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THE DEVELOPMENT AND OPERATION OF THE Q-BOP PROCESS IN THE UNITED STATES STEEL CORPORATION[1/]

by

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S U M M A R Y

Because of inherent advantages which were indicated to be attainable with the OBM bottom-blown oxygen process developed into commercial practice by Eisenwerk-Gesellschaft MAXIMILIANSHUTTE, mbh, U. S. Steel undertook a broad research program to develop the technology necessary to produce high quality steel in 200-ton furnaces. The results were highly successful and led to installation of commercial facilities by U. S. Steel.

U. S. Steel will have over 8 million tons annual steelmaking capacity in the Q-BOP at two steelmaking locations by the end of 1973. The first of these facilities is a converted BOP shop which is in operation at Gary Works, Gary, Indiana. The second Q-BOP shop is being installed in an existing open-hearth shop at Fairfield Works, Birmingham, Alabama, and will be in operation by the end of the year.

The start-up of the Q-BOP at Gary has been smooth, and U. S. Steel is enthusiastic about the future of Q-BOP steelmaking.

For some time, considerable experimentation has been directed at developing methods of economically bottom blowing pure oxygen to retain the advantages of a quieter blow and better bath mixing which are inherent in bottom blowing, and at the same time to make existing Bessemer shops more productive and competitive.

In 1967, Dr. Karl Brotzmann and his associates of Maxhütte worked with Guy Savard and Robert Lee of L'Aire Liquide, Canada, to adapt a unique gas-shrouded tuyere for use in the bottom-blown basic Bessemer converter. The tuyere consisted of an oxygen-blowing pipe encased within a slightly larger pipe, Figure 1. When a hydrocarbon, such as propane or natural gas, was blown through the annulus between the two pipes, the endothermic decomposition of the hydrocarbon at the mouth of the tuyere effectively cooled the tuyere. With this concentric tuyere, pure oxygen could be introduced into a steel bath without excessive refractory erosion. The first heat using the process, called OBM by Maxhütte, was made in December 1967; and by March of 1968 Maxhütte had a converter in operation on a full-scale production basis at Sulzbach-Rosenberg. By 1971, when U. S. Steel became interested in the process, its total steelmaking capacity was 5 million tons. This capacity consisted entirely of converted basic Bessemer process shops with 5- to 80-ton furnaces. The general operating practice employed was to blow the heat to very low carbon levels, and then recarburize as much as necessary.

To be of interest to U. S. Steel, however, the adaptation of the OBM to large furnaces and high tonnages was necessary. In addition, it was essential to develop a catch-carbon practice by which the blow could be stopped near the desired carbon level to produce high-quality steel from U. S. Steel's low-phosphorus hot metal. The 30-ton pilot BOP furnace, at our Steelmaking Laboratory, was quickly converted to bottom blowing and the first heat was blown on August 14, 1971. By the end of November 1971, 253 heats were produced at this pilot facility. The results of this developmental work were so successful that by mid-December U. S. Steel decided to install two 200-ton Q-BOP furnaces in the open-hearth shop of Fairfield Works. Shortly afterward, it was decided that the three BOP furnaces already under construction at the No. 2 BOP shop at Gary Works would be changed to Q-BOP. Blowing of heats in the pilot Q-BOP continued through mid-April 1972, with 84 additional heats being made to further refine the technology needed to operate the Q-BOP shops at Fairfield and Gary Works.

Fig. 1 - The Maxhütte tuyere

Experimental Work at the Steelmaking Laboratory

The conversion of the Steelmaking Laboratory 30-ton pilot BOP furnace to Q-BOP required major revision. The bottom of the furnace was cut off and replaced with a removable refractory-lined plug, Figure 2. To get adequate dephosphorization with the catch-carbon practice it was found to be essential to inject powdered lime through the bottom with oxygen. This was done by means of a specially designed injection system. Also, to prevent the backflow of molten metal through the tuyeres at any time, piping was installed to permit the blowing of inert gases through the tuyeres when the oxygen and hydrocarbon were turned off. To insure reproducible performance, all systems were fully instrumented. During the production of the 337 heats in the experimental program, various aspects of Q-BOP steelmaking were studied.

Tuyeres and Refractories

To determine the most suitable conditions for smooth blowing and minimum refractory wear, water model studies were conducted in the Laboratory, and then numerous tuyeres were designed and installed in the pilot furnace in various placement configurations in the bottom plugs. Both propane and natural gas were investigated as tuyere coolants, with the amounts of each varied to determine optimum usage.

This work led to the development of the technology needed to construct the plugs used in U. S. Steel's commercial furnaces. Little difference was noted between refractory wear in the barrel and cone of the Q-BOP and a BOP, so conventional BOP refractories were used in these areas of the pilot and commercial Q-BOPs.

