Department of Agricultural & Resource Economics, UCB
CUDARE Working Papers
(University of California, Berkeley)

Year 1977 *Paper* 24

Hard Driving and Efficiency: iron production in 1890

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Working Paper No. 24

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INTRODUCTION

In the 1880's the American technique for making iron diverged from the methods used by the British. This paper examines the divergence and seeks to determine whether it signifies economic inefficiency in the production of iron on the part of either country. It is commonly held that the divergence in technology represented a failure on the part of British entrepreneurs which implied a direct welfare loss in the sense that they were operating inside the relevant production possibilities frontier. The divergence was also part of a larger decline in Britain's industrial power over the latter half of the 19th Century. In this paper it is argued that there was a failure of British entrepreneurs in the iron industry, but this failure was of such a small magnitude in 1890 that correcting it would have provided only a small welfare gain and would not have affected decline.

The failure of the British iron entrepreneurs lay in not adopting the new technique of hard driving which was pioneered by the advanced American producers of pig iron in the 1880's and 1890's. Hard driving is a method of increasing the make (or output) of a furnace by blowing hot air through it at high pressure. Since the furnace make (output) was limited by the availability of air, increasing the air per unit time dramatically increased the furnace make. The way to force more air through a furnace of a given dimension was to increase the air pressure. The Americans drove their furnaces at about 9 pounds per square inch, while the British drove their furnaces at only 5 pounds per square inch. Hard driving enabled Americans to produce half again as much iron as the British with the same size furnace.[1]

The accusation that British entrepreneurs did not adopt new methods, particularly in ferrous metal production and chemicals, is a very old accusation. In the Iron and Steel Institute Journal (ISIJ), there is a long and sometimes acrimonious debate between English and American ironmasters on the subject of hard driving. For instance, Bell, a captain of the British iron industry, went to American in 1874 and again in 1890.[2] On both expeditions he wrote about American practices and criticized hard driving as a cause of excessive wear of furnace linings and the use of large amounts of coke. In 1887 Bell and Richards calculated the make per furnace lining in America and England and "made out that the quantity of iron made in English furnaces at that cost of £1,500 (per lining) would be four or five times as much as that of Chicago furnaces."

Contrast Bell's view with that of Potter of the South Chicago Works of the North Chicago Rolling Mill Company:

> "It has been said of our [U. S.] furnaces that 'they lead a short life, but a merry one.' That is literally true, and up to a certain point I regard it as the truest economy. . . . In the same length of time, with two relinings, the American furnace would have made 450,000 tons or nearly 30% more [than the English furnace] with the same plant, and an additional expense of ten cents per ton on the cost of iron. [After calculating capital costs per ton,] the difference in favor of a 'short and merry life' appears to be $52,500 each blast."[3]

The theme that British ironmasters were slow to adopt new technologies was bandied about in the popular press of that day and received the support of no less a person than Alfred Marshall writing for the House of Commons.[4] Burn revitalized the failure hypothesis, and it was picked up by the new economic historians in their 1970 conference sponsored by the National Science Foundation.[5] From this conference came the volume, Essays on a Mature Economy: Britain After 1840, edited by McCloskey (1971). This volume and the thesis, Economic Maturity and Entrepreneurial Decline, by McCloskey, are modern continuations of the failure debate begun nearly a century ago.[6] These recent contributions are much closer in spirit to the original debaters of 1887 than they are to the intervening economists and historians. The original debaters were concerned entirely with the question of whether neglect of a particular technique--hard driving or the Solvay process--was rational for British entreprenuers. Many of the interveners concentrated their inquiry on macro-parameters, rates of growth, and the like--parameters that cannot separate the effects of poor management for unfortunate location or adverse market structure.[7] The important findings of this new wave of economic historians are that (1) the British acted rationally in agriculture by not adopting mechanized equipment--no failure[8]; (2) neglect of the Solvay process for producing soda was increasingly costly after the late 1880's--failure[9]; and (3) Britain was actually superior to American in the production of iron in 1890--no failure.[10]

McCloskey's conclusion of no failure in the iron industry results from his methodology. Instead of asking the narrowly framed question of the efficacy of American as opposed to British techniques, McCloskey chooses to estimate a point on the production possibilities frontier of both countries from aggregate data and to ignore all factors except coke. Below, it will appear that the primary difference between the two countries was their usage of capital. This seriously flaws McCloskey's argument for British superiority. The use of aggregate data blurs the effects of vintage capital. In 1890 prices in America were high enough to call into use capital equipment of ancient vintage which was not at all efficient. High prices had the effect of producing aggregate data that were the average of the very latest equipment and the most ancient and decrepit equipment. In 1890 prices in Britain were so low that only the most modern plants could cover their variable costs. Low prices had the effect of producing aggregate data that were representative only of the best technique available in Britain. When McCloskey compared the best technique availabe in Britain to the average American technique, it was not surprising that he found the British had an advantage in the production of iron. The details of this argument are relegated to a later section.

This paper is dedicated to answering two questions: (1) Was there a failure of entrepreneurship in the British iron industry? The failure question is answered by showing that the adoption of different production techniques would have increased British profits.[11] (2) Did the failure of entrepreneurship have a serious effect on Britain's decline? The decline question is answered by showing that Britain's market share in the pig iron industry would not have increased appreciably if it had used the best techniques.

The comparison of British and American technique would have been easy if only both sides had been relatively homogeneous in the methods they used. The Americans, in particular, operated blast furnaces under a wide range of conditions--different factor prices, different qualities of ore, and different types of fuel--to name three. The British firms all looked very much alike (at least those represented as being in blast in 1890). The intent is to compare the British performance with the best American performance, that is, to compare hard-driven American firms with modern British firms. Converting a blast furnace of modern design to hard driving required a one-time rearrangement of plant and a not inconsiderable investment. It was possible to convert plants to hard driving by the addition of blowing engines; but this decision was a lumpy, risky one which--it is hypothesized--did not necessarily respond to market forces. The way to test this hypothesis of failure is to estimate conditional cost curves, appropriately adjusted for ore richness and type of fuel, that are further conditioned on the degree to which the plant in question was hard driven. If the market were working and entrepreneurs were making the proper decisions with regard to hard driving, then varying hard driving would not change the costs.[12]

Because of the diversity of data, it is easier to get at the cost curves by estimating the resultant factor demands. The next sections estimate the demands for coke, labor, capital, and ore. These demands are then combined to estimate the costs of changing to hard driving. The conclusion is that hard driving costs less than the British method and that the British should have adopted this technique. A very crude estimate of the demand facing British pig iron producers is then used to show that eliminating the entrepreneurial failure would not have changed Britain's market share by very much.

