THE MINIMUM OPTIMAL SCALE STEEL PLANT

IN THE MID-1970'S

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The subject of the minimum optimal scale (hereafter (MOS) steel plant has received considerable attention in the literature over the past twenty years.[1] Most of the estimates are reproduced below in Table 1. The consensus of the studies, such as Scherer [20], Leckie and Morris [10], the Benson Report [6] and Pratten and Dean [15] was that, in the mid-1960's, the MOS for a steel plant producing flat rolled products was 4 million tons per year (hereafter mtpy).

There have been some important developments in steelmaking technology since 1965. A very important change has been the development of the giant blast furnace; it is now assumed by many authors, that the blast furnace stage of steelmaking has overtaken the rolling mill and steel refining stages to set the MOS for a steelworks realizing all scale economies.[2] Based on this fact, the MOS steel plant has been placed at 8.5-9 mtpy or more.[3]

I contend in this paper that the giant blast furnaces are not more efficient than their somewhat smaller counterparts. Thus, it is argued here that the MOS, blast furnace--basic oxygen furnace, (hereafter BF/BOF, plant), is 6 mtpy. The 6 mtpy estimate, represents a 50% increase over the mid-1960's MOS, but is significantly smaller than the larger estimates.

Moreover, depending on the relative prices of the inputs, the BF/BOF process is not the least cost method of making steel. It is argued below,

TABLE 1

Estimates of Minimum Efficient Scale of Steelworks in terms of Annual Crude Steel Production

Production Route and Product-Mix	Minimum Efficient Scale (million tons of crude steel per annum)	Source and Date of Estimate	Basis of Estimate
Blast and Steel Furnaces/Flat and Other Rolled	4.0 and above	Pratten, 1971 (UK)	Engineering estimates
Blast and Steel Furnaces/Flat Rolled	1.0 – 2.5	Bain, 1956 (US)	Engineering estimates
	3.0 and above	Pratten and Dean, 1965 (UK)	Engineering estimates
	4.2	Benson, 1966 (UK)	Engineering estimates
	4.0	Leckie & Morris, 1968 (UK)	Engineering estimates
	8.0	Commission des Communautés Européennes, 1971 (E.E.C.)	Engineering estimates
Blast and Steel Furnaces/Other Rolled	3.0	Benson, 1966 (UK)	Engineering estimates
	1.5	Leckie and Morris, 1968 (UK)	Engineering estimates
	4.0	Commission des Communautés Européennes, 1971 (E.E.C.)	Engineering estimates
Steel Furnaces/Flat Rolled	0.5 – 1.0	Bain, 1956 (US)	Engineering estimates
Steel Furnaces/Other Rolled	0.1 – 0.5	Bain, 1956 (US)	Engineering estimates (applies also to special steel)
	1.0 – 1.5	Benson, 1966 (UK)	Engineering estimates (light rolled products)
	1.25	Leckie and Morris, 1968 (UK)	Engineering estimates (billet and medium-section mills)
	about 0.15	Pratten, 1971 (Germany, F.R.)	Engineering estimates
Unspecified	0.76	Stigler, 1958 (US 1930–51)	Survivor technique; converted from percentage share of total industry capacity.[a]
	0.8	Saving, 1961; Weiss, 1964 (US, 1947–54 census data)	Survivor technique; converted from employment data[b]
	2.25	Weiss, 1964 (US 1948–60)	Survivor technique; capacity data.

Source: Reproduced from Cockerill [4, p. 80].

that if scrap is cheap relative to iron ore, the electric furnace, (hereafter EF), method of steelmaking is less expensive than the BF/BOF; in addition if natural gas is cheap relative to coal, then the direct reduction-electric furnace, (hereafter DR/EF), process, is cheaper than BF/BOF. Depending on the product mix, electric steelmaking reduces the MOS steel plant to between .5 mtpy to 3 mtpy.

In Sections I and II estimates of the economies of scale in rolling mill technology and the BOF are presented respectively. The MOS blast furnace is discussed in Section III. Section IV discusses electric steelmaking with emphasis on when a scrap charged or direct reduction, (hereafter DR), charged electric furnace is efficient.

The concluding section summarizes the results and indicates the number of MOS plants that can exist in the U.S.

I. Rolling Mills

A. Primary Rolling Mills and Continuous Casting.

For thirty years preceeding the 1960's, primary rolling mill technology dominated the MOS steel plant. The MOS primary rolling mill has been estimated by Scherer [20] at 3.6-4.8 mtpy by Pratten [14] as 4.6 and 4.1 mtpy for slabbing and blooming mills respectively. The primary rolling mill no longer sets the MOS floor for a MOS BF/BOF steel plant, partly because iron making and steel refining have a higher MOS and partly because continuous casting is, in many circumstances, a cheaper way than primary rolling mills of producing semi-finished steel slabs. Estimates for a 1970's MOS continuous casting operation are: Pratten [14], 1 mtpy and Scherer[20], 3 mtpy.

B. Secondary Rolling Mills

Table 2 below is reprinted from Pratten [14]; he claims some economies of scale exist up to the largest mills that exist in the world, but the numbers slightly exaggerate realizable economies of scale in many situations. Scherer [20] estimates that the mid-1970's MOS hot strip mill is 4.5 to 5 mtpy.