Lime Injection

Lime injection proved to be essential to meet phosphorus requirements using the catch-carbon practice. The timing and the rate of lime injection were found to be important parameters in dephosphorization, and the optimum injection practice to minimize lime usage was determined experimentally. It was also found that the bottom injection, rather than the top charging of lime, resulted in much smoother furnace operation.

Charge Control and Scrap Melting

The charge-control model developed by U. S. Steel for its BOP operations was modified to comprehend the differences between the Q-BOP and BOP. The accurate control of carbon and temperature

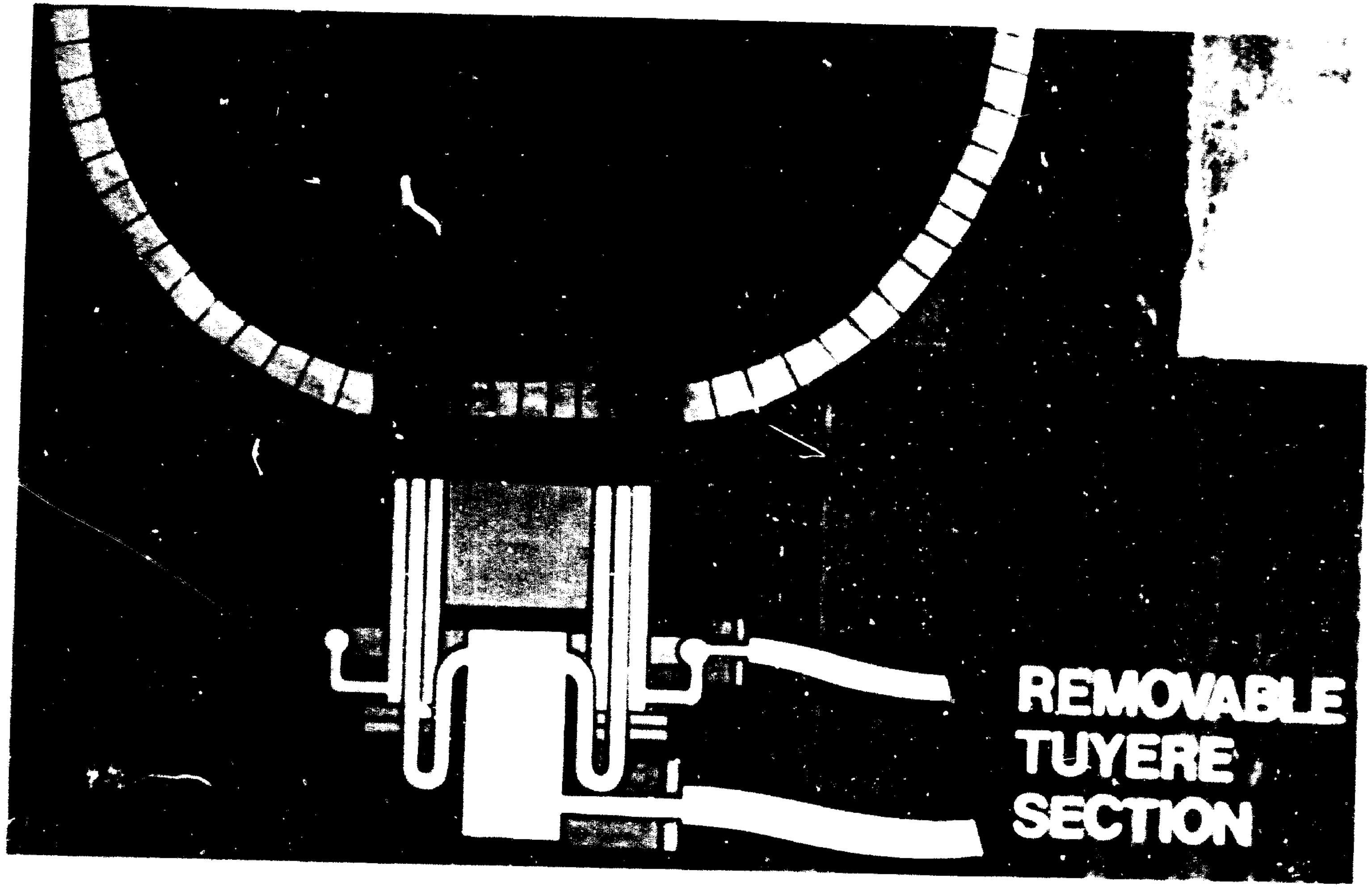

Fig. 2 - Furnace bottom arrangement

realized with this model, in combination with the proper lime-injection practice, permitted use of the catch-carbon practice for production of steels with acceptable phosphorus levels over a wide range of carbon contents.

