen miles to Collinsville from Hartford, the nearest seaport. Ironmasters, however, discovered that anthracite would not burn well in a firebox designed for bituminous coal or wood, and that a cold air blast extinguished it. Because anthracite burned with a short flame, they found it difficult to distribute the heat from an anthracite fire over a large area, such as a boiler or the roof of a reverberatory furnace. Nevertheless, Walter Johnson could report iron puddling in furnaces fired with anthracite well established in the United States by 1841.\textsuperscript{31}
Table 5-2 Rolling Mills with Anthracite Puddling Furnaces in 1850

<table>
<thead>
<tr>
<th>Date of Construction</th>
<th>Name</th>
<th>Location</th>
<th>Number of Furnaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>1830</td>
<td>Chester</td>
<td>Phoenixville</td>
<td>7</td>
</tr>
<tr>
<td>1830</td>
<td>Conshohocken</td>
<td>Conshohocken</td>
<td>2</td>
</tr>
<tr>
<td>1835</td>
<td>Phoenix</td>
<td>Phoenixville</td>
<td>15</td>
</tr>
<tr>
<td>1836</td>
<td>Reading</td>
<td>Reading</td>
<td>12</td>
</tr>
<tr>
<td>1839</td>
<td>Franklin</td>
<td>Port Clinton</td>
<td>2</td>
</tr>
<tr>
<td>1842</td>
<td>Wyoming</td>
<td>Wilkes-Barre</td>
<td>12</td>
</tr>
<tr>
<td>1844</td>
<td>Lackawanna</td>
<td>Scranton</td>
<td>24</td>
</tr>
<tr>
<td>1845</td>
<td>Bertholets</td>
<td>Reading</td>
<td>4</td>
</tr>
<tr>
<td>1845</td>
<td>Kensington</td>
<td>Philadelphia</td>
<td>10</td>
</tr>
<tr>
<td>1846</td>
<td>Phoenixia</td>
<td>Phoenixville</td>
<td>25</td>
</tr>
<tr>
<td>1846</td>
<td>Montour</td>
<td>Danville</td>
<td>30</td>
</tr>
<tr>
<td>1846</td>
<td>Pottsgrove</td>
<td>Pottstown</td>
<td>3</td>
</tr>
<tr>
<td>1846</td>
<td>Norristown</td>
<td>Norristown</td>
<td>10</td>
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<tr>
<td>1846</td>
<td>Fairmont</td>
<td>Spring Garden</td>
<td>7</td>
</tr>
<tr>
<td>1846</td>
<td>Treaty</td>
<td>Philadelphia</td>
<td>5</td>
</tr>
<tr>
<td>1847</td>
<td>Rough &amp; Ready</td>
<td>Danville</td>
<td>4</td>
</tr>
<tr>
<td>1848</td>
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</tr>
<tr>
<td>1848</td>
<td>Safe Harbor</td>
<td>Safe Harbor</td>
<td>24</td>
</tr>
</tbody>
</table>


Note: Mills using a small amount of anthracite in addition to bituminous coal are not included. Furnaces may have been added after the date of construction of a mill.

Essay on American industry, published in 1854, contains a list of the Pennsylvania rolling mills with anthracite-fired puddling furnaces in 1850, along with the dates they started (Table 5-2). Wilson’s list shows that Pennsylvanians were puddling iron with anthracite in 1830, greatly increased the number of these works in the 1840s, and concentrated them in the lower Schuylkill Valley.

Although nineteenth-century writers eagerly created industrial heroes by attaching the names of individual Americans to innovations made through the cumulative efforts of many artisans, they never managed to do this for iron puddling. We have scant information on the origins of the puddling technique that eastern Pennsylvanians developed. It relied on a new firebox and grate design and the addition of forced draft to British-style puddling furnaces (Fig. 5-5). One of James Swank’s un-
5-5. In the 1820s Pennsylvanians redesigned the English-style puddling furnace so that they could burn anthracite, giving it a larger firebox and a blower to drive the flame over the hearth, as shown here. Blower V forced air through a coal fire burning on grate E. Hot gas from the fire passed under the roof C and out flue D to the furnace stack (not shown), heating the hearth L. The puddler raised the door S to gain access to the hearth. English ironmasters relied on long-flame coal to fire their puddling furnaces. With it, flame licked across the hearth on its way to the stack. Anthracite burned with a short flame and did not adequately heat an ordinary puddling furnace. (From Kerl, Handbuch der metallurgischen Hüttenkunde, 1: pl. XI)

