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SUBSTITUTES FOR COKING COALS
IN THE BLAST FURNACE

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SUMMARY

The discussion on substitutes for coking coals in the blast furnace is presented in two parts. Part I reports research of the Bureau of Mines, United States Department of Interior, to make prereduced iron pellets by simultaneous induration and reduction of iron-ore concentrate balls with a solid reductant. The prereduced pellets were evaluated in a small-scale, experimental blast furnace. From the results obtained, it was concluded that prereduced burdens could conceivably eliminate need for perhaps 50 per cent of the coking coal currently consumed in ironmaking.

The functions of coke in a blast furnace and three methods of conserving coke are described in Part II. Other fuels may be used instead of coke if one of the so-called direct reduction processes are used to treat the iron ore. Formed coke may be substituted in the blast furnace stack for the metallurgical coke obtained from coking coals. Other fuels may be substituted for metallurgical coke in the blast furnace by injecting them into the combustion zone. Noncoking coals, petroleum products, and natural gas have been substituted successfully.

I. Introduction - Part I

1. One of the most effective means of "substituting" for something is to eliminate or lessen the need for it. A desire to dispense with coke in ironmaking was certainly one objective of the great amount of research and development work on direct reduction which sought to render the blast furnace obsolete. Although this desire has not come to pass, even the prospect of the elimination of the blast furnace has spurred other researchers into efforts to improve its operation.

2. A number of innovations in blast furnace practice have made significant contributions toward lower coke rates. These include higher hot-blast temperatures, hot air injection, and beneficiated burdens (improved both chemically and physically) such as sized ore and sinter, fluxed sinter, and iron ore pellets. Based on published announcements of projected agglomerating plants, pellets seem to occupy the most favoured position in terms of future growth.

3. Granted that iron ore pellets are an excellent blast furnace raw material, they can be made even better by prereduction. In addition to other benefits such as increased productivity which devolve from their use, prereduced pellets drastically lessen the need for coke. This is, in a sense, substitution, because lower rank or less expensive coals can be used to effect the prereduction, rather than metallurgical-grade coals which are relatively scarce in the United States.

4. The Bureau of Mines has devised a method to make prereduced iron pellets by simultaneous oxidation and reduction of green (moist) iron ore concentrate balls with a solid reductant.^{1/} The product was designed specifically for the blast furnace, moderate reduction (70-80 per cent) was considered adequate, but physical competence was a must. The feature of concurrent hardening and reduction is unique. Other processes^{2/ 3/ 4/} use already-fired iron ore pellets as the raw material and differ only in the apparatus recommended for the reduction. Almost complete reduction

^{1/} Fine, E. M., J. P. Hansen, and W. B. Heiber. Prereduced Iron Ore Pellets: A New Blast Furnace Raw Material. Bureau of Mines Report of Investigation 6152, 19 pp., (1962).

^{2/} Freeman, E. Direct Iron in Canada. Trans. Canadian Inst. Min. Met., v. 59, pp. 326-329, (April 1956).

^{3/} Mickland, T. G., C. L. Sellonberger, J. J. Platner, and W. V. Mens. Allis-Chalmers Agglomeration-Reduction Process (ACAR Process). Pres. at meeting of Electrochem. Soc., Chicago, Ill., (May 15, 1960).

^{4/} Sibikin, J. G. Development of the SL Direct Reduction Process. Pres. at general meeting of AISI, New York, N.Y., (May 23, 1962).

of the iron to metal is achieved, but a substantial percentage of the feed may degrade to chips and fragments due to reduction disintegration. This phenomenon, in varying degrees, afflicts all indurated iron ore agglomerates.

5. In the laboratory, concentrates from the following raw materials were investigated by the Bureau: Magnetic taconite, specular hematite, nonmagnetic taconite, and synthetic magnetite from roasting. Samples were pelletized batchwise in a 16- by 6-inch smooth steel drum using bentonite as the binder, usually 1 per cent of the dry concentrate weight. Green or dried 1/2-inch pellets were placed in fireclay crucibles, surrounded with reductant and fitted with a loose cover. The crucibles were heated for 30 to 120 minutes in a muffle furnace at 1,740° to 2,280° F. Batches of reduced pellets were evaluated chemically by analysis for total and metallic iron. The only physical test was crushing strength, the total load in pounds required to fracture or deform the 1/2-inch pellets as determined with a laboratory compression tester.