Modification of operating practices in the pilot Q-BOP enabled it to consume more scrap than is possible with the BOP. Inherently, scrap melting is favored in the Q-BOP by the absence of the water-cooled lance, which acts as a heat sink to remove heat from the BOP furnace, and by lower vaporization of iron in the Q-BOP compared to a BOP. In addition, bottom blowing in the pilot furnace could proceed at a higher rate than top blowing, so blowing time was shortened, decreasing heat loss from the furnace and also increasing furnace availability by up to 10 percent. Firing of the furnace during nonblowing periods resulted in increased scrap consumption without the lengthening of tap-to-tap times experienced with the usual scrap preheating practices. Oxygen-jet lances installed in the side of the furnace gave additional heat by burning carbon monoxide to carbon dioxide and significantly increased the scrap-melting capability. Blowing oxygen and natural gas instead of an inert gas during furnace rotation was also effective in increasing scrap consumption. Taken together, for shops with identical hot-metal composition and temperature, these practices enable the Q-BOP to melt up to one-fifth more scrap than the BOP, without lowering productivity, which is a significant advantage when economic conditions warrant.

It was found that the better mixing of the steel bath from bottom blowing allowed the Q-BOP to melt larger scrap pieces than are possible with the BOP. Ingot butts measuring 28 by 38 by 35 inches and weighing up to 10,700 pounds (710 by 965 by 890 mm and 4,850 kg) were charged and were completely melted when the furnace was turned down for sampling after a ten-minute blow. Butts this large had to be cut into smaller sections to be melted in the pilot BOP furnace.

Related Topics

Other subjects of a more limited scope were also investigated during the primary Q-BOP development. Degassing of steel in the furnace with argon was tried and found to be successful; a reduction in dissolved oxygen content of up to 70 percent could be effected with a one-minute argon purge of the bath. Also, hot metal containing 1 percent phosphorus was processed with a single-slag technique, and alloy steels such as 3 percent silicon steel and several grades of stainless steel were made.