named informants asserted that puddlers used anthracite at Jonah and George Thompson’s Phoenixville rolling mill in 1827 and at Pottsville’s Buckley and Swift mill in 1834.34 Then in 1835 M. Brooke Buckley patented a blower and a new form of firebox for anthracite-fired puddling furnaces.35

In another Pennsylvania innovation, in 1846 the proprietors of the Moore and Hoven rolling mill in Norristown, Pennsylvania, placed boilers over their puddling furnaces to use the waste heat to raise steam (Fig. 5-6). According to Swank, they
were the first in any country to do this, but he was wrong: John Raistrick had initiated this practice, widely adopted by British ironmasters, in 1827.36

Operators of finery forges and puddling works in Europe often replaced their helves with steam hammers (Fig. 5-7) because the hammer driver could control the force of each stroke. He started with light taps and gradually increased the force of the blows to drive slag out of the loup or puddle ball without disintegrating it. American finery forge operators generally preferred their helves; a few puddling-works proprietors adopted steam hammers and the English term *shingling* for the process. In the 1830s managers of American puddling works began to substitute squeezers for hammers in the initial removal of excess slag from the puddle balls (Fig. 5-8). Artisans passed the still hot metal that emerged from the squeezer through a train of rolls for shaping into muck bars. Americans called these rolls, usually two 16-inch or 20-inch stands, the puddle train, muck mill, or puddle mill (Fig. 5-9).37 Millhands cut up the roughly rolled muck bars into short lengths, bundled them into piles, and put them in reheating furnaces. When the metal reached welding heat, they rolled the piles into finished bars. For the best grades of iron, they repeated the piling and rolling several times.
5-7. This shingling hammer at the Ramnäs Bruk in Sweden operated until 1964. Some American ironmasters preferred to consolidate iron from a puddling furnace or finery with a steam hammer rather than a squeezer and rolls. The hammer driver worked the controls at the left while the shingler manipulated the hot metal between blows to expel slag and shape the bar. The driver and shingler had to coordinate their movements precisely. (Courtesy of the Smithsonian Institution)

5-8. In this puddle-ball squeezer rotation of the drum b rolled the metal into the ever decreasing space bounded by the outer ring c until it dropped out at the opening f. After pulling the puddle ball from the furnace, the puddler or helper took it while still white-hot to the squeezer to press out as much of the liquid slag as possible. (From Kerl, Handbuch der metallurgischen Hüttenkunde, 3: pl. VII)
Although puddlers carried out the same basic chemical and physical processes as finers, they worked their metal on a hearth separated from the fuel, where they could always see it. They handled about 600 pounds of iron in a heat, three times as much as a finer. Because puddlers continued to work into the twentieth century, we have descriptions of the technique they used in wet puddling (pig boiling).

A puddler always had a helper, usually a younger man learning the art. Fathers passed their furnaces on to their sons in some American puddling works. In 1885 James J. Davis began learning the technique at age twelve by getting a sixty-year-old puddler who needed an extra hand at his furnace to take him on as a boy. Davis began by doing little chores that saved time for the puddler and helper, such as leveling the fire. Later, he learned the fine points from his father and by the age of sixteen was ready to take on his own furnace.

Standing in front of the working door of his furnace, the puddler had the firing hole, about 10 inches square, to one side and the chain for adjusting the stack damper on the other. His tools rested in a tub of water (the bosh) conveniently at hand. Pigs and coal were piled on the cast iron floor plates in front of the furnace. The puddler's tools, heavy iron bars about 8 feet long, included three or four paddles (bars flattened at the end), two or three rabbles (bars with hooked ends), and two hoe-shaped daubers. Whenever a tool got too hot to handle, the puddler dropped it in the bosh and took up a cool one. He also had a coal shovel and, suspended from a beam overhead, a pair of heavy tongs. One of his most important aids was a hand rag, about the size of a thick washcloth, which he used to grip the rabbles and paddles at the end near the furnace.
controlled the oxidizing power of the furnace atmosphere and the temperature of the hearth by manipulating the damper and the amount of coal on the firebox grate. By lowering the damper he could make a smoky flame and a reducing atmosphere in the furnace.