6. Both reduction and crushing strength were generally proportional to time and temperature. Adequate reduction was attained in some cases at 1,900° but at least 2,100° F was required to develop hardness. In a typical experiment, green magnetite balls (64 per cent Fe), treated with lignite for 1 hour at 2,100° F, had crushing strengths of 500 pounds. The reduced pellets analyzed about 80 per cent Fe including 60 per cent metallic iron.

7. An important variable in the present process is the solid reductant. In terms of reduction alone lignite or lignite char was equally effective and superior to other solid fuels. Anthracite and metallurgical coke were good; both petroleum coke and bituminous coal rated lowest. One would expect this to be a function of the CO potential which in turn is related to reactivity of the fuel carbon. There was no simple relationship between reductant and the hardness (expressed as crushing strength) of reduced pellets. With the better reductants, satisfactory hardness was ensured by the expenditure of adequate time at a minimum temperature. Paradoxically, some of the poorest reductions with other coals resulted in very strong pellets.

II. Pilot Plant Production and Evaluation

8. The process has been confirmed on a continuous basis using magnetic taconite concentrate (54 per cent Fe) and North Dakota lignite with the following procedure: Moist concentrate (8-10 per cent H₂O) plus 0.8 per cent bentonite was pelletized (5/8- to 1/4-inch pellets) in a 54-inch disc at the rate of 400-500 lb/hr. Other raw

materials were minus 1-inch lignite (300-350 lb/ton) and minus 1/4-inch limestone (2-3 per cent of the concentrate weight). All raw materials were charged into a 3- x 24-foot rotary kiln, natural gas-fired, with a temperature gradient of 450° to 2,100° F. Retention time was estimated as 1.5 hours. The kiln discharge consisted of reduced pellets, slag fragments, sulfur-containing lime, and partially burned reductant. The pellets, recovered by screening and magnetic separation, analyzed 79.0 per cent Fe and 30.5 per cent metallic Fe.

9. Tonnage quantities of the above pellets were smelted in the Bureau's experimental blast furnace in competition with commercial iron ore pellets manufactured from the same raw material. In addition, some higher grade reduced pellets produced by the SA process were smelted for comparison. Three blast-temperature levels (1,900°, 1,800°, and 1,700° F) were employed at a wind rate of 300 scfm. Natural gas at 1.1 per cent of the wind was also added. Table 1 summarizes the results.

TABLE 1 - Blast furnace results ^{a/}

	Base 1	Test 1	Base 2	Test 2	Base 3-4	Test 3	Test 4
Fe in burden, per cent	31.3	70.0	31.3	79.0	56.1	30.1	36.5
Production rate, net t/d	15.2	20.0	13.1	24.5	13.1	25.0	23.0
Per cent increase	—	33.5	—	35.4	—	33.1	54.7
Coke rate, lb/ton pig iron	1,103	900	1,075	792	1,103	722	611
Per cent decrease	—	20.2	—	38.7	—	33.8	43.3

^{a/} These data were abstracted from Melcher, H. B. Smelting Pre-reduced Iron Ore Pellets. J. Metals, pp. 290-301, (April 1963).

10. In table 1 the base burdens were iron oxide pellets, the test periods were with Bureau and SA pellets. The increase and decrease in production and coke rate respectively were a comparison between the tests and the immediately preceding base period. With more iron in the burden, productivity of the furnace increased and coke consumption declined sharply. With the highly reduced burden of Test 4, productivity was up 54.7 per cent and coke rate down 43.3 per cent. The experimental blast furnace was readily adapted to the high iron raw material and completely operable.

III. Conclusions

11. Prereduced burdens could conceivably eliminate the need for perhaps 50 per cent of the coke now being consumed in ironmaking. In effect this is a substitution of the lower cost fuels (lignite, anthracite) used in the prereduction for coke. Manufacture and utilization of prereduced iron pellets is a tested technique which can improve the productivity of existing blast furnaces and do so with considerably less coke.