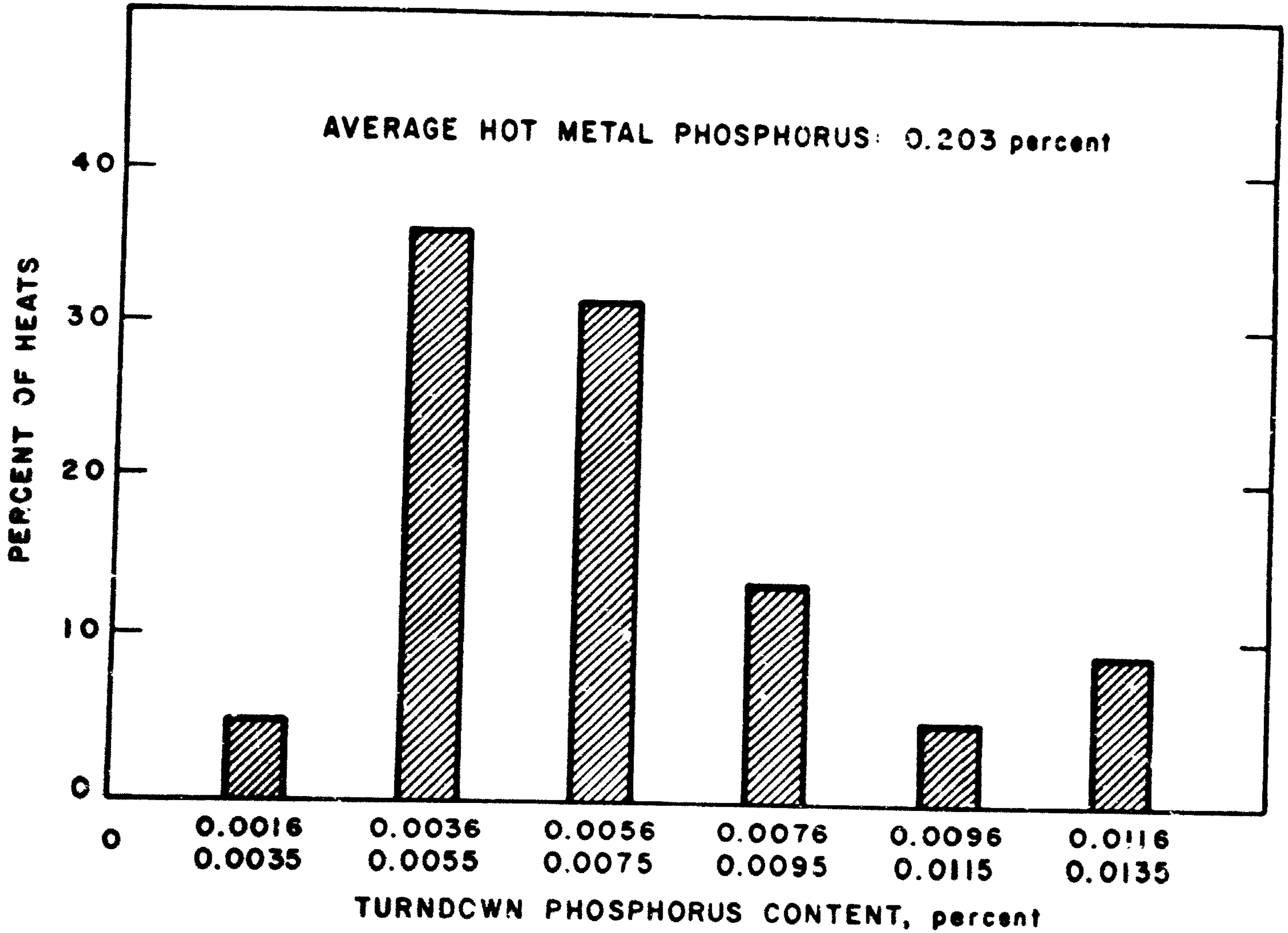

Fig. 3 - Phosphorus levels in Q-BOP steel

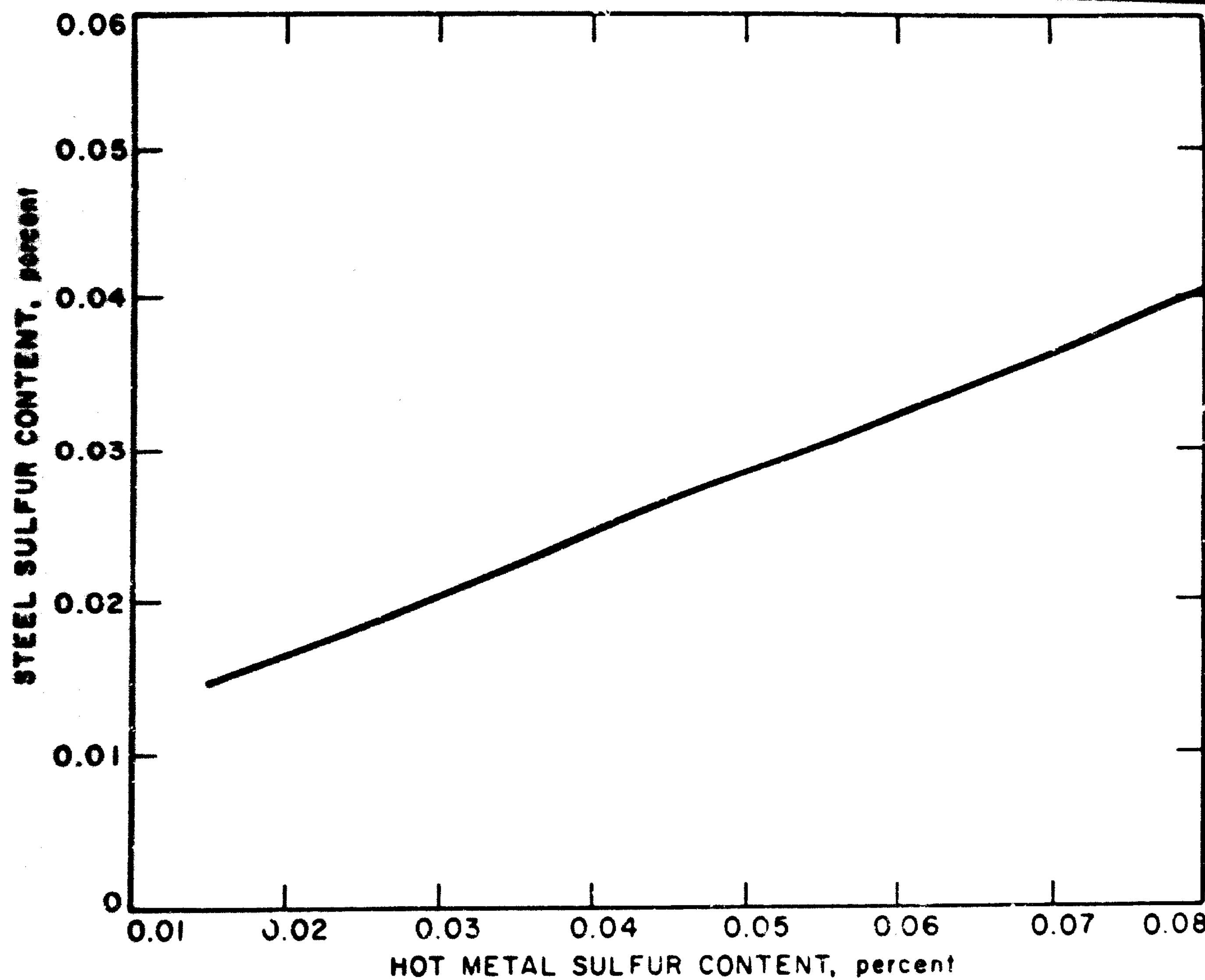

Fig. 4 - Sulfur levels in Q-BOP steel

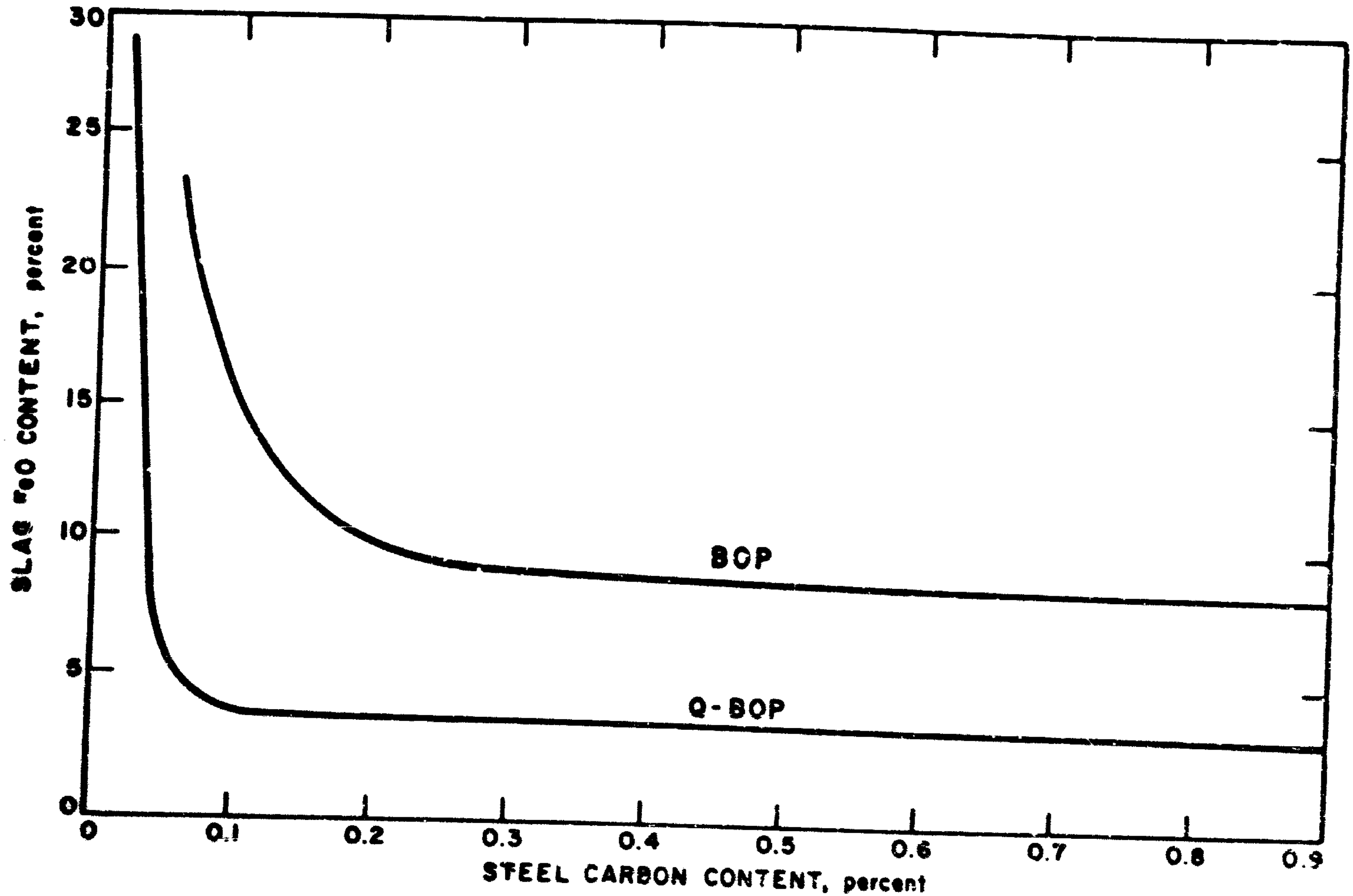

Fig. 5 - Slag FeO contents in Q-BOP steel as compared with normal BOP practice

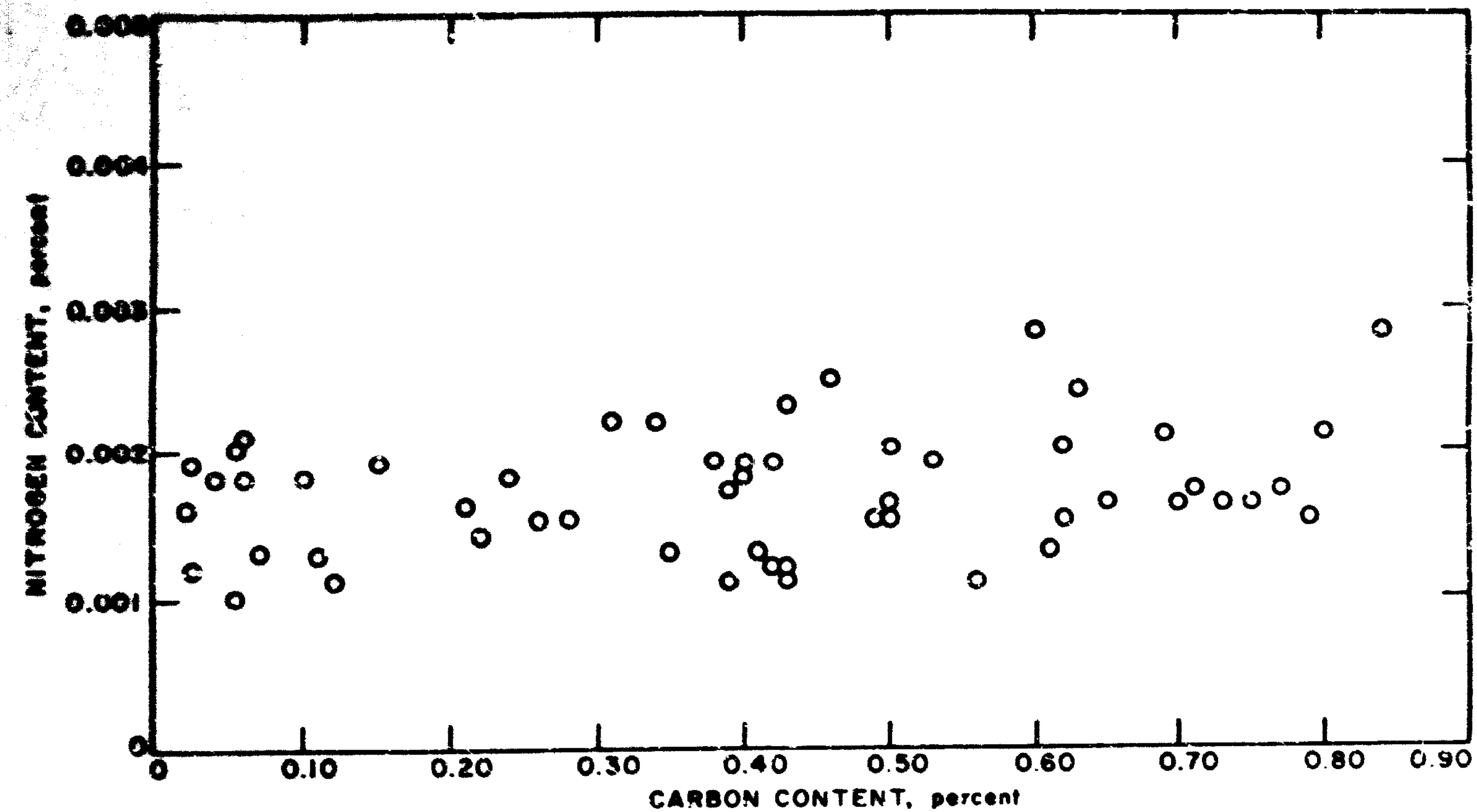

Fig. 6 - Nitrogen levels at turndown in Q-BOP

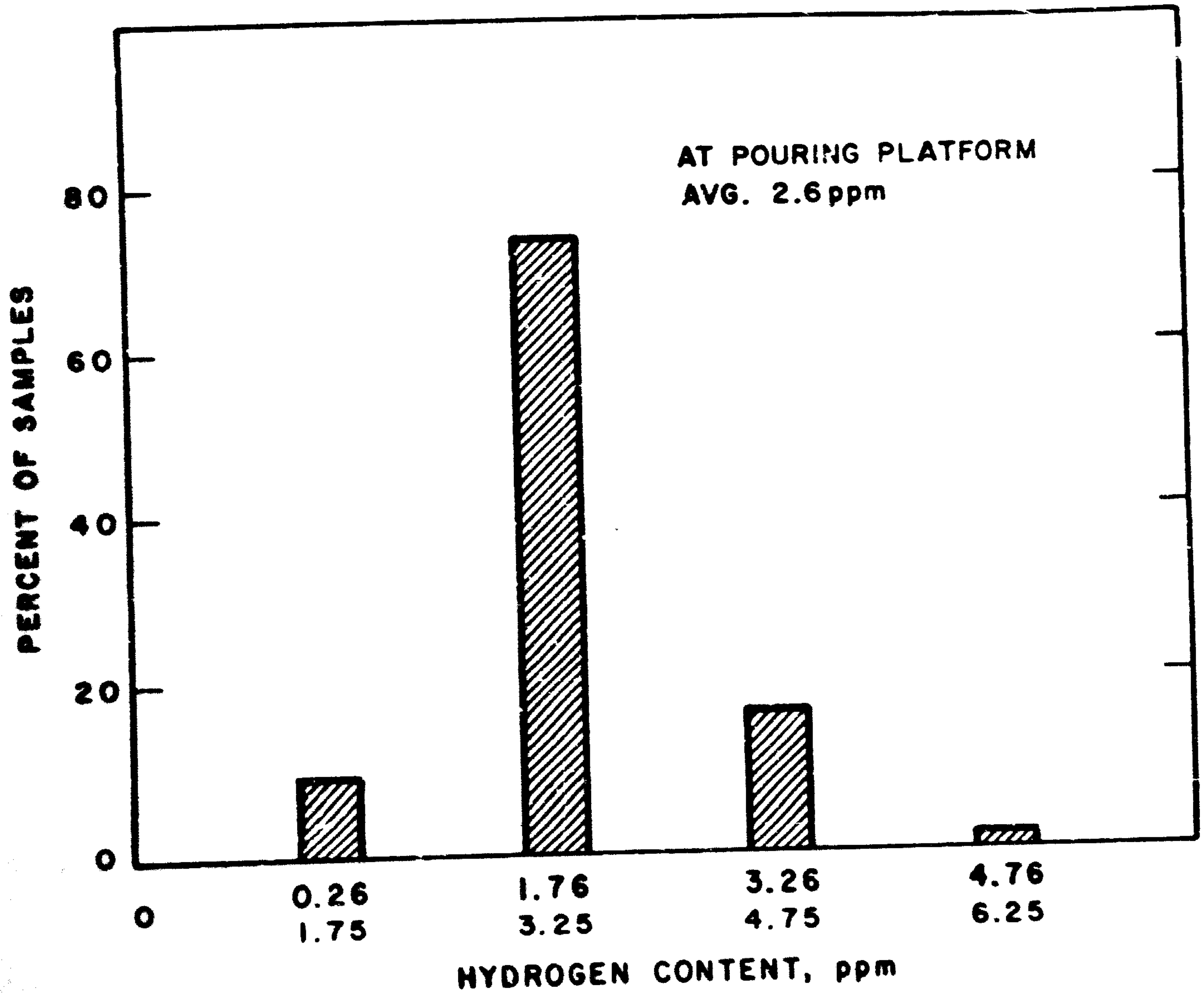

Fig. 7 - Hydrogen level at turndown in Q-BOP

Metallurgical Aspects of the Q-BOP

The metallurgical performance of the pilot Q-BOP proved to be excellent.