CAPITAL COSTS

The first step in deciding whether hard driving paid is to approximate the capital requirements per ton of output of hard-driven and not-hard-driven plants. For modern firms, such as those described in ISIJ for 1887, the cost of constructing a new plant was £73,500 in Cleveland (England) and $720,000 in Chicago (the United States). The English plant had three furnaces while the American plant had four. Is it fair to compare these furnaces? It would be a fair comparison if the American furnace could be built in England for the English cost (and vice versa). Converting the costs by the exchange rate will not solve the problem. More bricks, engines, and labor in the United Kingdom were bought for £1.00 than $4.86 bought in the United States. Judging from the price of firebrick, blowing engines, and labor--all important ingredients in a blast furnace plant--the ratio of the price of blast furnaces in the United Kingdom to that of blast furnaces in the United States after the exchange rate conversion is .75.[13] On this basis, one English furnace would cost $158,760 if built in the United States, while an American furnace would cost $180,000. If built in the United Kingdom, the costs would be £24,449 and £27,720, respectively.[14] That is, if an entrepreneur were to take the plans for an American-style furnace plant as printed in ISIJ and construct that plant in Cleveland, England, it would cost the entrepreneur £27,720. If anything, this underestimates the cost of the English furnace if built in the United States and overstates the cost of the American furnace if built in the United Kingdom.

The British-style plant would produce between 30,000 tons (judging from the Report of the U. S. Department of Labor)[15] and 25,000 tons (Bell and Richards' estimate)[16] per furnace per year. The estimate used here is 30,000 tons per year. Four furnaces in the Report, all American, made more than 52,690 tons per furnace per year. There would seem to be some danger that 52,690 tons would overstate the make expected from the plant that Potter describes. The danger is small since Potter's own estimate is 60,000 tons per year. Nevertheless, computations are also done for a much more conservative make of 43,500 tons per furnace per year. From the figures above, it would appear that an additional outlay of £3,000 would purchase in the United Kingdom the American-style plant which was capable of 20,000 tons per year of additional output. But the £3,000 was not the only additional capital cost.

The cost of hard driving was thought to be the rapid deterioration of furnace linings. Although 2.5 and 12 years are used to represent, respectively, the lining life of hard-driven and not-hard-driven furnaces, these numbers are suspect. The short life of American furnace linings probably is the effect of chilling during cyclical trade downswings as much as hard driving. The 12-year lining life for England comes from Bell and Richards and is substantiated by the data in the Report.[17] The 2.5-year lining life comes from the Report. These numbers are chosen as representative of lining life in hard-driven and British-style furnaces. Relining was necessary many times. To compare these future costs with the present cost of construction, a discount rate should be employed.

The least sum of money that, if deposited at interest, would pay the costs of relining as they would occur is the present value of the cost of relining.[18] In addition to the frequency of relining, the present value of cost depends on the price of linings, the period over which the calculation is made, and the interest rate. The results of the present value calculations are sensitive to the interest rate and to the time period over which they are made. In 1887 the yield of the United Kingdom consols was 3 percent.[19] In the United States, railroad bonds yielded 4.65 percent.[20] Consols were certainly a safer asset than railroad bonds. In 1900, the first year for which this figure is available, U. S. municipal bonds yielded .7 percent less than railroad bonds. Taking the .7 percent as a risk premium, U. S. low-risk securities should have yielded about 4 percent in 1887. Unfortunately, blast furnace bonds were a high-risk security. The evidence on these securities is contained in Bridge's work.[21] Bridge does not mention any bonds issued in 1887. The years for which there are figures are 1876 (6 percent, 5 year) and 1899 (7 percent, long-term gold). On the basis of this evidence, the appropriate interest rate in the United States seems to be 6 percent, while the English rate should be somewhat less--perhaps 5 percent extrapolating from the difference in the safe rates.

The time period used should be equivalent to the period it would take the furnace itself to deteriorate. Twenty-five years has been chosen. The results are insensitive to lengthening the period, and shortening it will make hard driving more attractive. Potter estimated the cost of linings to be $15,000 in the United States. If converted by the exchange rate and an estimate of the relative prices of capital, this would be £2,300 for a lining in the United Kingdom rather than Bell and Richards' estimate of £1,500.[22] In the United Kingdom, the linings are assumed to cost £1,900, the average of these two estimates.

In England, at an interest rate of 5 percent, 25 years of furnace linings could be bought with an endowment of £1,681 for an English-style plant and £10,320 for an American-style, hard-driven plant. In the United States, at an interest rate of 6 percent, the endowment would have to be $11,365 for the English-style plant and $73,365 for the American-style, hard-driven plant.

Adding the costs of the relining fund and the construction costs gives an estimate of the total capital requirements of the two types of plants in the two countries. These estimates appear in Table 1. Since English-style and American-style plants had different outputs, the relevant measure is not total costs but total cost per ton per year. The cost per ton is found by dividing the cost by the estimate of output. Two estimates of output are used for the American-style plants. As explained earlier, the 52,600-tons-per-year output is what the proponents of hard driving thought their plants did produce. The estimate of 43,500 tons per year was chosen because it represents the minimum output required for hard driving to be superior to the British method. The output of 43,500 tons per year is certainly a lower bound on the capacity of hard-driven American furnaces.

Table 1 shows that, if hard-driven furnaces produced as much metal per year as their proponents claimed, then hard driving was a capital-saving innovation, both at English and American prices. In the United States the savings in capital costs from running a hard-driven rather than an English-style furnace would have been $44,710 in present value for 52,690 tons of installed capacity. The savings in the United Kingdom would have been £7,785. The savings from using the technique favored by the Pittsburgh ironmakers is on the order of one-sixth of the capital costs of a new furnace plant. Although a savings of $40,000 may at first seem large, it should be remembered that this saving is over a 25-year period during which more than one million tons of metal are to be produced. Looking at this in a crude per ton perspective, the savings in yearly capital rental are on the order of 5 cents per ton. Before concluding that hard driving saves capital at both English and American prices, it should be remembered that the result is very sensitive to the amount the make increases when furnaces are harder driven. The assumption used here has been that hard driving increases the make from 30,000 tons to 52,600 tons per year. If hard driving increases the make only to 43,500 tons per year, then hard driving would not be capital saving at either the American or English prices. The historical evidence is not terribly clear on this point. A cautious interpretation of the results would be that hard driving saves some capital costs but probably not as much as the estimated $44,710.