II. Basic Oxygen Furnace Steelmaking.

Table 3 below, summarizes data from a study by Professor Hermann Schenck and presents the Pratten data. The Pratten study concludes that the main economies of scale are captured at 5 mtpy. The Schenck study reveals further capital and labor unit cost saving out to 7.68 mtpy; however, the inclusion of materials costs in the Schenck data, would reduce the percentage unit savings. Moreover, as heats of steel are commonly made for specific customer orders, BOF shops with three vessels over 275 tons are rare and there are few BOF shops with three vessels exceeding 250 tons.[4] Thus, the MOS BOF shop is approximately 6 mtpy, unless the company's usual order is in sufficiently large amounts to utilize the large vessels effectively.

III. Blast Furnaces

In the construction of giant blast furnaces, Japan and the Soviet Union, and to a lesser extent West Germany, have led the world. Table 4 below presents a list of the 46 blast furnaces in the world with a hearth diameter of at least eleven meters. The largest BF in the U.S. ranks 19th in the world. However, Inland Steel at Indiana Harbor and Bethlehem Steel at Sparrows Point are building blast furnaces with a hearth diameter of 13.7 meters while National Steel at Portage, Indiana is building one of almost identical size.

TABLE 2

The Optimum Scale for Rolling Mills

Type of Mill	Product	Capital Cost per annual ton of capacity for Rolling Mills (Mechanical equipment only)(a) £	Annual Output of largest mill (m. tons)(b) U.K.	World	Total U.K. output (1965)
Slabbing mill	slabs	1.2	4.0	4.5	7.5(c)
Blooming mill	blooms	1.25	3.0	4.0	10.5(d)
Continuous casting machines	slabs	3.1	1.0	1.0	7.5(e)
Continuous casting machines	blooms	2.4	0.5	1.0	10.5(e)
Billet mill	billets	3.1	3.0	5.5	6.0
Hot strip mill	hot–rolled wide strip	4.0	3.5	6.0	4.3
Cold strip mill and temper mill	cold–rolled sheet in coil	3.8	1.0	2.0	3.0
Tinplate mill and temper mills	tinplate base	8.3	0.6	0.6	1.2
Narrow strip mill	hot–rolled strip up to 18" wide	5.3	0.5	0.5	1.8
Heavy plate mill	plates	11.0	1.0	2.4	2.4(f)
Beam and section mill	beams and sections	14.5	0.6	0.75	2.9
Rod mill	bars and rods in coil	6.0	0.14	0.6	1.8
Bar mill	light sections and bars	9.0	0.4	1.0	2.8

(a) The estimates of capital costs for the mechanical equipment of mills are included to provide a very crude indication of the capital costs for each type of rolling mill. As an extremely crude guide these costs form of the order of a quarter of the installed capital cost of mills. The ratio varies for different types of mill. The costs given for mechanical equipment are for large mills and are approximate.

(b) Actual or contemplated.

(c) Including slabs for plate mills.

(d) The total output of blooms is not recorded as much of it is immediately re–rolled, and the figure given is an estimate.

(e) Only a small proportion of the U.K. output of slabs and blooms is made by continuous casting.

(f) Excluding plate from strip mills.

Source: Reproduced from Pratten [14, p. 109]

TABLE 3

V *Indices of Unit Capital and Operating Costs in Two- and Three-Converter BOS at Various Annual Output Rates*

Converter Capacity (tons/heat)	Annual Output ('000 tons)	Indices of Unit Costs (3 × 300t converters = 100)	
		Capital	Operating
2-converter system			
100	1,280	208	127
200	2,560	158	112
300	3,840	134	106
3-converter system			
100	2,568	149	114
200	5,120	113	104
300	7,680	100	100

Source: Commission des Communautés Européennes, *Projet de Memorandum sur les Objectifs Généraux de la Sidérurgie de la Communauté pour les années 1975–80*, mimeo., 1971. Data are summarised from a study commissioned from Professor T. Schenck.