About once a week the puddler prepared the bottom of the furnace. He charged some crop ends of wrought iron bars and made an oxidizing flame by opening the damper. He might also add some rich ore or roll scale, depending on what he had at hand. This iron oxide iron made an infusible slag that formed a hard, smooth surface on the iron furnace plates; it resisted the attack of the silica-rich puddling slag and retained a smooth surface that inhibited "stacking" of the iron. The puddler applied

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a “fix” composed of a refractory iron ore as free of silica as possible, generally ground and in a plastic state, to the sides of the hearth. He also adjusted the “monkey,” a pile of brick on the firebridge, to direct the heat where he wanted it on the hearth.

To start a heat, the puddler shoveled in about 50 pounds of mill scale. Then his helper placed some 600 pounds of pig iron on top of the mill scale, using broken pigs weighing about 50 pounds each. Charging the furnace took about two minutes. Some puddlers preferred to add all the mill scale (the oxidizing agent) at this time, others added it later. The puddler closed and sealed the furnace door with coal dust and put the upper and lower heat shields in place while the helper built up the fire, keeping the damper open to get a strong draft. (While they worked one heat, the helper shoveled altogether about 500 pounds of coal onto the fire.) After about fifteen minutes the helper turned the pigs over with a paddle; in another fifteen minutes they had melted.

The puddler now had to remove from the molten pig metal as much as possible of the silicon, manganese, and phosphorus. To remove phosphorus, he first had to oxidize the silicon and manganese, but not the carbon. This was called “clearing the iron,” and the process took about ten minutes. The puddler then lowered the damper to keep the temperature low and make the furnace atmosphere less oxidizing, while directing his helper to stir the bath so that all the metal was exposed to the oxide-rich slag. The puddler closely watched the color of the metal for the subtle change from a reddish to a bluish hue, which showed that as much phosphorus as could be removed had been removed.

As soon as the iron was cleared, the puddler brought on the boil. He had to initiate oxidation of the carbon without allowing the phosphorus, now in the slag, to return to the metal. He did this by lowering the damper so as to fill the hearth with a smoky flame. He might also open the door a little and throw in some water. While the helper stirred the bath with a paddle, the puddler added the amount of roll scale he thought necessary through the puddling hole. This lowered the temperature of the bath, making it pasty and hard to stir. After about ten minutes of strenuous stirring, the slag became more fluid as its iron oxide content dropped. Carbon in the metal began to oxidize, and the slag was said to rise to the boil.

As the temperature increased, making the bath of slag and iron more fluid, rapid decarburization took place, giving off large volumes of carbon monoxide. Bubbles of this gas burst through the slag and ignited in a bluish flame, forming “puddler’s candles.” The bath swelled and entered what was known as the high boil. Frothy slag began to run out the puddle hole into a small wagon placed to receive it. The puddler raised the damper a bit to make the furnace gas more oxidizing. In the words of one puddler, he had to keep the iron boiling by building the fire up to “just that certain temperature.” Since the reaction
5-11. This puddler worked at the Youngstown Sheet and Tube Company in Ohio in the 1920s. As the boil ended, less slag drained from the puddling furnace hearth, and with most of the metal solid, the puddler would exert his full strength to shape the 600 pounds of white-hot metal on the hearth into puddle balls. (Courtesy of the Smithsonian Institution)

took place at the interface between the slag and the metal, the bath would soon skim over with solidifying iron if the puddler did not continue vigorous stirring. He also had to prevent any portion of the bath from continuing to rest on the relatively cold furnace bottom. Whenever he saw lumps of solidifying iron appear through the slag, he stirred them under at once so that they would not be oxidized by the flame. As the carbon content dropped, the bath became stiffer and the stirring ever more difficult (Fig. 5-11). Fortunately, this phase lasted only six to eight minutes. Then, with elimination of carbon nearly complete, the boiling subsided and the apparent volume of the slag diminished; the puddler called this the drop. The grains of iron, each enveloped in slag, formed clusters, from which the excess slag drained off to rest tranquilly on the bottom. The puddler said the iron had then come to nature.