FUEL, LABOR, AND ORE COSTS

Demands for the remaining factors--labor, fuel, and ore--are estimated from the Report. The method is to assume a family of conditional cost curves, each cost curve corresponding to a slightly different technology. Technologies are distinguished by the quality of the iron ore used which is measured by the percent of iron in the ore (pct); the type of fuel on which the plant was built to operate, measured by the ratio of coke to fuel (frat); and how hard the plant was driven which is measured by a ratio of output to plant size (drv). The assumption is that entrepreneurs were not free to vary these technical factors. In the case of ore, location decided the ore type. The percent of coke in the fuel mixture was partially a matter of location and partially furnace design. In any event, neither modern American nor modern British firms used any fuel but coke. It is hypothesized that hard driving was determined by a constraint of entrepreneurship. If the interpretation of failure is true, then moving to harder driven furnaces should decrease the cost of operation.

The explanation given above about the form of the cost function is expanded upon in the Appendix and leads to estimating factor demands with the following variables:

$$\frac{L}{Q} = L\ (\text{pct, frat, drv}, P_K, P_L, P_C)$$

$$\frac{C}{Q} = C\ (\text{pct, frat, drv}, P_K, P_L, P_C)$$

$$\frac{O}{Q} = O\ (\text{pct, constant})$$

where pct, frat, and drv are defined above and P_K, P_L, and P_C are the prices of capital, labor, and coke, respectively. L, C, O, and Q are labor, coke, ore, and the output, pig iron.

These equations were estimated for the English and American data both separately and pooled. Comparing the residuals of the two sets of regression results in a test of the hypothesis that the English and American firms were all part of the same sample. Another way to interpret this test is to say that it tests the hypothesis that being English per se had no effect on technical efficiency. This was done by an F test of the equality of coefficients from two sets of regressions—one with and the other without the English data.[23] The value of F(14,174) was 1.5. The appropriate critical region is $F_{.95}$ greater than 1.74. Thus, the hypothesis that the coefficients for the conditional factor demand regressions on English data are the same as those for American data is accepted.

Given these equations, failure can be partially tested by seeing if hard driving saved labor and fuel. If hard driving saved labor and fuel, then (since the argument has already been presented that it saved capital) hard driving would lead to lower costs. Rational entrepreneurs choose methods with low costs. The t test of the effect of hard driving on the factor demands for fuel and labor amounts to a t test of the hypothesis of failure. For this t test, the dimensions and prices of a typical hard-driven American firm were used (the use of English values makes no noticeable difference). The values of t(85) were 2.9 for fuel and 2.4 for labor. Both are significant at the .01 level of significance. Hard driving was judged to save fuel and labor. It was argued that hard driving saved capital. These savings are significant because they provide the partial test promised earlier in the paper. The coefficients were estimated on the assumption that each firm was driving its furnaces as hard as it could; physical or stupidity constraints prevented harder driving. This assumption is now (partially) justified; there was a failure of British entrepreneurs.

Before proceeding to quantify the extent of the British failure and discussing the relationship of the failure to the decline, McCloskey's results on technique, which are contradictory to the results just presented, will be examined.

McCloskey's argument is flawed in three ways. (1) He aggregated the data for each country; however, the effects of vintage capital and market conditions, which are quite important, are then lost. (2) He focused only on coke demand; however, it is the capital requirements that set the British and American methods apart. (3) He crudely accounted for the differences in ore quality; however, only slight adjustments in his judgments are sufficient to reverse his conclusions.

The last of these accusations is easiest to prove and depends least on the conclusions drawn elsewhere in this paper. To arrive at his conclusion for 1889, McCloskey computed an index of technology A* which he implicitly defined in a footnote by the following formula:

$$\frac{(Q/C)\ \text{Eng} - (Q/C)\ \text{US}}{(Q/C)\ \text{Average}} = A^* + S_k\ E_{kc}\ \frac{\left(P_c/r\right)\ \text{Eng} - \left(P_c/r\right)\ \text{US}}{\left(P_c/r\right)\ \text{Average}}$$

$$+ S_1\ E_{\ell c}\ \frac{\left(P_c/w\right)\ \text{Eng} - \left(P_c/w\right)\ \text{US}}{\left(P_c/w\right)\ \text{Average}}$$

where Q = output, C = coke input, S_k = cost share of capital, S_1 = cost share of labor, $E_{\ell c}$ = partial elasticity of substitution between labor and coke, E_{kc} = partial elasticity of substitution between capital and coke, P_c = price of coke, w = price of labor, and r = rental rate of capital. McCloskey argued that the British coke rate, the ratio of output to coke, was 10 percent better than the American coke rate; and the substitution terms (those with partial elasticities) were at most 6 percent. Thus, A* = .04, and the British used a technology superior to the one used by the Americans.

First, consider McCloskey's numbers. Where does the 10 percent number come from? He argued that, with iron ore as rich as the American ore, the British coke rate should be .90. His argument for this number depended on his observation that a 1 percent increase in the ore content leads to a 1 percent increase in the coke rate. Yet, his estimate from cross-section data for 1887 is .7 percent; this would imply the coke rate would be about .87 and not .90. He chooses 1 percent as the average of the measure in 1887 (.7 percent), 1897 (1 percent), and 1912 (2 percent). If 1 percent were the right estimate for 1887, it would have a very great variance.[24] The American coke rate for 1889 is .83. The average of the two nations is .865. Using McCloskey's technique of computing percentage changes on the average, the answer is that the British rate is greater than the American rate by only 8 percent. If one uses .87 as the British rate, as suggested above, the difference amounts to 4¾ percent. If the price effects were 6 percent, then A* = -1¼ showing that the American technique was superior.[25] It is of some interest to ask how McCloskey estimated the price effect. The answer is that he conjured an "upper bound" on the elasticities from thin air.

McCloskey's focus on coke rates only is erroneous because, as this paper shows, the difference in capitalization in the two countries was vast and greatly outweighed considerations of the other inputs.