Phosphorus. Phosphorus could be removed to low levels quite easily when making steels containing up to 0.05 percent carbon, Figure 3. Over 40 percent of the heats contained 0.005 percent phosphorus or less, and 90 percent contained a maximum of 0.010 percent phosphorus. At higher carbon levels, temperature and lime-injection practice had to be controlled accurately. Satisfactory phosphorus levels were attained from hot metal containing 0.2 percent phosphorus in heats containing up to 1 percent carbon.

Sulfur. The ability to introduce powdered lime into the steel bath resulted in good desulfurization. Steel with only 0.035 percent sulfur was produced from hot metal containing 0.070 percent sulfur, Figure 4. Modification of the lime-injection practice gave still better desulfurization. For example, heats averaging 0.020 percent sulfur at turndown were made from hot metal averaging 0.07 percent sulfur when a special lime-injection practice was used. It should be mentioned that all hot metal was skimmed to remove blast-furnace slag and kish prior to charging.

Steel Composition. The iron oxide contents of the pilot Q-BOP slags were lower than those of comparable BOP or open-hearth heats, Figure 5. As a result, residual manganese contents were slightly higher with the Q-BOP than with the BOP and open hearth. Oxygen content of the Q-BOP steel bath, however, approached equilibrium similar to that of the BOP and open hearth.

Nitrogen levels at turndown were consistently below 0.0025 percent for a wide range of steel carbon contents, Figure 6. Hydrogen content averaged 2.6 ppm at the pouring platform, Figure 7, which is comparable to the BOP, but ranged between 2 and 6 ppm at furnace turndown, slightly higher than for the BOP. The decrease in hydrogen content between the furnace and the pouring platform could be attributed to the purging of the bath by the nitrogen blown during the furnace rollover from the sampling to tapping position.