The puddler next undertook the turning and balling. He exchanged his rabble for a paddle, adjusted the draft and fire to give a welding heat, and lifting the lumps of iron so that they would not stick to the cold bottom of the hearth, he turned
Here the puddler shown in Figure 5-10 is removing a puddle ball from the furnace. After dividing the metal on the hearth into three balls, the puddler would tell his helper to lift the furnace door. The puddler would then grasp one of the 200-pound balls with long tongs suspended with a chain from an overhead track and swing it, dripping liquid slag, out of the furnace. (Courtesy of the Smithsonian Institution.)

them into one mass. Punching and prying at this, he separated one lump of about 200 pounds, which he shaped into a ball. He pushed this into the firebridge corner of the hearth. Next, he separated the remaining metal into two balls, putting one in the flue bridge corner and the other near the door. He kept them separated because, if they touched, they would weld together. The puddler had to make the balls as near as possible to 200 pounds in weight; he was paid by the pound, and was not paid for any iron in a ball in excess of 200 pounds: that went free to the proprietor. While the helper held the door open, the puddler withdrew the first ball and placed it on a buggy to be trundled to the squeezer (Fig. 5-12). He had spent about ten minutes balling and drawing the iron. After the last ball was out, he repaired any damage to the hearth with fettling and was ready to start the next heat. The puddler had to see that the bottom of the furnace was “just so” and know the proper time to start charging pig again.

In the puddling shop shown in Figure 5-13, helpers placed
The Reading Railroad puddling works in Reading, Pennsylvania, were constructed in 1868. Iron plates were laid on the floor to make smooth paths from each furnace to the squeezer, located in the center of the room. Once the puddler had the puddle ball out of the furnace and drained of its excess slag, he would place it on a buggy for a helper to wheel to the squeezer. Workers had left several buggies near the squeezer when this picture was taken. The forge train can be seen behind the squeezer, and behind that, the mill engine, which was supplied with steam from the boilers placed over the puddling furnaces. (Courtesy of Robert Vogel)

puddle balls on wheeled buggies that they could roll to the squeezer along paths made of iron plates. The squeezer operator (Fig. 5-14) inserted a ball and let the rotation of the inner, serrated drum roll it into the ever diminishing space between the inner and outer rings, thereby pressing out the liquid slag and shaping the metal into a rough cylinder. The compacted metal that dropped out of the squeezer was ready for its first pass through the rolls of the forge train. Here American and British practice differed significantly. British ironmasters seldom used squeezers, preferring to shingle puddle balls under a steam hammer. The shingler manipulated the ball under the hammer with tongs while the hammer driver, working partly by signals from the shingler but mostly from experience, regulated the strength of the hammer blows.

Before ironmasters adopted squeezers or steam hammers, they used helves to consolidate the iron and expel the slag from
puddle balls. Then the puddler had to square up the ball, and as the helper took it to the helveman, a boy carrying a staff with one end heated to welding temperature followed him. The helveman welded the staff to the ball to use as a handle for manipulating the iron under the hammer. He had to use the first few hammer blows to get the ball into a shape that he could then work into a compact block. If he failed, he likely had a row with the puddler.