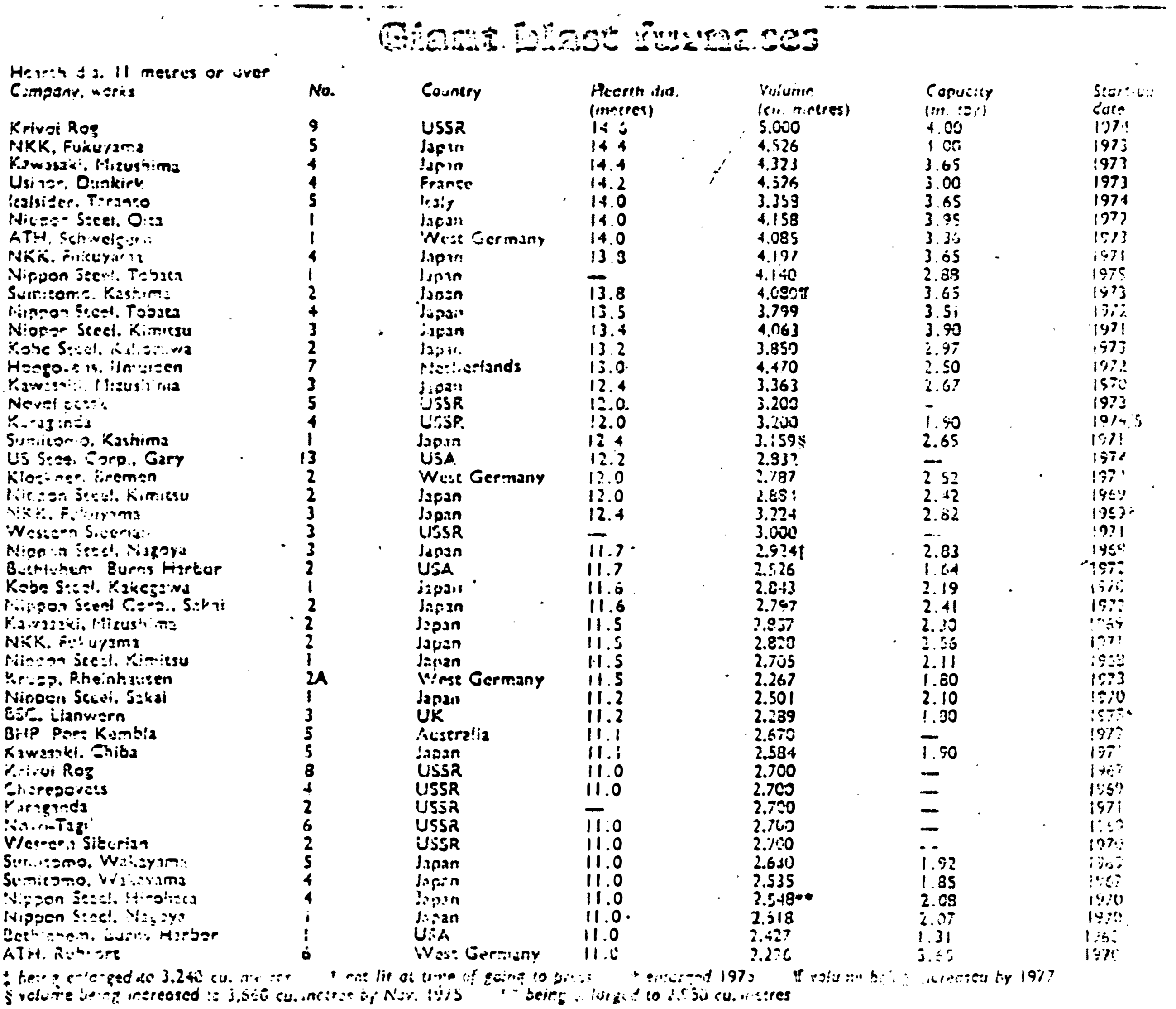
[redacted] *Indices of Average Annual Total Production Cost and its Components at Various Levels of Steel Output, Integrated Steelworks*

Annual Steel Output (million tons)	Materials	Indices of Unit Costs		
		Operating	Capital	Total
0.25	100	100	100	100
1.02	84	67	68	80
2.03	81	61	52	75
5.08	80	60	41	73
10.16	79	60	40	72

Source: C.F. Pratten, op. cit., 1971.

Source: Reproduced from Cockerill [3, p. 72]

TABLE 4



Giant blast furnaces

Hearth dia. 11 metres or over

Company, works	No.	Country	Hearth dia. (metres)	Volume (cu. metres)	Capacity (m. t/y)	Start-up date
Krivoi Rog	9	USSR	14.6	5,000	4.00	1974
NKK, Fukuyama	5	Japan	14.4	4,526	4.00	1973
Kawasaki, Mizushima	4	Japan	14.4	4,323	3.65	1973
Usinor, Dunkirk	4	France	14.2	4,576	3.00	1973
Italsider, Taranto	5	Italy	14.0	3,353	3.65	1974
Nippon Steel, Oita	1	Japan	14.0	4,158	3.95	1972
ATH, Schwelgern	1	West Germany	14.0	4,085	3.36	1973
NKK, Fukuyama	4	Japan	13.8	4,197	3.65	1971
Nippon Steel, Tobata	1	Japan	—	4,140	2.88	1975
Sumitomo, Kashima	2	Japan	13.8	4,080¶	3.65	1973
Nippon Steel, Tobata	4	Japan	13.5	3,799	3.51	1972
Nippon Steel, Kimitsu	3	Japan	13.4	4,063	3.90	1971
Kobe Steel, Kakogawa	2	Japan	13.2	3,850	2.97	1973
Hoogovens, IJmuiden	7	Netherlands	13.0	4,470	2.50	1972
Kawasaki, Mizushima	3	Japan	12.4	3,363	2.67	1970
Novolipetsk	5	USSR	12.0	3,200	-	1973
Karaganda	4	USSR	12.0	3,200	1.90	1974/5
Sumitomo, Kashima	1	Japan	12.4	3,159§	2.65	1971
US Steel Corp., Gary	13	USA	12.2	2,832	—	1974
Klockner, Bremen	2	West Germany	12.0	2,787	2.52	1971
Nippon Steel, Kimitsu	2	Japan	12.0	2,884	2.42	1969
NKK, Fukuyama	3	Japan	12.4	3,224	2.62	1969*
Western Siberian	3	USSR	—	3,000	—	1971
Nippon Steel, Nagoya	3	Japan	11.7	2,924‡	2.83	1969
Bethlehem, Burns Harbor	2	USA	11.7	2,526	1.64	1972
Kobe Steel, Kakogawa	1	Japan	11.6	2,843	2.19	1970
Nippon Steel Corp., Sakai	2	Japan	11.6	2,797	2.41	1972
Kawasaki, Mizushima	2	Japan	11.5	2,857	2.30	1969
NKK, Fukuyama	2	Japan	11.5	2,828	2.56	1971
Nippon Steel, Kimitsu	1	Japan	11.5	2,705	2.11	1968
Krupp, Rheinhausen	2A	West Germany	11.5	2,267	1.80	1973
Nippon Steel, Sakai	1	Japan	11.2	2.501	2.10	1970
BSC, Llanwern	3	UK	11.2	2,289	1.80	1975*
BHP, Port Kembla	5	Australia	11.1	2,670	—	1972
Kawasaki, Chiba	5	Japan	11.1	2,584	1.90	1971
Krivoi Rog	8	USSR	11.0	2,700	—	1967
Cherepovets	4	USSR	11.0	2,700	—	1969
Karaganda	2	USSR	—	2,700	—	1971
Novo-Tagil	6	USSR	11.0	2,700	—	1963
Western Siberian	2	USSR	11.0	2,700	--	1970
Sumitomo, Wakayama	5	Japan	11.0	2,630	1.92	1967
Sumitomo, Wakayama	4	Japan	11.0	2,535	1.85	1967
Nippon Steel, Hirohata	4	Japan	11.0	2,548**	2.08	1970
Nippon Steel, Nagoya	1	Japan	11.0	2,518	2.07	1970
Bethlehem, Burns Harbor	1	USA	11.0	2,427	1.31	1962
ATH, Ruhrort	6	West Germany	11.0	2,276	1.65	1970