The major quarrel with McCloskey's work is his aggregation. As shown above, British and American plants can be viewed as coming from the same family of technologies. The reason there was both good and bad American practice was that prices were very high in the United States (when compared with the average costs of efficient firms). These high prices kept inefficient firms in production. Average American technique was the average of firms that earned profits and firms that just broke even, and these two sets of producers were worlds apart in technique and efficiency. By and large, the efficient American producers were located around Pittsburgh (where the high-quality coke was located). Earlier, American firms had established themselves in the south and in the anthracite regions of Pennsylvania. These earlier firms were kept in production by the failure of the efficient firms to expand faster than the demand for iron. In England the conditions of trade were much different. Prices were nearly the same as average costs of the efficient firms. Less efficient firms would make losses. Thus, McCloskey is comparing good British technique with average American technique. It is not surprising that he finds the British technique to be better. McCloskey's conclusion does not speak to the question of whether the British used the most efficient techniques; rather, it speaks to the market conditions of the two countries and the effect of the tariff wall that separated them.

FAILURE AND DECLINE

How much did the entrepreneurial failure cost the British? The first effect of a failure is a loss of efficiency. Less resources are needed to produce the same product. The exercise on capital costs and the regression equations provide estimates of the gain to hard driving. Hard driving was found to save small amounts of both labor and coke. For a typical British-style firm contemplating increasing output from 30,000 tons to 45,000 tons by hard driving, the regression equations show these savings for a firm operating at British factor prices would be .115 tons of coke per ton of furnace capacity (per year) and .145 man days of labor per ton of furnace capacity (per year). The numbers using Pittsburg area factor prices are .085 and .109, respectively. Although these numbers are small, they are different from zero at the .01 level of significance. On the increased make of 45,000 (from 30,000) tons per year, the savings per year in fuel and labor costs attributable to hard driving are £10,800 and £4,000 in Great Britain and $11,400 and $7,300 in the United States. The present value (over 25 years) of these savings is £264,000 for an English firm. A similar calculation shows an American firm would lose $209,000 (in present value) by giving up hard driving. Assuming all British firms were to convert to hard driving, the 178 firms of 45,000 tons per year output necessary to produce the 8 million tons of iron produced in 1890 in Britain would each save £264,000 in present value. The single-year value of the savings is £2.6 million per year in lost welfare. Although the calculation of both welfare loss and the repercussions of higher prices for trade requires a careful calculation of the percent of plants amenable to hard driving, the data are not detailed enough on the British plants to support such a calculation. Judging from the American data, which are admittedly not strictly applicable to the English situation, about 40 percent of the capital stock could have been upgraded in the manner suggested in this paper.[26] This crude adjustment for the vintage of the capital stock would reduce the welfare loss to about 1 million pounds. As welfare losses go, £2.6 million in a national income of £1,410 million is very little. (Of course, the author would gladly accept such an amount in lieu of one year's salary and, in this sense, it is a lot.) If the only problem with inefficiency were the direct welfare loss, the problem would hardly be worth study. Did the cost disadvantage have an adverse effect on the British market share? To put the question differently, would lowering average costs (and, thus, price in equilibrium) by £.10 by the estimated amount of the remediable inefficiency have affected Britain's trade much? The presumptive cost savings were on the order of 5 percent of price. It would take an elasticity of demand of 10 for the price change attendant on more efficient techniques to make the demand for British iron great enough for the United Kingdom to equal the United States in iron production in the decade 1890 to 1900. Not only would the elasticity of demand have had to be 10 but also all of the preceding, very generous assumptions--including the assumption that all of the gains from efficiency would be passed on as lower prices and that none of them would be captured as rents--would also have had to be true. The answer to the British decline in the iron industry lies elsewhere. Temin argues that Britain did not have access to the German and American markets because of the tariff wall.[27] For steel, of which iron is a large part, Temin pointed out that the tariff wall prohibited the British from supplying the two fastest growing segments of the steel market: America and Germany. Table 2 gives a rough idea of the increasing importance of German and American production. Temin argued that, even if the British were able to reverse the share of the "neutral" markets that Britain and Germany held, Britain would still be left without her accustomed lion's share of the world market. Although Temin makes his argument for steel in 1913, the same arguments hold for iron in 1890. Because the market was spatially distributed, a small decrease in price would only make British steel or iron cheaper than the German or American product in a small part of the world. Since it was location and custom that determined where the Americans, as opposed to the Europeans (the British and Germans, principally), would sell, a small price difference would not be expected to shift such markets as Canada into the European column. Presumably, small price differences would be influential in determining who sold to Latin America and Japan, whether it be Britain or Germany or America or Europe. Temin's assumption is that small changes in price would only affect the distribution of shares between England and Germany and would not remove business from the Americans. In the case of iron in 1890, the Americans were extremely high priced compared to the British. It is very difficult to imagine that what amounts to an epsilon price difference (the 5 percent of price lost for inefficiency) would have affected a market in which a price difference of about one-third of the price already existed.

The questions of failure and decline have been settled. Failure has been demonstrated, and a crude argument has been made that the failure in 1890 was neither significant as a welfare problem in its own right nor an important reason why Britain lost her share of the world iron market. Given these conclusions, why the 90-year debate on hard driving? The fantastic fact about American hard-driven blast furnaces was the profits they made.

The appendices to Temin's book[28] and McCloskey's book[29] provide estimates of the prices of Bessemer iron in the United States and in the United Kingdom. The Report provides estimates of the average cost of production excluding the cost of capital. Earlier, the cost of capital (construction and relining) was estimated for 25 years. That estimate can be used to derive an estimate for the yearly capital cost (or rental fee): hard driven (American style), $16,516; and £3,331 (English style) in the United Kingdom.[30] Dividing by the output per year gives capital cost per ton: $0.31 (United States) and £.06 (United Kingdom). This is added to the costs shown in the Report. In 1889 the range of average cost for English plants was £2.07-£2.05; and for American plants it was $14-$17. Costs for the years 1884 to 1888 were estimated by deflating the 1889 figures by a price index.[31] Subtracting from the price for the years 1884 to 1889 and averaging gives the average range of profits per ton in both countries: £.28-£.26 in the United Kingdom and $3.95-$0.79 in the United States. Multiplying by the yearly makes shows the marked difference in American and British markets. U. S. profits would be $200,000 per year, while English profits would only be £14,000 (which is only $70,000 at the exchange rate). Looking at it another way, a U. S. firm would recover its entire construction costs in one year. An English firm would take three years to recover its construction cost. The incentive for hard driving would not just be the cost savings--it would also be the profits on the expanded makes. The present value of these profits over a 25-year period would be $2,800,000 (United States) and £220,000 (United Kingdom). Thus, the incentive to try the new techniques was much greater for the Americans than it was for the British.