IV. Introduction - Part II

10. The principle of reducing iron ore in blast furnaces has remained basically the same as when the blast furnace was first conceived more than six centuries ago - a column of iron ore, carbonaceous fuel, and flux descending in a vertical shaft through a large volume of reducing gases, with metallic iron and slag being drawn from the bottom of the furnace. Many changes have occurred, however, in the types of carbonaceous fuels used, and in the size and efficiency of blast furnaces. In the first years of ironmaking in the United States, as well as in other countries, blast furnaces were small, crude, hand-operated converters that used charcoal for fuel. As supplies of wood charcoal diminished, other metallurgical fuels were tested and, in subsequent years, raw bituminous coal, anthracite, and bituminous coal in the form of coke, were used as metallurgical fuels. Coke soon became the preferred blast-furnace fuel and, except for several countries that currently produce charcoal pig iron because they have ample supplies of wood and no coking coal, coke is now the established blast-furnace fuel in all countries.

13. The reasons for this preference may be attributed to the three necessary functions it performs in a blast furnace, as follows: (1) Coke serves as a reducing agent, (2) it supplies heat to melt the iron and slag, and (3) it maintains permeability of the stock column. In addition, it must be strong enough to support the burden as it descends in the furnace. Coke, therefore, is an ideal blast-furnace fuel, and its unique properties have made possible the development of modern blast furnaces. These mechanical giants rise to a height of more than 100 feet, with hearth diameters approaching 30 feet, and are capable of producing more than 3,000 tons of pig iron daily. Requirements of coke in such furnaces are enormous; roughly 3/4 ton of coke, 1-1/2 tons of ores, and 1/4 ton of fluxing material are required to produce each ton of pig iron.

14. Coke, however, is a processed fuel that requires a special-purpose coking coal, and its manufacture is costly. All bituminous coals do not possess coking characteristics and, consequently, coking coals frequently have to be transported great distances to the iron-producing centers for carbonization. For example, Japan and Italy import most of their coking coal, and the indigenous coals of India, France, Poland, Yugoslavia, and many other countries, which are not strongly coking, must be blended with high-grade imported coals to produce high-quality metallurgical coke. Also, because coking coals must meet exacting specifications, they usually bring premium prices in the market place. Therefore, coke manufacturing costs are necessarily high because of high coal costs, transportation charges, etc.

V. Substitution of Other Fuels by Use of Direct Reduction Processes

15. Because coke is one of the major cost items in pig-iron production, iron producers throughout the world have endeavored to reduce or replace coke in the ironmaking process, and a variety of processes and schemes have been developed that either reduce the quantities of coke required or eliminate coke entirely. For example, the Krupp-Bosch, the R-I, the Strategic-Udy, and the Bassett processes use reducing or smelting carbon in the form of coke breeze, or even low-volatile coal, instead of lump-size metallurgical carbon. Other processes, such as the Hy-L process, the H-Iron process, the Nu-Iron process, and many others, employ gases as reducing agents. The proposed processes vary widely, but all have two things in common - they have a relatively low capital cost when compared with blast-furnace installations, and virtually all use reducing agents less costly than metallurgical coke.

16. Generally, the term "direct reduction" is incorrectly applied to all processes that produce iron outside of a blast furnace, rather than to those that reduce iron oxide by reacting it directly with hydrogen and carbon monoxide. The term, however, has found general usage, and all alternate processes for making iron will be referred to as direct-reduction processes.

17. These processes can be divided into two groups - methods that use solid carbon for reduction, and methods that employ gases as reducing agents. The former is based on reduction by solid fuels such as coal, coke, and breeze; the latter reduces iron ore by reacting it with externally produced hydrogen, carbon monoxide, or a mixture of both gases. In some of the processes, reduction is accomplished in electric furnaces, while others use rotary furnaces, cylindrical retorts, low-shaft

furnaces, and fluidized beds. Another distinction between the processes is that some produce sponge iron that requires additional heat for refining, whereas others produce molten iron that can be charged directly into open-hearth or electric furnaces.