John Fritz relates that before ironmasters adopted squeezers, the hammerman was the "king bee" in the works and any puddler on bad terms with him was in for trouble. Some ironmasters resisted use of both steam hammers and squeezers, considering them inimical to making good iron. With a crocodile squeezer, a puddler could shape his own ball and could coax bad iron through it. This had been impossible with a helve hammer. In a Burden rotary squeezer, however, a bad ball broke up regardless of who operated the machine. When this happened the puddler picked up the pieces and took them back to his furnace to rework.42

The roller took the elongated, red-hot block (sometimes called a bloom) from the squeezer and inserted it into the roughing-down rolls. Each pass in these rolls was an open-box pair of grooves with their surfaces roughened to make them grab
the inserted bar. The catcher, standing at the back of the mill, picked up the bar with his tongs and returned it over the top of the rolls for the next pass. After running the bar through the passes in the roughing rolls, the roller took it to the adjacent stand of the finishing rolls, containing closed-box passes (Fig. 5-15). After a total of about nine passes through the roughing and finishing rolls, he had reduced the squeezed ball to a bar ¾ inch thick by 2.5–8 inches wide and 15–30 feet long, known as a muck bar. Because more slag squeezed out of the bar in each pass, its surface was rough. The iron cooled on each pass, and eventually the slag in it solidified. The roller could then reheat the bar, provided it was not already too long to fit in a furnace. Usually, artisans cut the muck bars into pieces 2–4 feet long and piled them according to the size of product to be made. Heaters put the piles into furnaces to bring them to white heat and then passed them to rollers to be welded together and rolled into merchant iron (sheet, plates, bars, or shapes). As the rollers thinned the bars, the catchers had to handle great lengths of hot metal on the iron plates that made up the mill floor.

5-15. This roller worked at an Ohio puddling works in the 1920s. After leaving the squeezer (see Fig. 5-14), the squeezed iron was shaped by successive passes of the puddle-train rolls into a thick bar and then into a flattened plate called a muck bar. Additional, still liquid slag was forced out of the iron in each pass through the rolls. Here the roller uses a three-high roll stand to bring the muck bar to its final shape. (Courtesy of the Smithsonian Institution)
5-16. Puddling works contributed to local air pollution, as seen in this photograph of a rolling mill in Coatsville, Pennsylvania, in the 1870s. At this mill, each of the puddling or heating furnace stacks (fitted with dampers) releases a plume of translucent smoke. Plumes of water vapor from the exhaust steam of the noncondensing mill engines trail from pipes through the roof of the shed on the right. Since the steam was generated in waste-heat boilers over the puddling furnaces, the mill owners did not need a separate stack for their engines. (Courtesy of Robert Vogel)

**ENVIRONMENTAL EFFECTS**

Puddlers outside of eastern Pennsylvania burned bituminous coal on their furnace grates. Additionally, all puddlers used a smoky flame at times (particularly in steel puddling). They contributed to local air pollution in proportion to the amount of coal they burned (Fig. 5-16). Neighbors sometimes considered them a nuisance. Peter Cooper built an ironworks in New York City at the corner of Thirty-third Street and Third Avenue, which he later leased to George Peacock and John S. Gustin to operate as a wire factory. They used puddling furnaces and a rolling mill to prepare the wire rods for the draw benches. After the panic of 1837, when Peacock and Gustin could not repay their debt
to Cooper, he took over the works and in July 1838 placed his brother Thomas in charge. Cooper explained, “In the course of a few years the noise and smoke of bituminous coal was found objectionable to some of the neighbors and I bought a place in Trenton with waterpower and removed the rolling mill from Thirty-third Street to the very end of the canal that takes the water from the Delaware River for some miles . . . After enlarging this rolling mill several times, I built a second rolling mill for the purpose of rolling wire rods for the mill in Trenton and also other forms of similar iron.” Cooper called this the Trenton Iron Company, and he had it managed by his son Edward and Abram Hewitt. Cooper’s neighbors in Trenton must have been more tolerant of coal smoke than those in New York City.

Puddlers dumped the slag from their furnaces on the nearest convenient open space. The slag contained nearly as much iron as some ores, and blast furnace proprietors sometimes collected it to add to their furnace charges. One enterprising company in Boonton, New Jersey, ground it up (a difficult task) to make “slag paint.”