‡ being enlarged to 3,240 cu. metres † not lit at time of going to press * enlarged 1975 ¶ volume being increased by 1977

§ volume being increased to 3,660 cu. metres by Nov. 1975 ** being enlarged to 2,950 cu. metres

Source: Metal Bulletin Monthly, April 1975.

If economies of scale exist out to the largest of these furnaces, then the MOS BF/BOF steel plant is about 9 mtpy. However, on the basis of the available evidence, I would conclude that the MOS BF for the U.S. is significantly less than the largest units in production.

Shinroku Yamashita, the senior managing director of Nippon Kokkan KK, presented extremely relevant data on this subject at the 1972 International Iron and Steel Association meetings. Table 5 and Figure 1 below are reprinted from his article [23].

Yamashita states that:

> Under the same raw materials conditions and at the same daily productivity, there would be no marked difference in fuel consumption between different furnace capacities.

It is clear from Figure 1, that no further unit cost savings are present beyond 3600-3700 cubic meters (m^3); moreover, if materials costs were included in Figure 1, the curve would be flatter as it approached 3600 m^3, i.e., the unit cost savings are less than indicated in Figure 1 because there are no materials savings associated with scale.

The Yamashita data on investment costs is supported by a study by H. Yoshida [24] of the Kawasaki Steel Corporation. Kawasaki, through their Mizushima works, has a plant with 4 blast furnaces ranging from 10.4 to 14.4 meters in hearth diameter. Applying conversion factors relevant to Japan yields data very similar to Yamashita's on investment costs.

TABLE 5 and FIGURE 1

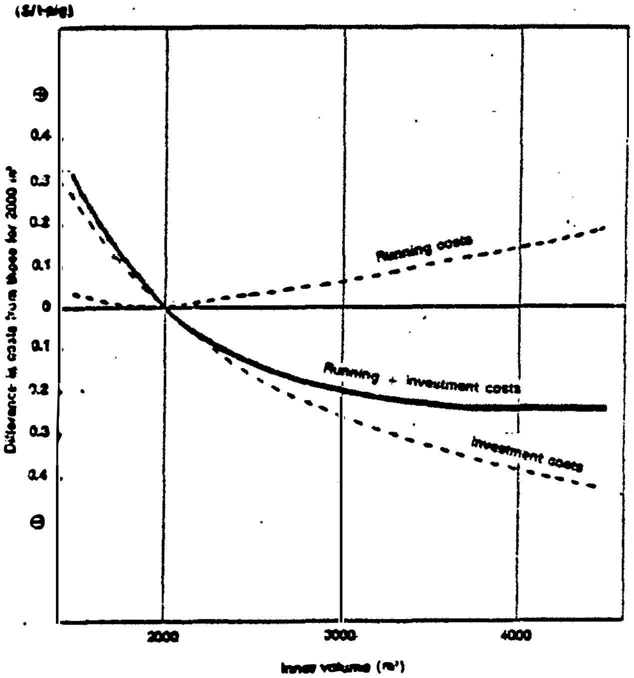
OPERATING DATA OF FUKUYAMA BLAST FURNACES (NKK)
(MONTHLY DATA A YEAR AFTER BLOWING-IN)

	1 BF	2 BF	3 BF	4 BF*
Blowing-in	Aug. 26 '66	Feb. 15 '68	Jul. 25 '69	Apr. 26 '71
Inner volume, m^3	2,004	2,626	3,016	4,197
Hearth dia., m	9.8	11.2	11.8	13.8
Production, t/d	4,639	6,064	6,834	10,017
Productivity, $t/d/m^3$	2.32	2.31	2.27	2.39
Coke rate, kg/t	469	469	465	437
Oil rate, kg/t	34	26	40	52
Fuel rate, kg/t	503	495	505	489
Sinter rate, %	70	64	76	80
Slag volume, kg/t	253	260	274	290
Blast volume, Nm^3/min	4,073	5,309	5,842	7,722
Blast pressure, kg/cm^2	2.24	2.61	2.93	3.61
Top pressure, kg/cm^2	0.59	0.99	1.36	2.10
Blast temp., °C	1,112	1,146	1,159	1,200
O_2 enrichment, %	0	0	0.6	1.4
Si % in pig	0.71	0.69	0.66	0.71
S % in pig	0.038	0.037	0.038	0.032
CaO/SiO_2 in slag	1.23	1.17	1.16	1.13
Coke ash, %	9.2	9.1	10.6	10.5
Drum index (DI^{30}_{15})**	92.4	93.2	91.8	92.0

* Monthly data seven months after the blowing-in (maximum monthly production achieved).