What do these enormous profits mean? Economic theory suggests that the rigors of competition and the free entry for firms will drive economic profits to zero. Moreover, inefficient firms--those with high costs--will be driven from the market. First, examine the English market. The spread in costs is small. From the most- to the least-efficient plant given in the Report, there is only a cost difference of £.02 on a cost of £2.00 per ton or 1 percent of the cost. This agrees with theory. Yet, profits appear to be about £.26 per ton or one-eighth the cost. (One might hypothesize that the data in the Report do not account for all the costs. Though this may be true, one does not know what was omitted.) For the United Kingdom, one piece of evidence argues for long-run equilibrium and one does not. Now consider the northern United States. The spread in costs is immense. There was a difference of $3.00 or 20 percent of cost between the least- and most-efficient firm. Profits were 25 percent of costs. Both pieces of evidence argue that U. S. industry was not in long-run equilibrium. How could this come about? One argument would be that there were barriers to entry. The price of $250,000 per furnace undoubtedly made entry somewhat difficult. Not everyone could raise that much money in 1890, especially for a risky venture. Another argument would be that the high prices of iron (and profits) were not anticipated in America. This is plausible. The dawning of the steel age was in 1870, and iron and its products were used in an increasing number of applications. In the United States, production of iron increased fivefold between 1870 (1,665 K tons) and 1890 (9,203 K tons); it tripled again between 1890 and 1910 (27,304 K tons). Offhand, one cannot tell how much of this increase was from decreased price and how much was from increased demand (new uses). Yet, the sheer size of the increase makes it believable that people did not anticipate the demand, prices, and profits of making iron. The market in the United Kingdom also saw an increase in the quantity of iron products, but the production growth was more sedate. Pig iron output increased by a factor of 1.5 from 1870 (5,963 K tons) to 1890 (7,904 K tons) and by 1.5 again from 1890 to 1910 (10,012 K tons).[32] It is easier to believe that English entrepreneurs foresaw the increases in the United Kingdom than it is to believe that the American entrepreneurs foresaw the increase in the U. S. demand. To sum this up, whenever entrepreneurs anticipate positive profits, they will build more furnaces, increase supply, and drive the profit rate back toward zero. If the profits (prices and demands) are not properly anticipated, then and only then can profits actually appear. The major difference between the United States and the United Kingdom may well have been the stability of demand and, therefore, the ability of entrepreneurs to predict prices and profits.

CONCLUSIONS

1. Hard driving saved labor, coke, and capital. The cost curves of hard-driven firms were just barely inside those of the British-style firms at all relevant prices.

2. Because the cost curves of hard-driven firms are inside those of British-style firms, the production function of hard-driven firms was above that of British-style firms at all relevant factor intensities (Shephard's duality theorem for cost curves and production functions). British-style firms were mildly inefficient.

3. The inefficiency of British firms amounts to £.10 per ton or 5.0 percent of the market price. It is hard to see how this could have influenced the share of the world market held by the United Kingdom firms to any great degree. It is hard to see how the "entrepreneurial failure" had much to do with Britain's supposed decline.

4. Market conditions varied greatly between the United States and the United Kingdom. The spread between price and average cost was much greater in the United States. It is postulated that this spread resulted from the unanticipated nature of increased American demand for iron.

5. The major incentive to hard driving was the profits on the increased make. Because the profits per ton in the United States were much larger than those in the United Kingdom, the incentive for hard driving in the United States was much larger than the incentive in the United Kingdom.

6. The present value (over 25 years at 6 percent) of the profits from one hard-driven blast furnace in the United States was $2,868,000. As Andrew Carnegie said: "Where is there such a business?"

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APPENDIX

To determine the relative efficiency of the British and modern American-style furnaces, it is necessary to estimate conditional cost functions for plants driven at various air pressures and having various operational characteristics. Given a set of conditional cost functions, it is then easy to compare the costs of a hypothetical British-style plant operating in the United States to an American-style plant operating in its own country and vice versa.

For the moment, let us set aside the question of relative prices and assume firms have U-shaped cost curves. Why are there different types of firms (low, high, and middle cost)? If this were an agricultural example, the three cost curves could come from three different qualities of land. In a cross-country comparison, the claim would be that the countries had different technologies. In a vintage capital model, it would be the vintage of the capital that explains the lower and higher costs. Instead of indexing the firms by vintage (on which there are no data), the firms will be indexed by how hard they drove their blast furnaces. In 1889 progress in blast-furnace technology had been in the faster working of the metal which is called hard driving. Since the 1870's, English furnaces had led the way in this practice but were soon overtaken by the Pittsburgh-area (or North) American furnaces. Hard driving required major renovation (or building anew) to change a plant from a slow-working to a hard-driven one. The degree to which a plant was hard driven reflected at least two things: (1) the year the plant was built (or rebuilt) and (2) the daring of the entrepreneur who built the plant. All the ironmasters agreed that blowing air at 5 pounds per square inch was an improvement over not blowing air. All new plants could be expected to be driven by at least 5 pounds of pressure. But what about 9 pounds? Would 9 pounds destroy the linings and reduce the all-important coke rate (ratio of iron to coke)? The ironmasters were unsure. Iron making was very much an art. A single wrong move could cost $15,000 for a new lining (and this was in the days when the President of the United States made $50,000). Daring was necessary for even a slight departure from the established formula. As a result, the degree to which a furnace was hard driven could be conceived as a facet of plant operation only slightly more alterable than the quality of agricultural land or the vintage of a machine factory.

To include the effects of prices and different grades of ore in the analysis, one posits that there was a family of conditional cost functions of the form

$$C(z) = C\left(\frac{P_1}{A_1(z)}, \ldots, \frac{P_n}{A_n(z)}\right)$$

where

$P_1, \ldots, P_n$ = prices

Q = quantity of output

$A_1(z), \ldots, A_n(z)$ = continuous real valued functions of their argument z which are indices of factor-augmenting technical change.