**Further Development of Puddling**

Once they had the process working, Americans continued to experiment with the anthracite-fired puddling technique. Thomas Cooper, manager of his brother Peter’s New York City ironworks, got U.S. Patent No. 1,733 on 25 August 1840 for improvements in anthracite-fired puddling furnaces. He insulated the walls of the firebox with ashes, placed a tuyere at the bottom of the firebox to admit air that had been preheated in chambers under the furnace, and added a boiler heated by the stack gases. Because he asserted that preheating the air for the fire was important, and did not claim the technique as original, American ironmasters must have used it before 1840. In another experiment, John S. Gustin, an associate of the Coopers, experimented with tuyeres that directed an air blast onto the molten metal in a puddling furnace to increase the rate of conversion of the iron. He instructed the puddler to bring any solidified iron under the tuyere, where the air blast would remelt it. (This idea was an important precursor for pneumatic steelmaking processes.) Gustin explained that although any kind of fuel might be used in the puddling furnace, he preferred anthracite because it released less ash that might be blown across the firebridge to contaminate the metal. Other ironmasters disagreed with him: Lewis Scofield and Edward Cooper (Peter’s son) reported that the air blast used to burn anthracite forced ash particles onto the hearth, and they patented a furnace design that incorporated an ash trap to counteract this problem.

As they gained experience with puddling, Americans departed from British practice by building double puddling furnaces. They made the hearth larger and put doors for working it on both sides of the furnace. In the 1870s the Vulcan Iron Works
in Missouri had eighteen double puddling furnaces, each holding a charge of 1,050 pounds. Five men worked each furnace, making five heats in eleven hours.48

Puddlers used 3,000–3,200 pounds of coal to make a ton of iron. In western Pennsylvania ironmasters began to use the abundant natural gas resources around Pittsburgh in their puddling furnaces; they obtained better iron with this cleaner fuel. William Siemens showed the advantages of puddling in a furnace fitted with gas producers and regenerative chambers. He could make the flame, which was free of ash and dust, oxidizing or reducing at will while maintaining the necessary temperature. He used only 1,250 pounds of slack coal to make a ton of iron. Some rolling mill managers adopted Siemens’s puddling furnace design; others near Pittsburgh successfully substituted natural gas for coal in their puddling furnaces.49 Most, however, simply continued with their traditional equipment.

The amount of iron any puddler could handle was limited by his strength. Consequently, ironmasters could only increase their output of wrought iron by building more puddling furnaces. Inventors in Europe and America attempted to overcome this production bottleneck by applying mechanical power to the puddler’s work. Some inserted shafts geared to engines through the tops of their furnaces to turn paddles on the hearth. Others devised systems of gears and levers intended to reproduce the movements of the puddler’s rabble. None of these inventions helped with balling the iron, the most exhausting part of the puddler’s work.50

Samuel Danks of the Cincinnati Railway Ironworks devised a more effective mechanical puddler. In 1870 he built a fixed firebox and firebridge that fed flame into a cylinder that could be rotated about a horizontal axis. He fitted a series of wedge-shaped recesses into the cylinder to hold fettling. Danks melted iron in a separate cupola and ran it into the rotating cylinder in the presence of flame from the firebox. Here it reacted with the fettling, and the rotary motion formed the puddle balls. British ironmasters, faced with competition from Bessemer steel, were searching for a way to improve the productivity of their puddling works at this time, and they sent a committee of their Iron and Steel Institute to investigate. Danks’s system impressed them, and by the end of 1872 English ironmasters had some seventy-two Danks furnaces under construction. Over the next twenty years numerous American ironmasters used Danks furnaces.51 However, their British counterparts never made it a success “owing to the abundant supply of skilled labour available at a relatively low price.”52 In America most investors preferred to put their money into steelworks rather than into re-equipping ironworks.