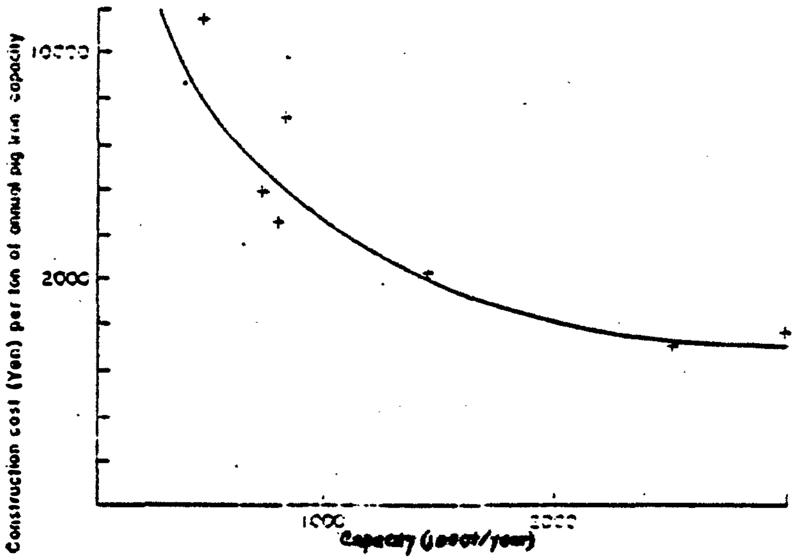
** Testing method: JIS.K2151-1972.

FIG. 4. — Inner volume of blast furnace and running and investment costs.



Source: Yamashita, [23, pp. 94-95].

FIGURE 2



Source: Yoshida [24], reproduced from Gold [7;p. 9].

At a productivity rate of 2.3 tons per day per m^3, a 3600 m^3 BF will produce 8280 tons per day. At an average rate of operation of 345 days per year,[5] the single unit MOS BF would produce 2.86 mtpy.

However, the main source of the economies of scale, investment costs, is challenged by W. D. Roepke [17], the technical manager of Kolsch Folzer-Werke AG. He provides data on investment costs (Figure 3 below) and argues that the 14 meter hearth diameter BF has only a slight advantage over two ten meter BFs. Moreover, the investment cost advantage of the large BF will persist only if both small and large vessels have the same rate of availability. Due to factors such as breakouts of the tuyures, the giant blast furnaces have experienced a lower availability rate.

FIGURE 3

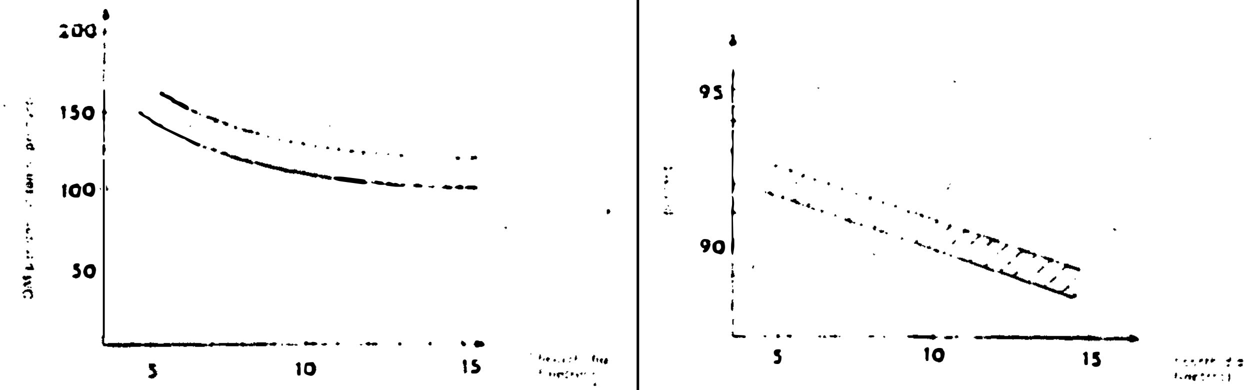


Fig. 1: Range of specific investment costs for a blast furnace unit depending on technical standard and market situation

Fig. 2: Specific availability of blast furnace (a period of 6 years is considered)