In this case z will be a semicontrollable variable--hard driving. In most comparisons, z would be a country or other uncontrollable variables. The difference is not trivial.

A profit-maximizing entrepreneur would choose z to minimize C. He would choose either the lowest or the greatest possible z or one for which the derivative of C with respect to z is zero. First, consider a solution with $dC/dz = 0$, i.e., an interior solution. This solution gives z as a function of prices and output, $z = \hat{z}(P_1 \ldots P_n, Q)$. Substituting this back into the cost function will give a cost function of the usual type--one with only prices and quantity.

$$\hat{C} = C\left(\frac{P_1}{A_1(\hat{z})} \cdots \frac{P_n}{A_n(\hat{z})}, Q\right).$$

By its construction, this function will have the special property, $d\hat{C}/dz = 0$. In other words, z would be a jointly determined variable and would vanish from the cost function.

The second case to consider is the case where $dC/dz < 0$ (resp. > 0), and a constraint $z \leqq b$ (resp. $z = 0$) is binding. In case 2 it is assumed that entrepreneurs exhibit cost-minimizing behavior with respect to all variables except hard driving. Furnaces are driven at the pressures customary at the time they were erected; fear of burning furnace linings stops the entrepreneurs from changing the plant to be harder driven.

Combining the two cases, the entrepreneurs can be described as follows. If

$0 < z < b$, then $z^* = \hat{z}(P, Q)$

$z = b$, then $z^* = b$

$$C = C\left(\frac{P_i}{A_i(z^*)}, Q\right).$$

Both z and C would then be endogenous variables.

The object of this exercise is to estimate the parameters of C and A. If there were observations (or any information) on b, one could apply simultaneous equation techniques to estimate the parameters. But in at least some cases, b represents a stupidity constraint and is unmeasurable. This is unfortunate. It means that the only way to estimate the functions consistently is to know whether $z = b$, but the only way to know if $z = b$ is to estimate the functions. There are two things left to do. Assume z is less than b and estimate, and assume $z = b$ and estimate. The first procedure (assuming z is less than b and estimating) will yield no new information. Apart from a disturbance term, $\partial C/\partial z = 0$ for the estimated cost function. This is by the construction of z. Fortunately, assuming $z = b$ does not imply $\partial C/\partial z < 0$. Thus, one can partially test the hypothesis ($\partial C/\partial z < 0$) by assuming $z = b$, estimating

$$C\left(\frac{P_1}{A_1(z)} \cdots \frac{P_n}{A_n(z)},\ Q\right)$$

using the observed values of z, and then testing to see if $\partial C/\partial z < 0$ is indeed true.

The available data pose some further restrictions on the estimation procedure. There are data on variable inputs for a cross-section of firms for the year 1889.[33] These data do not contain capital costs, but two extraordinary accounts of the cost of building a blast furnace plant do provide some information on the cost of capital. The way to combine these two sources is to estimate conditional factor demands. Because the data on capital are so sparse, the results will give only a rough idea of the effect of hard driving on capital requirements; but this is the best one can do.

Let the cost function be of the form proposed by Diewert.[34]

$$C = Q \cdot \sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij} \sqrt{P_i} \sqrt{P_j} \sqrt{A_i(z)} \sqrt{A_j(z)}$$

and $d_{ij} = d_{ji}$ are parameters where

Q = output per furance

P_j = price of the *i*th factor

z = vector of attributes

A_i = real valued function.

The additional assumption is made that relative factor prices did not influence the conditional factor demand for ore. This means $d_{\text{ore}\ j} = 0$ for every $j \neq$ ore. This assumption is plausible (and was made by McCloskey). It means that other factors of production could not be substituted for ore. (The assumption is especially convenient because it is hard to view the price of ore as predetermined.)

A vector z will be the variables hard driving (drv), ratio of coal to coke (frat), and percent of iron in the ore (pct). For an explanation of why the fuel ratio was important, see Temin's Appendix B.[35] The percent of iron in ore was primarily determined by a firm's location. It influenced all the variables because it made ore less bulky for a given iron content. This cut handling and shipping costs and lessened the amount of coke needed to reduce the ore. The presence of hard driving has already been explained.

From physical arguments, air pressure should have been proportional to

$$\frac{\text{output per day}}{\text{(diameter of bosh)**2} \cdot \text{height of stack}} .$$

This variable was used to represent hard driving (drv). It captures the idea of a large make from a small furnace. (Letting drv = output per day per diameter of bosh makes little difference to the results.)

The data are taken from the Report; they are a cross-section study of 118 furnaces, about 15 percent of those cited in the next census. The price of capital is presented earlier in this paper. Ninety-seven of the points were used--90 in the United States and 7 in England. Furnaces were excluded either because they burned charcoal or because data about them were missing. An additional problem was encountered with data for wage rates. There were only data on 17 firms. For these 17 firms, the wage rate was regressed on a dummy for region and the percent of iron in the ore used by the furnaces. The use of estimated wage rates introduces an error in the variables problem. The coefficients are biased downward. The assumption is that wages were determined by location, and ore content is an indicator of location. The coefficients of this regression were then used to predict the wage rates at all the other firms in the sample. Furnaces often burned more than one fuel. Fuels were aggregated by the formula: fuel = coke + .75 anthracite + .63 bituminous--all in tons. This aggregation, suggested by McCloskey, is based on the carbon content of one ton of each of the fuels.[36]

All discussions (and statistical tests but not estimation) are done for a hypothetical firm that approximates the dimensions and conditions of efficient firms in the 1890 Report. Both hard-driven and British-style firms were assumed to have furnaces 240 inches across the bosh, with 75-foot stacks. They burned no anthracite. The hard-driven furnace was assumed to make 52,690 tons per year from ore, with an iron content of 60 percent. The British-style furnace was assumed to make 30,000 tons per year from ore, with 50 percent content of iron. Prices in America were taken as $1.50 per man day for labor and

\$3.00 per ton for coke. In the United Kingdom they were £.12 per man day for labor and £.41 per ton for coke.