18. Gaseous-reduction processes are particularly interesting in that they use hydrogen and/or carbon monoxide obtainable by conversion from natural gas, crude oil, or coal. The type of reductant, of course, varies with the process, but a major factor for consideration is availability and cost of the fuel from which the reductant is produced. Some processes use a mixture of hydrogen and carbon monoxide, produced by the water-gas reaction, while others generate hydrogen by partially oxidizing natural gas with air. Still others use a synthesis gas. The raw fuel used for producing the reducing gases is not important, however, for hydrogen and carbon monoxide can be made from any fuel, and the fuel that produces the cheapest gas obviously would be used for each process.

19. In addition to having a relatively low capital cost and being able to use lower grade and/or gaseous fuels, direct-reduction processes offer other advantages. Two of particular significance are size of the unit and flexibility of operations. Whereas blast furnaces must be large and kept operating continuously to be economical, it is conceivable that some of the direct processes could be built in any size and operated at any rate necessary to satisfy requirements. One developer claims that his process can be designed for units that will produce as little as 50 tons per day, while maximum capacity is unlimited. Also, plants could be built in practically any area with a supply of iron ore and fuel for making reducing gases, rather than being confined to the steel centers where iron ore and coking coal exist or can be economically brought together.

20. Another advantage that some of the direct processes claim is that ore size is not critical that either lumps or dust can be processed. They can also handle complex ores and selectively remove phosphorus, sulfur, and other elements. However, some processes do require specially prepared ores, and the fluidized-gaseous methods can remove only oxygen and a little sulfur.

21. Some ideas of the volume of effort devoted to direct-reduction processes can be obtained by noting that, in the United States alone, before 1951, over 240 processes were patented. The processes, however, are in very different stages of development, and only a few are being operated commercially except those that produce sponge iron for powder metallurgy.

VI. Substitution of "Formed" Coke in the Blast Furnace Stack

22. Notwithstanding all the research and development work done on direct-reduction processes, the modern blast furnace still represents the most economical means of reducing iron ores on a large scale, and blast furnaces continue as the prime producers of pig iron. Blast-furnace fuel costs have increased greatly in recent years, however, particularly in areas where coking coals are limited or not available, and much effort has been expended in finding a substitute for coke. One of the most promising developments is "formed" coke, a carbonized briquet produced from noncoking coals. As far back as 1939, large-scale blast-furnace tests were conducted with so-called formed coke produced from Yugoslav lignite and in the late 1950's, extensive tests were conducted in Poland to develop a method of producing metallurgical briquets from high-volatile noncoking coal. The Polish process consisted essentially of three steps: (1) The manufacture of a char of low-volatile content by fluidized carbonization of the coal, (2) the briquetting of this char with the soft pitch obtained in (1), and (3) the mild heat treatment of these briquets in an oxidizing atmosphere at temperatures of about 250° C. A fourth step, final carbonization, could be added, but the objective of the Polish process was to obtain hard briquets suitable for use in blast furnaces and foundry cupolas by mild heat treatment alone. Although no full-scale blast-furnace tests were made using formed coke alone, because of insufficient supply, a 70- per cent oven-coke and 30- per cent formed-coke mixture performed well in a blast furnace.

23. Great Britain, France, West Germany, East Germany, and several other countries also have done considerable research and development work on the problem of utilizing noncoking coals. However, information is sketchy on the use of formed coke in blast furnaces in these countries.

24. In the United States a process has been developed for making metallurgical coke from low-rank western coals. This process, developed by the EC Corp. to produce a suitable carbon for use in the reduction of phosphate rock in this company's electric furnaces at Pocatello, Idaho, is a multistage process, also, in which high-volatile subbituminous noncoking coal is crushed, dried, carbonized, and calcined to produce a uniform carbon product called calcinate. Gas and liquids are recovered from the coal during processing; the gas is used as a fuel and the tar is processed to obtain liquid binder used in briquetting. The calcinate is combined with liquid binder and formed into briquets of the desired shape and size. The green briquets are

then cured and coked to produce a low-volatile (1.9 per cent), high-strength product. Results of laboratory tests indicated that these briquets might be suitable for many applications, including possible replacement for metallurgical coke. Accordingly, a joint research and development venture was established in 1961 between FMC Corp. and United States Steel Corp., and a \$2.5 million plant, designed to produce 250 tons of briquets daily, was constructed near Kemmerer, Wyoming, to process local sub-bituminous coal. In 1962, nearly 2,000 tons of this carbon product was used during an 18-week test period in United States Steel's experimental blast furnace at Universal, Pennsylvania. It has been reported that the briquets performed excellently over a range of wind rates.