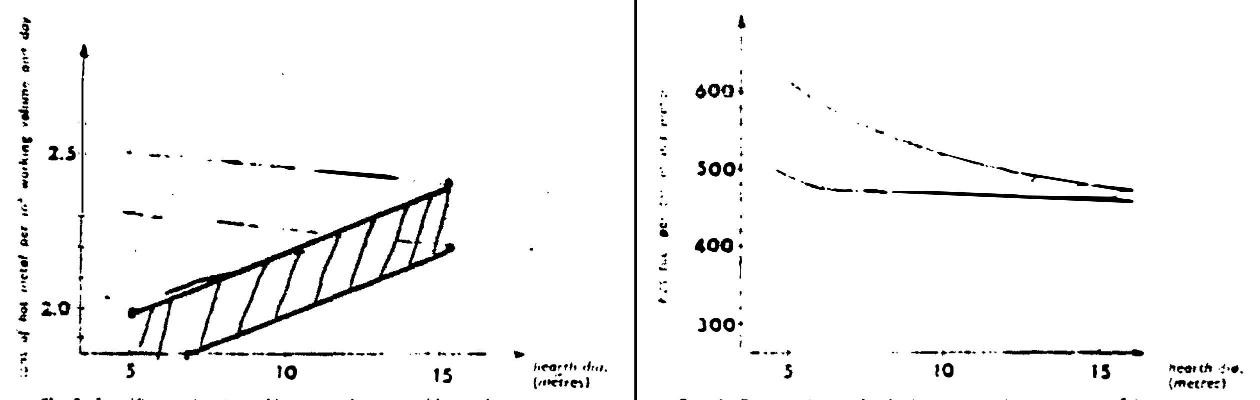


Fig. 3: Specific production of hot-metal per working volume of a blast furnace

Fig. 4 Range of specific fuel consumption per ton of hot metal (including oil valued at average exchange rate to coke)

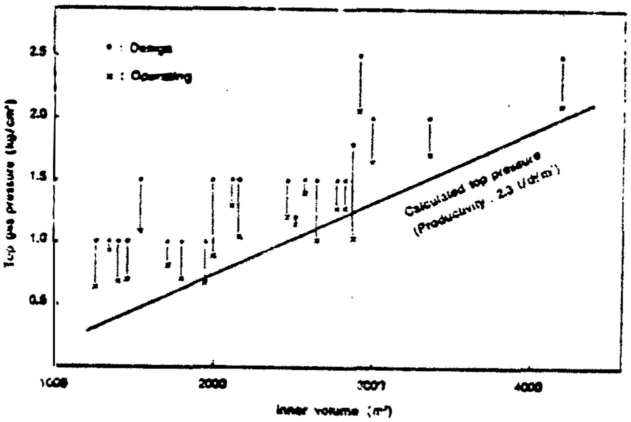
Source: [17, p. 37] and correspondence with Dr. Roepke.

It is probable that the availability rates will improve for the big blast furnaces as experience in operation is gained. However, the greater pressure in the big furnaces presents a problem regarding availability not present in the smaller units.

> The theoretical top pressures necessary at a daily productivity of 2.3 tons per day per m^3, which is considered standard productivity in Japan were calculated and drawn in a line in this Figure [Figure 4 below] . . . . All the facilities in a large blast furnace are exposed to very severe operating conditions due to the high pressure handling of massive quantities of material, and trouble of repair work may lead to considerable decrease in production. Maintenance of facilities has, therefore, a great significance. With this in view, all the facilities are designed to make maintenance and inspection easy and materials of a longer service life are selected for bells, refractories and ramming mixes. For the tuyeres, which have so far given much trouble, the use of an increased amount of cooling water and a higher water pressure and the improvement of design are largely reducing breakouts. [23, pp. 92-93]

FIGURE 4

FIG. 3. — Inner volume and top gas pressure in Japan.



Source: Yamashita [23, p. 92].

The improvements in availability rates are coming at the expense of higher investment costs, partially cancelling the theoretical cost advantage of the larger units; because of the greater stress on the facilities, it remains to be seen if availability rates of the larger units can be economically raised to those of the smaller furnaces.

Thus, it seems more reasonable to assume that currently a MOS BF has an inner volume of 3000 m^3 rather than 3600 m^3, which using the same conversion factors as above yields 2.42 mtpy rather than 2.86 mtpy.

Relining of BFs occurs for a period of two months, every 3-4 years. A plant with only one BF would be without hot metal capacity during relining. Thus, at least 2 BFs are required at a MOS plant. A plant with 3 BFs would have slightly better balance than one with two. However, according to Yamashita:

> When one of two blast furnaces of the same capacity is to be relined for a period of two months, for example, a 10 percent production increase in the blast furnace in operation, a 10 percent decrease in the hot metal ratio in converters and the storage of additional ingots for a period of three months prior to the relining, would permit maintenance of a production of about 80 percent on rolling facilities even during relining.

Thus, a two BF plant would capture virtually all the economies of scale.[6] Depending on the investment cost assumptions discussed above, the plant would have a hot metal output of 4.84 mtpy to 5.72 mtpy. Mixed with scrap and alloys, at a .73 hot metal to .27 scrap and alloy ratio, the BOF gross metallic charge would be 6.63 mtpy to 7.84 mtpy.

There is a crucial qualification to this estimate. It is based on Japanese experience of 2.3 tons per day per cubic meter of BF volume.

Gold [7] in his interviews found that

> Japanese engineers claimed that a 4000 cubic foot [meter] blast furnace would yield only 60-70% as much pig iron annually at the driving rates used in the U.S. as would result from Japanese practices. . . . it is argued that the major limitations on the effective size of blast furnaces derives from the size and efficiency of the blowing engines which generate the blast in the furnaces.

Gold's interviews are supported by the data in Table 6 below and Table 1.

TABLE 6

Large Blast Furnaces in the U.S.

Company Works	Hearth Diameter meters	Volume (Cubicmeters)	Capacity mtpy	Start up date
Bethlehem, Burns Harbor	11.0	2427	1.31	1968
Bethlehem, Burns Harbor	11.7	2526	1.64	1972
U.S. Steel, Gary	12.2	2832	-	1974
Bethlemen, Sparrows Pt.	13.7	3679	2.65	1976
Inland, Indiana Harbor	13.7	3679	2.32* 3.31 **	1978
National, Portage		3680	1.80	1976

* initial announced capacity; ** final announced capacity.