By Shephard's lemma, the factor demand for a factor is the partial derivative of the cost function with respect to its own price.

$$\frac{C}{Q} = d_{CC}\, A_C(z) + d_{CK} \sqrt{A_C(z)} \cdot \sqrt{A_K(z)} \sqrt{\frac{P_K}{P_C}}$$

$$+ d_{CL} \sqrt{A_C(z) \cdot A_L(z)} \sqrt{\frac{P_L}{P_C}}$$

$$\frac{L}{Q} = d_{LL}\, A_L(z) + d_{LK} \sqrt{A_K(z)\, A_L(z)} \sqrt{\frac{P_K}{P_L}}$$

$$+ d_{CL} \sqrt{A_C(z) \cdot A_L(z)} \sqrt{\frac{P_L}{P_C}}$$

$$\frac{Ore}{L} = d_{OO}\, A_O(z)$$

L = labor

C = fuel

O = ore

K = capital.

For purely technical reasons (mostly multicollinearity), the richest specifications for the A_i that could be estimated were

$$\sqrt{A_i(z)\, A_j(z)} = a_{ij1} \cdot pct + a_{ij2} \cdot frat + a_{ij3} \cdot drv.$$

Substituting the above relationship into the factor demand equations gives three equations to be estimated. Notice the equality constraint on some coefficients of the first and second equations. To use these constraints, it was necessary to estimate the standard error of each equation, divide each equation by its standard error, and then estimate jointly using the cross-equation constraints. Ordinary least squares was used throughout.

$$\frac{L}{Q} = \underset{(5.59)}{2.27} - \underset{(.042)}{.0091}\ \text{pct} - \underset{(5.05)}{1.79}\ \text{frat} + \underset{(50{,}700)}{22{,}000}\ \text{drv}$$

$$+ \sqrt{\frac{P_K}{P_L}}\ (\underset{(.073)}{-.024} + \underset{(.00061)}{.00017}\ \text{pct} + \underset{(.0056)}{.0376}\ \text{frat} - \underset{(660.9)}{522}\ \text{drv})$$

$$+ \sqrt{\frac{P_C}{P_L}}\ (\underset{(1.08)}{1.113} - \underset{(.0176)}{.011}\ \text{pct} - \underset{(.628)}{.955}\ \text{frat} + \underset{(14{,}900)}{10{,}300}\ \text{drv})$$

$$R^2 = .423$$

$$\frac{C}{Q} = \underset{(.90)}{-.84} + \underset{(.018)}{.035}\ \text{pct} + \underset{(.450)}{.87}\ \text{frat} - \underset{(13{,}500)}{17{,}700}\ \text{drv}$$

$$+ \sqrt{\frac{P_K}{P_C}}\ (\underset{(.021)}{.042} - \underset{(.000371)}{.0006}\ \text{pct} - \underset{(.0110)}{.0002}\ \text{frat} + \underset{(283.0)}{74}\ \text{drv})$$

$$+ \sqrt{\frac{P_L}{P_C}}\ (\underset{(1.08)}{1.13} - \underset{(.0176)}{.011}\ \text{pct} - \underset{(6.28)}{.955}\ \text{frat} + \underset{(14{,}900)}{10{,}300}\ \text{drv})$$

$$R^2 = .606$$

$$\frac{O}{Q} = \underset{(.274)}{-3.6021}\ \text{pct} + \underset{(14.986)}{390.791} \qquad R^2 = .6440$$

A striking feature of these regression equations is the relatively large standard errors attached to the parameters. This apparent lack of confidence is illusory since the interest in the equations does not attach to individual coefficients which account for mixed effects--e.g., the effect of prices and hard driving working together--but to the pure effects of hard driving, factor prices, etc. These tests are realized as t tests of appropriate sums of parameters and are described below.

The following tests were performed. First, the hypothesis that the English plants were not really part of the sample was tested. This was done by an F test of the equality of coefficients from two sets of regressions--one with and one without the English data.[37] The value of F(14,174) was 1.5. The appropriate critical region is $F_{.95}$ greater than 1.74. Thus, the hypothesis that the coefficients for the conditional factor demand regressions on English data are the same as that for American data is accepted. The second test performed was a test of the hypothesis that hard driving saved fuel and labor. This amounts to a t test of the hypothesis d fuel/d drv = 0 and d labor/d drv = 0. Because the variable drv is multiplied by other variables and is used in more than one form in the regression equation, the covariances of the OLS estimator enter into the t test.[38] Here the dimensions and prices of a typical hard-driven American firm were used (using the English values makes no noticeable difference). The values of t(85) were 2.9 for fuel and 2.4 for labor. Both are significant at the .01 level of significance. Hard driving was judged to save fuel and labor. In the text, it was argued that hard driving saved capital. These savings are significant because they provide the partial test promised earlier in the paper. The coefficients were estimated on the assumption each firm was driving its furnaces as hard as it could: physical or stupidity constraints prevented harder driving. This assumption is now (partially) justified.

FOOTNOTES

Giannini Foundation Paper No. . Peter Temin provided the impetus for writing this paper as well as useful comments. Franklin Fisher and Jerry Hausman also made useful comments. The author, however, is solely responsible for the remaining errors.

[1] J. C. Carr and W. Tapin, *History of the British Steel Industry* (Oxford, 1962).

[2] I. Lowthian Bell, "Iron and Steel Institute in America in 1890," *Iron and Steel Institute Journal*, 38 (1891).

[3] M. R. Potter, "The South Chicago Works of the North Chicago Rolling Mill Company," *Iron and Steel Institute Journal* (1887).

[4] Alfred Marshall, *Memorandum on Fiscal Policy of International Trade,* House of Commons, No. 321, Sect. 1 (November 1908).

[5] Duncan L. Burn, *Economic History of Steelmaking, 1867-1939: A Study in Competition* (Cambridge, England, 1940).

[6] Donald N. McCloskey, *Economic Maturity and Entrepreneurial Decline: British Iron and Steel, 1870-1913* (Cambridge, 1973).

[7] E. H. Phelps-Brown and S. J. Handfield-Jones, "The Climacteric of the 1890's: A Study in the Expanding Economy," *Oxford Economic Papers*, 4 (October 1952).

[8] Paul A. David, "The Landscape and the Machine: Technical Interrelatedness, Land Tenure and the Mechanization of the Corn Harvest in Victorian Britain," in Donald N. McCloskey, ed., *Essays on a Mature Economy: Britain After 1840* (Princeton, N. J., 1971).

[9] Peter H. Lindert and Keith Trace, "Yardsticks for Victorian Entrepreneurs," in Donald N. McCloskey, ed., *Essays on a Mature Economy: Britain After 1840* (Princeton, N. J., 1971).