25. Obviously, nearly all of the formed-coke processes require more than one step. However, most of the steps do not require expensive and elaborate high-temperature plant equipment, and each step is continuous. A physical characteristic of formed coke that could make it an ideal blast-furnace fuel (if it meets all other requirements) is its uniformity of size and shape. The cost of formed coke will govern the extent to which it will replace metallurgical coke in blast furnaces. If production costs of formed coke can be made competitive with oven coke, the future of formed coke for metallurgical application appears promising.

VII. Substitution of Other Fuels by Injection in the Blast Furnace Combustion Zone

26. Other research programmes aimed at improving blast-furnace operations have succeeded in greatly reducing coke requirements, and the modern blast furnace uses less coke today than at any time in the history of ironmaking. In the United States, coke rates have decreased 24 per cent in the past 10 years, and current coke consumption per ton of hot-metal production is less than 1,400 pounds. Similar results have been accomplished in the USSR, Great Britain, West Germany, France, Japan, and many other countries. A number of technological developments have contributed to this reduction, but the most prominent are: (1) Improved burden preparation, both by increasing the iron content of the ore and by producing a feed having superior physical properties, such as pellets and self-fluxing sinter, (2) higher blast temperatures, (3) humidification of the blast, (4) oxygen enrichment of the blast, and (5) the injection of hydrocarbons.

27. Undoubtedly, the most important development in iron metallurgy in recent years has been the injection of hydrocarbons to replace coke in blast-furnace operations. The first completely successful fuel-injection experiments in the United States, which were the result of a co-operative project between the Bureau of Mines, United States Department of the Interior, and the United States Steel Corp., were made in the Bureau's experimental blast furnace at Pittsburgh, Pennsylvania, in January 1959.⁵ These tests were conducted with natural gas, but in later tests, anthracite fines and fuel oil were used.⁶ 7

28. The method of injecting a gaseous fuel is relatively simple. In most cases, gas is fed to a circle pipe around the furnace at a pressure higher than that of the air blast and is introduced into the furnace combustion zone by means of an injection orifice leading through the water-cooled portion of each tuyere. The injection of oil is similar to that of gas, being accomplished through a header or circle pipe around the furnace with an offtake for each tuyere. Since the combustion rate of oil is less than that of gas, oil is generally introduced farther back from the nose of the tuyere or by means of a lance through the blowpipe, so that it enters the air stream as much as one foot back from the tuyere. The injection of pulverized or powdered coal is more complicated because of the difficulty in feeding solid particles uniformly into the high-pressure, hot-blast air stream.

29. The injection of solid fuels through the tuyeres of a blast furnace has intrigued blast-furnace operators for many years, and the literature reports that attempts to inject solid fuels were made as early as 1840. In 1877, a patent was issued in Germany which pertained to the injection of fine run-of-mine coal, coke, or charcoal into a blast furnace.⁸ In 1937, Mr. E. Bertram, also of Germany, described the injection of fusible and combustible materials into the blast-furnace

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- 5/ Melcher, Norwood B., J. P. Morris, E. J. Ostrowski, and P. L. Woolf. Use of Natural Gas in an Experimental Blast Furnace. Bureau of Mines Report of Investigations 5621, 15 pp., (1960).
- 6/ Ostrowski, E. J., M. E. Royer, and L. J. Kopelowski. Injecting Solid Fuels into Smelting Zone of an Experimental Blast Furnace. Bureau of Mines Report of Investigations 5648, 13 pp., (1960).
- 7/ Woolf, P. L., V. M. Mahan. Fuel Oil Injection in an Experimental Blast Furnace. Bureau of Mines Report of Investigations 6150, 23 pp., (1963).
- 8/ Albers, K. German Patent No. 682, (1877).