Sources: Metal Bulletin Monthly, April 1975 and 33 Magazine, August 1975.

Dividing the rated capacity of the Burns Harbor furnaces by the rated capacity of the Japanese furnaces with the same hearth diameter yields numbers: .63, .629, .708, .682, .579 and .749. For the Sparrows Point furnace, the closest comparable furnace is Nippon's number four at Tobata; the analogous number is .755.

Thus, even if the appropriate factor for U.S. experience is as high as .75 times Japanese experience, the MOS ironmaking facility composed of two equally sized MOS BFs will produce 3.63 mtpy to 4.29 mtpy of hot metal. Mixed with scrap the BOF gross metallic charge would equal 4.97 mtpy to 5.88 mtpy.[7]

One should regard the different investment decisions of the Japanese and Americans as appropriate profit maximizing behavior for all concerned given the relative factor costs and regulatory environment in which the firms operate. In particular, the Japanese steel industry is said to regulate capacity expansion through granting permission to a plant to have a given number of blast furnaces, cf. Gold [7] and Nakamura [13]. The Ministry of International Trade and Industry is said to mediate disputes amongst companies with its "recommendation," which for a number of reasons companies are loathe to ignore.[8] "It is understandable that company managements would seek to make the most of an opportunity to add capacity which might not recur for an extended period as competitors are granted allocations in turn." [7, p. 11]

Given these facts, the estimate of the MOS, BF/BOF plant in the U.S. is 6 mtpy and is set by the BOF shop. The assumption that the BOF shop sets the MOS in a U.S. plant is consistent with the responses we have obtained from our interviews with members of the U.S. steel industry.

IV. Electric Steelmaking

The BF/BOF process is not the least cost method of manufacturing steel under any configuration of factor costs. In particular, a study by Quintana, Bueno and Vargas [16] showed that if the cost of iron ore is priced high relative to scrap, then if electricity is not too expensive, the electric furnace (EF) with a 100% scrap charge is a cheaper method of making steel than the BF/BOF.[9] The open hearth furnace which uses scrap more intensively than the BOF, has been superceded by the BOF. With the EF proportion held constant, an increase in the BOF proportion of total steelmaking will depress the price of scrap. The low scrap price encourages the construction of an EF rather than a BOF; the more EF's in production, based on a scrap charge, the higher the price of scrap. Thus, it would appear that there is an equilibrium ratio of BOF to EF. In the U.S., as open hearths are being phased out, we are approaching a BOF to EF ratio of 3 to 1, (see Table 7 below).

TABLE 7

Raw Steel Production by Furnace Type in The U.S.
(Percent of total steel output)

	Open hearth	Basic oxygen	Electric	Total
1961	86.2%	4.9%	8.9%	100.0%
1962	84.4	6.5	9.1	100.0
1963	81.2	8.8	10.0	100.0
1964	77.2	12.8	10.0	100.0
1965	71.6	17.9	10.5	100.0
1966	63.4	25.5	11.1	100.0
1967	55.7	32.7	11.6	100.0
1968	50.0	37.2	12.8	100.0
1969	43.1	42.6	14.3	100.0
1970	36.6	48.2	15.2	100.0
1971	29.5	53.1	17.4	100.0
1972	26.2	56.0	17.8	100.0
1973	26.4	55.3	18.3	100.0
1974	24.4	56.0	19.6	100.0

Source: American Iron and Steel Institute, Annual Statistical Reports, various issues.

In a scrap charged EF plant, the rolling mills set the MOS. Cockerill [4] has estimated the MOS scrap charged EF plant, producing bars only, at between .1 and .5 mtpy. That estimate is consistent with Pratten's [14] for a similar plant producing nonflat rolled products. If flat rolled products are to be produced, the MOS would range from .5 mtpy for narrow strip to 4.5 to 5 for very wide strip. The 3 mtpy new strip mill of Republic Steel, at its Cleveland works, rolls strip of all widths from 14 to 82 inches. Thus, considerable flexibility in flat rolled products production is possible with a 3 mtpy capacity.

Two recent technological developments will affect, in opposite directions, the BF:EF ratio, namely continuous casting and direct reduction. Continuous casting, by eliminating the ingot stage, generates less scrap. Thus, to the extent that continuous casting is adopted, the EF will have a more difficult time competing with the BOF.

Direct reduction (DR) is a process which makes a scrap like product from iron ore pellets; most operating DR units employ natural gas as the reductant although the SL/RN process uses coal. As of December 1974, there were almost 19 mtpy of DR units in operation or on order throughout the world [12, p. 14].

A very detailed study by Jack Miller [12] has demonstrated that for Venezuela where natural gas is very cheap relative to coal, the DR/EF process is cheaper than the BF/BOF process for a 3-4 mtpy steel plant. As the DR/EF process has a MOS, through the slab stage of less than one mtpy, where natural gas is sufficiently cheap relative to coal, it represents a considerable reduction in the MOS.[10] The DR/EF MOS would depend on product mix; it would be the same as the scrap charged EF plant except that DR units have a MOS of .4 mtpy.