[10] McCloskey, *Economic Maturity and Entrepreneurial Decline*.

[11] Lindert and Trace, *Essays on a Mature Economy*.

[12] For a more exact expansion of this idea, see the Appendix.

[13] If anything, this number is far too high. The ratio of .5 of the wage rate (directly and indirectly) was probably 70 percent of the costs.

[14] For example, $720,000/4 furnaces = $180,000; £73,500 · $4.86/£/(price of capital in England/price of capital in the United States = .75)/3 furnaces = $158,760.

[15] U. S. Department of Labor, *Sixth Annual Report of the Commissioner of Labor, 1891* (Washington, 1892).

[16] I. Lowthian Bell and Windsor E. Richards, "Discussion: On the English and American Furnace Practice," *Iron and Steel Institute Journal* (1887).

[17] Ibid., p. 181.

[18] The derivation of the cost of relining every I years for a total period of L years follows. R is the cost of one relining, and i is the interest rate.

$$\text{Cost } (I, \infty) = R \sum_{j=1}^{\infty} (1 + i)^{-Ij} = R[(1 + j)^{I} - 1]^{-1}$$

$$\text{Cost } (I, L) = \text{cost } (I, \infty)\ [1 - (1 + i)^{-L}].$$

[19] B. R. Mitchell, *Abstract of British Historical Statistics* (Cambridge, England, 1962), p. 455.

[20] U. S. Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1957* (Washington, 1960), p. 656.

[21] James Howard Bridge, *Inside History of the Carnegie Steel Company* (New York, 1903).

[22] Bell and Richards, "English and American Furnace Practice," p. 181.

[23] F. M. Fisher, "Tests of Equality Between Sets of Coefficients in Two Linear Regressions: An Expository Note," *Econometrica*, 38 (March 1970).

[24] McCloskey, *Economic Maturity and Entrepreneurial Decline*, pp. 80 and 115.

[25] Alternatively, see McCloskey's finding that a subgroup of American firms using the same quality ore as that used in South Wales had only a 5 percent lower coke rate; now the countries appear even, ibid.

[26] This calculation is based on the percent of firms in the sample with furnaces bigger than 200 inches across the bosh.

[27] Peter Temin, "The Relative Decline of the British Steel Industry, 1880-1913," in Henry Rosovsky, ed., *Industrialization in Two Systems: Essays in Honor of Alexander Gerschenkron* (New York, 1966), p. 138.

[28] Peter Temin, *Iron and Steel in the Nineteenth Century America* (Cambridge, 1964).

[29] McCloskey, *Economic Maturity and Entrepreneurial Decline*.

[30] Yearly capital costs (r) are the interest on a sum of money just large enough (when placed at interest) to provide an operating blast furnace forever. Let C be the construction cost plus the value of a 25-year relining fund. Then:

$$r = i \cdot C \cdot [(1 + i)^{25} - 1]^{-1}.$$

[31] U. S. prices were deflated by the wholesale price index; English prices, by an index of wages. Neither index is ideal; see U. S. Bureau of the Census, *Historical Statistics of the United States*, p. 115 and Mitchell, *Abstract of British Historical Statistics*, p. 343.

[32] Mitchell, ibid.

[33] The data came from the Report of the U. S. Commissioner of Labor. However, it does not include observations on capital costs; see U. S. Department of Labor, *Sixth Annual Report of the Commissioner of Labor, 1891.*

[34] W. E. Diewert, "An Application of the Shephard Duality Theorem: A Generalized Leontief Production Function," *Journal of Political Economy*, 79 (June 1971), p. 497.

[35] Temin, *Iron and Steel in the Nineteenth Century America.*

[36] McCloskey, *Economic Maturity and Entrepreneurial Decline,* p. 116.

[37] Fisher, "Tests of Equality."

[38] Henri Theil, *Principles of Econometrics* (New York, 1971), p. 138.

TABLE 1

Relative Capital Requirements of English-Style and American-Style (Hard Driven) Furnaces, 1890

Location and type of plant	Capacity	Plant cost	Relining fund	Capital required	Capital required per ton of capacity	Capital required for 52,600 tons of capacity
	tons per year	pounds (English)				
England						
English style	30,000	24,449	1,681	26,130	.871	45,814
American-style hard driven[a]	43,500	27,720	10,320	38,040	.874	45,972
American-style hard driven[b]	52,600	27,720	10,320	38,040	.723	38,029
		dollars (U. S.)				
United States						
English style	30,000	158,760	11,365	170,125	5.67	298,242
American-style hard driven[a]	43,500	180,000	73,365	253,365	5.96	313,496
American-style hard driven[b]	52,600	180,000	73,365	253,365	4.82	253,532

[a] Pessimistic figure.

[b] Optimistic figure.

TABLE 2

Pig Iron Production, 1880-1910[a]

Country	1880		1890		1900		1910	
	Amount	Percent	Amount	Percent	Amount	Percent	Amount	Percent
Great Britain	7,749,233	42.87	7,904,214	29.13	8,959,691	22.18	10,012,098	15.21
United States	3,835,191	21.22	9,202,703	33.91	13,789,242	34.13	27,303,567	41.47
Germany and Luxemburg	2,729,038	15.10	4,658,451	17.17	8,520,541	21.09	14,793,604	22.47
France	1,725,293	9.54	1,962,196	7.23	2,714,298	6.72	4,038,297	6.14
Belgium	608,084	3.36	787,836	2.90	1,018,507	2.52	1,852,090	2.81
Other countries	1,430,161	7.91	2,621,729	9.66	5,397,721	13.36	7,835,344	11.90
World total	18,077,000	100.00	27,137,129	100.00	40,400,000	100.00	65,835,000	100.00

[a] Tons of 2,240 pounds are used in giving production for Great Britain, the United States, and "other countries"; metric tons of 2,204 pounds are used for all the continental countries of Europe.

Sources:

1880: American Iron and Steel Association, *Annual Statistical Report: 1894* (Philadelphia: American Iron and Steel Association, May, 1895), pp. 1-38 (Supplement).

1890: *Ibid., 1892* (May, 1893), p. 31 (Supplement).

1900: *Ibid., 1901* (June, 1902), pp. 61-63.

1910: *Ibid., 1911* (October, 1912), p. 56 (Part II).