In 1868 the American inventor Francis Ellershausen developed a process intended to make wrought iron without puddling. In addition to reducing labor costs, Ellershausen believed
This illustration shows how Francis Ellershausen's scheme for making wrought iron without puddling was supposed to work. The plan, developed in 1868, involved mixing liquid iron flowing from a blast furnace with pulverized ore drawn from the hopper and allowing the mixture to solidify in the pans placed on the revolving table. The cakes were supposed to form puddle balls when reheated. (From H. S. Osborn, The Metallurgy of Iron and Steel [Philadelphia: Baird, 1869])

he could use low-grade ores to make high-grade iron. He arranged a hopper that would drop pulverized ore into a stream of liquid iron issuing from a blast furnace. The mixture was collected in pans placed on a revolving table (Fig. 5-17). Artisans then placed cakes of the ore-iron mixture in a reverberatory furnace where, Ellershausen asserted, the cakes would transform to puddle balls at a bright yellow heat without rabbling. Ellershausen believed that the ore would oxidize the carbon and form a slag with the silicon in the pig iron in a process that "required absolutely no skill" to carry out. He did not explain how he would ensure accurate proportioning and homogeneous mixing of the iron with the ore or how the slag would separate from the solidifying metal.

In the 1860s William Menelaus, works manager of the Dowlais Iron Co. in Wales, wanted to increase wrought iron production without adding more puddling furnaces. Between 1870 and 1876 he experimented with two American inventions, Danks's puddling machine and the Ellershausen process. Menelaus later sent John Percy an account of the Ellershausen experiments at Dowlais, explaining that "it was such a piece of humbug that it hardly deserves notice from you but perhaps it may be as well to tell the story—if only as an example of American impudence."
The proprietor of the process, Mr. Blair of Pittsburgh, claimed that the iron was puddled more readily and that high-quality bar iron could be made from low-quality pig. Blair ran iron from a blast furnace and a stream of finely ground iron ore onto a revolving table divided by loose plates into cells about 15 inches square and 8 inches deep. According to Menelaus, this made rough blocks of a spongy material with a good deal of dry ore mixed in. Blair threw the blocks into a puddling furnace, where they were to be easily converted to superior iron. Menelaus reported that in the furnace they were difficult to melt and stuck together in a most provoking way, it required more labor to break them up in the Puddling Furnace than the labour saved if indeed there was any saving of labor in the puddling—Mr. Blair managed the whole thing himself, he was most indefatigable, he was ingenious and fruitful in resource but—with all his skill and energy and after many months of trials, he fairly failed to produce good results, in fact it was about as great a failure as Bessemer’s first experiments at Dowlais. 56

It is easy to imagine Blair’s difficulties and disappointment. He tried the process at several other English works, without better success. Evidently, American innovators had something of a reputation in England since Menelaus remarked at the end of his account, “I have troubled you with the particulars of Blair’s doings here because Schemers, especially American Schemers, if they do not succeed in their plans are in the habit of asserting that they have not had fair play—We had a notable instance in Sherman, who, being the biggest Quack who ever tried to impose on the Trade was hard to silence.” The technological difficulties proved equally formidable in America, and the Ellershausen process soon dropped out of sight.

In 1869 the proprietors of the Clifton Works, twenty-five miles from DeKalb Junction, New York, adopted George H. Smith’s patented process for making steel directly from ore without melting. Artisans pulverized high-grade magnetite ore and fed it into a wood-fired reverberatory furnace that Smith had fitted with a retort charged with petroleum or coal tar. In about five hours they reduced a charge of ore to steel sponge with the aid of the hydrocarbon vapors released from the petroleum. The artisans were then instructed to place the sponge in a wood-fired puddling furnace for conversion into a puddle ball of steel. According to H. S. Osborn of Lafayette College, the Clifton artisans, after successfully reducing the ore in the first step, could not keep the metal from decarburizing in the second step. 57

A sample of rail made by Smith’s process is actually wrought iron with steely bands and abundant slag inclusions, confirming Osborn’s report. Although the metal is low in phosphorus and had good ductility, it is not steel and, additionally, splits easily because of the slag it contains.

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American innovators did not match the accomplishments of Bessemer, Siemens, Göransson, Thomas, or the Martins when they attempted novel metallurgical processes that included chemical transformations. Ellershausen, Smith, and others tried to reduce the skilled labor of artisans by speeding up established processes. They did not appreciate that increased speed entailed loss of control and that American artisans had learned to manage complex chemical reactions without formal knowledge of chemistry. The work of these innovators showed how a little knowledge of principles untempered with appreciation of the complexities of metallurgical processes could lead to failure. However, when Americans undertook mechanical or thermal innovations—as in waste heat recovery, the adoption of anthracite, the mechanizing of blast furnaces, and new rolling and forming techniques, they did much better. These processes lent themselves to improvement through experimentation by imaginative artisans.