9. Solid-fuels injection experiments were reported in the Soviet Union in 1943, when pulverized coal was injected for short periods into a blast furnace at the Dzerzhinskii plant, and, in 1955, these coal-injection experiments were continued on a blast furnace with coal injected intermittently through a limited number of blast-furnace tuyeres.¹⁰

10. The first solid-fuel injection experiments in the United States were conducted in 1959 by the Bureau of Mines, using anthracite fines in a pilot-plant blast furnace at Pittsburgh, Pennsylvania. The first coal-injection system on a commercial blast furnace, however, was installed by the National Steel Corp. on its No. 2 blast furnace at Buffalo, New York, in 1960. This system used coal crushed to minus 1/8 inch, and tests showed that a coal-to-coke replacement rate of approximately 1.1 was obtained when coal was injected into the blast furnace at a rate of about 17 per cent of the total blast-furnace fuel requirements. This company recently has installed a different type of system on its No. 4 blast furnace at Weirton, West Virginia, which, it has been reported, can replace up to 15 per cent of the coke with injected coal. In addition, National Steel plans to add oxygen to the blast, a procedure that should increase the proportion of coal that can be injected into the furnace and further reduce coke requirements.

11. The coke savings that can be obtained at any particular blast furnace depend on a number of factors such as the quality of the burden materials, the furnace production rate, and the maximum attainable hot-blast temperatures. Because of differences in these factors, results from various plants injecting hydrocarbon fuels appear to vary; however, if allowances are made for blast temperatures, blast humidity, ore and coke burdens, and hot metal quality, actual coke savings are in all cases approximately the same. According to calculations made by a research engineer of a large American iron and steel-producing company, the amount of various fuels that could be injected while maintaining iron productive efficiency are as follows:^{11/}

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- 9/ Bertram, E. The Injection of Fusible and Combustible Materials into the Blast Furnace Hearth. Archiv Eisenhüttenwesen, Vol. 1, pp. 18-32, (1927-1928).
- 10/ Luginov, V. I., G. G. Oreshkin, I. G. Polouchenko, A. A. Sarokin, and I. N. Kordasevich. Injection of Powdered Coal into Blast Furnace Hearth. Stal, Vol. 16, pp. 675-682, (1956).
- 11/ Agarwal, J. C. Technical Considerations of Fuel Injection into the Blast Furnace. Winter Annual Meeting, The American Society of Mechanical Engineers, New York, N.Y., Paper No. 62-WA-236, 9 pp., (Nov. 23-30, 1962).