V. Conclusions

It has been argued that there is not one method of steelmaking that is the most efficient under any configuration of factor costs. In particular, a scrap charged EF is superior to the BF/BOF if scrap is cheap relative to iron ore. An integrated DR/EF plant is superior to a BF/BOF works if natural gas is sufficiently cheap relative to coal. In all other situations, the BF/BOF is the most efficient. In practice, there is an equilibrium between the processes, with both the BF and the EF operating efficiently simultaneously.

I have concluded that in the U.S., the BF/BOF process has a MOS of 6 mtpy; this estimate will not depend significantly on product mix. The EF process, whether scrap or direct reduction fed has a MOS of .5 mtpy to 3 mtpy. The MOS for the EF would be at the high end of the range if wide flat products are being rolled.

The output of the U.S. steel industry in the peak year of 1973 was 150 million tons. According to Hogan [8] the industry plans to add 22.93 million tons of capacity by 1980 while 2 million tons will have to be retired. Suppose that the BOF:EF ratio is 3 to 1 and the MOS EF is 3 mtpy. Then in 1973 there were potentially 31 MOS plants, 19 BOF and 12 EF, while in 1980 there will be 35 potential MOS plants, 21 BOF and 14 EF.

FOOTNOTES

* The author is a senior economist with the Bureau of Economics, Federal Trade Commission. I would like to acknowledge the helpful comments on earlier drafts of W. D. Reopke of Kolsch Folzer-Werke AG, M. Boylan of Case Western Reserve University, W. J. Vaughn of Resources for the Future, R. Koller of Brigham Young University and R. Duke, R. Johnson, M. Lynch, H. Muellar and F.M. Scherer of the Federal Trade Commission.

(1) The term MOS is taken, in textbook examples, as that rate of output at which average costs attain their minimum. However, it is possible that average costs approach their mimimum asymptotically; in this case the limiting minimum would have no economic significance. Consequently, Cockerill [4] defines the MOS as that output at which a further doubling of the output rate reduces average costs by less than five percent. Inasmuch as the U.S. industry's return on sales averaged 4.7% for the decade ending in 1972 and 6.1% for the decade ending in 1962, Cockerill's five percent figure seems excessive and I shall define the MOS as that output at which a further doubling of the output rate reduces average costs by less than two percent.

(2) See Pratten [14] and Cockerill [4] for example.

(3) See Pratten [14] and Cockerill [4].

(4) According to the Kaiser engineers newsletter [9], there were only 9 BOF shops in the world, outside of the Soviet Union, which had three vessels exceeding 250 tons per vessel and only three of those shops had vessels exceeding 275 tons each. The three largest were: Italsider's Taranto works 3X300; Bethlehem's Lackawanna plant, 3X300 and British Steel Corporation's Scunthorpe works, 3X300. Five of the remaining six are located in Japan with capacities from 3X265 to 3X275; August Thyssen's Beeckerwerth plant, with a BOF shop of 3X275, completes the list.

Moreover a modern single slab caster can process on average, 3.3 tons of steel per minute or 200 metric tons per hour. Since, for metallurgical reasons, a heat of steel should not be kept in a ladle for more than 60 minutes, vessels in excess of 200 metric tons are somewhat ill advised if slabs are produced on a single continuous caster.

(5) This conversion factor was obtained through interviews with steel engineering firms.

(6) This estimate is consistent with that of M. Boylan; he has communicated to me he found, after extensive investigation, that virtually no further economies of scale exist in multi-blast furnace operations beyond two blast furnaces.

(7) A BOF gross metallic charge of 5mtpy, for example, will yield approximately 4.3 mtpy of raw steel. The reason is that the hot metal is only about 93% pure iron and the scrap contains about 2% impurities. The impurities are eliminated as slag during the refining stage; moreover, factors such as sloppage and loss of steel in the slag result in about 86% of the gross metallic charge being yielded as raw steel. Thus, gross metallic charges of 4.97 mtpy and 5.88 mtpy will yield 4.27 mtpy and 5.06 mtpy of raw steel.

(8) Reasons given to us in our interviews ranged from Japanese tradition to an unwillingness of electric companies to supply power and banks refusing to loan money if the steel company refused to follow MITI's recommendation.

(9) Using a linear programming model, Vaughn and Russell [25] have recently estimated the optimal ratio of BOF to EF. They conclude that the optimal mix depends on the relative price of scrap to molten iron and the type of steel being manufactured. The lower the relative price of scrap and the less "drawing" quality steel compared to alloy steel manufactured, the more appropriate is the EF. For "commercial" quality steel the relative price is the crucial variable.

(10) In states such as Texas and Louisiana, the price of natural gas relative to coal is low compared to the northern U.S., but not as low as in Venezuela. DR based electric furnaces may become common in these states. In 1973, Armco built a DR unit at its Houston plant. Recently, U.S. Steel and Korf Industries built EF plants on the Houston ship canal and Beaumont, Texas respectively. While in the initial stages Korf Industries will supply its Beaumont works with sponge iron from its South Carolina DR unit, they will construct a DR unit at Beaumont. Members of the steel community in the U.S., with whom I have spoken, have indicated that the decisions of Armco and Korf Industries to construct DR/EF plants in Texas, are reflective of the fact that at the unregulated relative prices prevailing in Texas, the DR/EF process is very competitive with BF/BOF.

In addition a study is currently being conducted, by companies in the DR field, regarding the feasibility of a DR complex in Texas or Louisiana which would barge its sponge iron product up the inland waterway system to EF plants in states such as Illinois. However this latter project is speculative.

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