Chemistry of Puddling

Wet puddling was still an important component of ironmaking when European chemists began to study metallurgical processes. In 1857 Crace Calvert and Richard Johnson of Manchester, and M. Lan of the School of Mines at Saint-Etienne, took samples from puddling furnaces at successive times. They found that the puddler oxidized first the silicon and then the carbon in the molten iron. Additionally, reaction with the iron-rich slag gradually removed phosphorus. A little sulfur entered the slag from the metal toward the end of the process. At this time, most ironmasters believed that the flame in the furnace oxidized the silicon and carbon. Percy showed from Calvert and Johnson's data that iron oxide in the slag was the effective oxidizing agent. Consequently, the flame in the furnace did not need to contain excess oxygen. Siemens confirmed this with additional experiments. Percy had found from the analyses done for Bessemer that air alone would not remove phosphorus from molten iron. He concluded that the slag in the puddling furnace was essential for this too. However, debate about the mechanism of phosphorus removal in puddling continued through the 1890s.

Puddlers strove to control the phosphorus in the metal they made because it hardened iron and reduced its ductility: a sharp blow could shatter iron containing more than 0.5 percent phosphorus. As long as phosphorus content remained under this limit, puddlers could control the strength and ductility of wrought iron by adjusting the amount of phosphorus left in it. They made rail iron with about 0.3 percent phosphorus and tough iron for machinery with as little as 0.03 percent of this element.

In the early twentieth century, Americans investigated the chemical changes in the conversion of pig to puddled iron (Table 5-3). They found the same changes as those observed earlier in England and explained them in terms of the thermo-
Table 5-3 Composition Changes in Iron during Puddling

<table>
<thead>
<tr>
<th></th>
<th>% Carbon</th>
<th>% Silicon</th>
<th>% Manganese</th>
<th>% Phosphorus</th>
<th>% Sulfur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig</td>
<td>3.3</td>
<td>1.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.03</td>
</tr>
<tr>
<td>After clearing</td>
<td>3.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.03</td>
</tr>
<tr>
<td>Finished iron</td>
<td>0.05</td>
<td>0.2</td>
<td>0.06</td>
<td>0.2</td>
<td>0.02</td>
</tr>
</tbody>
</table>


chemistry of the reactions. The stability of the oxides determined the order of removal of elements from the pig iron. Because the oxide of phosphorus was just slightly more stable than the iron oxides, separation of phosphorus from iron was always difficult. The puddler needed slag rich in iron oxide in his furnace to remove phosphorus from the metal. Because oxidation of silicon and manganese released more heat than the oxidation of phosphorus, the puddler had to eliminate them from the iron before he could begin dephosphorization. Then, once he had raised the temperature after the clearing stage and started the boil, phosphorus removal stopped because all the available iron oxide was reacting with carbon. Later in the boil, more iron oxide was available in the slag. However, by then the metal had begun to solidify. The diffusion rate of phosphorus in solid iron is much slower than that of carbon, so although some decarburization continued at this stage, practically no phosphorus was removed. A puddler needed slag with less than 40 percent silica, and preferably less than 30 percent, to remove phosphorus. Some puddling works managers used the refinery to remove part of the silicon from the pig and obtain a more actively oxidizing slag in their puddling furnaces.

The removal of phosphorus depended on the puddler’s skill and the quality of the fettling he used. Ore with a very low phosphorus content or mill scale (which was very pure iron oxide) made the best fettling; scale from the squeezer and muck mill was less pure and was not used for making the best grades of iron. Even with the best materials and practice, the puddler could never completely remove phosphorus from his iron. Additionally, he could remove only a little of the sulfur, except from high-sulfur pig (containing more than 0.06 percent sulfur). An ironmaster controlled the phosphorus and sulfur in the iron he sold by selection of the pig he used and by standardizing puddling practice. Ironmasters and puddlers had to pay close attention to every detail of the puddling process to make wrought iron with consistent properties.