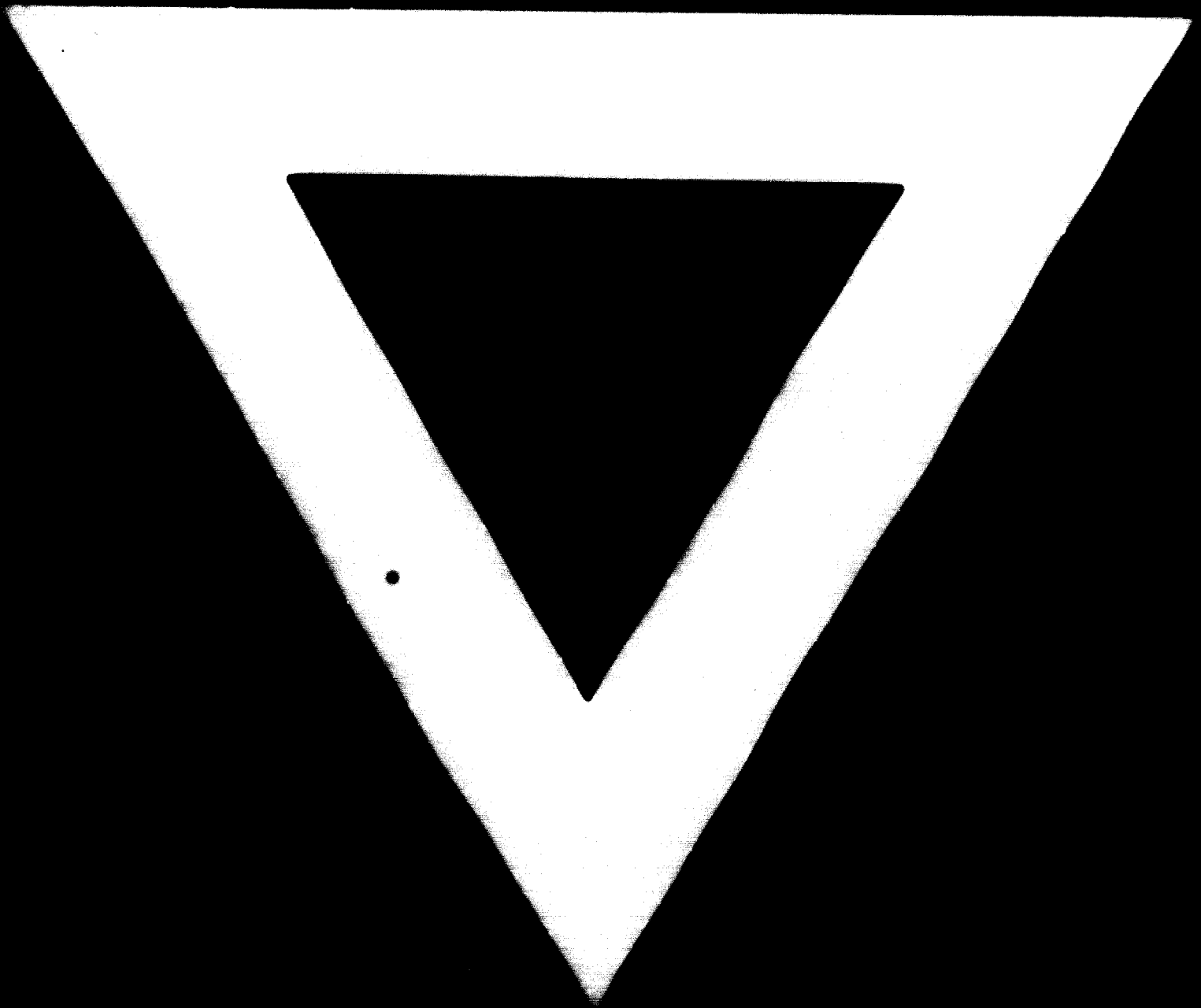
Savings in coke consumption

Fuel	Pounds of fuel injected per ton of iron	Pounds of coke saved per ton of hot metal	Pounds of coke saved per pound of fuel injected
Natural gas	18	103	1.59
Fuel oil	110	160	1.38
Coal	193	231	1.16

32. To explore the potential benefits that may be obtained from blast-furnace fuel injection, a co-operative agreement to conduct a comprehensive research programme on fuel injection was consummated in March 1962 between the Bureau of Mines and Blast Furnace Research, Inc., an organization representing 22 major iron and steel producers in the United States and Canada. All investigations will be conducted in the Bureau's experimental blast furnace at Bruceton, Pennsylvania, and the test programme, which started in August 1962, will require several years to complete. Although the research is concerned primarily with supplemental-fuels injection, including the injection of pulverized solid fuels, coal-oil and coal-water slurries, natural gas, and fuel oil, other operating variables of the blast furnace, such as oxygen enrichment and humidification of the blast, and changes in blast temperatures, will be studied also. The results of this work will be published eventually after representatives of Blast Furnace Research, Inc., and the Bureau of Mines have evaluated the data obtained in the experiments.

33. In 1962, there were 26 iron and steel-producing companies employing tuyere fuel injection. Roughly, 44 blast furnaces were using natural gas; 2, coke-oven gas; 7, fuel oil; 4, a mixture of oil and gas; and 1, powdered coal. As explained previously, coke savings varied because of different operating conditions and ranged from 75 to 350 pounds per ton of hot metal.

34. The impact of fuel injection on overall blast-furnace coke requirements in the United States has not become evident thus far, because of the small number of blast furnaces using this new technique. However, developments in the past several years indicate that supplemental fuel injection will become widespread and should reduce coke requirements substantially in the next decade. It is, therefore, not unreasonable to assume that with the use of specially-prepared burdens and improved operating blast-furnace techniques, particularly the injection of supplemental fuels, coke rates approaching 700 pounds per ton of hot metal, or about half of the quantity used in 1962, will be attained.



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