Steel Quality

To ensure that steels made by the Q-BOP met the same high quality standards as steels made by other processes, many of the ingots from the 30-ton pilot heats were processed on the regular production facilities at U. S. Steel plants, and the products subjected to extensive testing.

The Q-BOP heats evaluated for product quality included hot- and cold-rolled, rimmed, capped, and aluminum-killed sheets, tin-mill products, structural sections, plates, rails, billet products a[illegible] electrical sheets. The results of this testing at the plants, at the Research Laboratory, and in some instances by customers, showed that the quality of all grades of steel made with the Q-BOP was equal to the quality of steel made by the BOP and open hearth.

Performance of Hot- and Cold-Rolled Sheets. The steel was inspected for defects after slabbing, after hot rolling, and after cold rolling. Conditioning requirements and rejection rates were determined for comparison with standard BOP product. In addition, the sheet product was subjected to chemical analysis and to micro-cleanliness, microstructure, tension, hardness, bend, welding, plastic anisotropy, strain hardening, strain aging, and special formability tests. These tests showed that the quality and properties of Q-BOP steel, including the special surface quality required for exposed applications, are comparable to those of product produced from open-hearth and BOP steel. Commercial-quality (CQ) and drawing-quality (DQ) sheets and coils were used to produce water-heater outer jackets, stove backs, boiler door panels, elevator cab panels and doors, and exposed parts for metal caskets. All product exhibited satisfactory surface quality and fabrication performance.

Tin-Mill Products. Three different steel compositions were melted for the manufacture of five types of tinplate having a wide range of properties. The applications included double-reduced beer and soft-drink can-body stock, beaded can bodies for food products, and single-reduced box-annealed product for severe forming applications such as aerosol domes, and paint cans with clinched ears. Samples were also evaluated in an experimental program to develop full-removal steel ends.

Evaluation of the tinplate by U. S. Steel and some of our customers showed that the microstructure and mechanical properties are equivalent or similar to those of the same grades of open-hearth and BOP steels used commercially for tin-mill products. Special property tests indicated that the tinplate made from Q-BOP steel would be satisfactory for applications requiring Type K tinplate. Commercial fabrication of the product was reported satisfactory. As a result of these tests, our customers indicated that they anticipate no difficulty in using tin-mill products made from Q-BOP steel and waived the normal pack storage tests.

Performance of Structural Steel. Q-BOP slabs of semikilled and killed steel were rolled to 1/4- to 3-inch-thick plate, and blooms of semikilled steel were rolled to angles. The surface quality, microstructure, microcleanliness, tension tests, bend tests, and fatigue tests were similar to those of conventional open-hearth and BOP steel plates and angles with similar compositions. The plates and angles met the required ASTM specifications or specific customer requirements, and no problems were encountered during fabrication.

Performance of Rail Steel. Ingots of Q-BOP steel were processed to 119- and 132-pound rail. The tensile tests, nick and break tests, drop tests, and microcleanliness and macroetch tests were satisfactory and comparable to those of open-hearth rails. Although the rails were not placed in service, the tests showed that rails produced by the Q-BOP process had properties comparable to those of conventional open-hearth-steel rails and would be expected to have comparable service performance.

Performance of Billet Steel. Ingots of Q-BOP rimmed, semikilled, and killed carbon steel were processed to billets and bars or flats. The properties of the bars and flats were considered satisfactory for supplying on regular orders.

Performance of Silicon Steel Sheet. One Q-BOP heat of 3-percent silicon steel was processed to 0.011-inch thick oriented electrical sheet product. The results of magnetic property tests indicate that oriented silicon steel of excellent quality can be produced from Q-BOP steel. The coils have been applied on customer orders with satisfactory performance.

The results of this product evaluation showed that the Q-BOP produced high-quality steel, while the operation of the pilot Q-BOP furnace demonstrated advantages in operating costs; therefore, work quickly started on installing Q-BOP in the Fairfield open-hearth shop and the Gary No. 2 BOP shop. The construction of these two shops illustrates the alterations which are necessary to convert existing open-hearth and BOP shops to Q-BOP.

Installation of Q-BOP in the No. 1 Open-Hearth Shop at Fairfield Works

Bottom injection of powdered lime and bottom blowing of pure oxygen in the Q-BOP eliminate the need for overhead storage bins and the oxygen lance required for a BOP. This means that an existing open-hearth shop may have sufficient headroom for the installation of a Q-BOP. This is presently being done at U. S. Steel's Fairfield Works in Birmingham, Alabama, at an investment of approximately half of that required for a BOP shop of identical capacity.

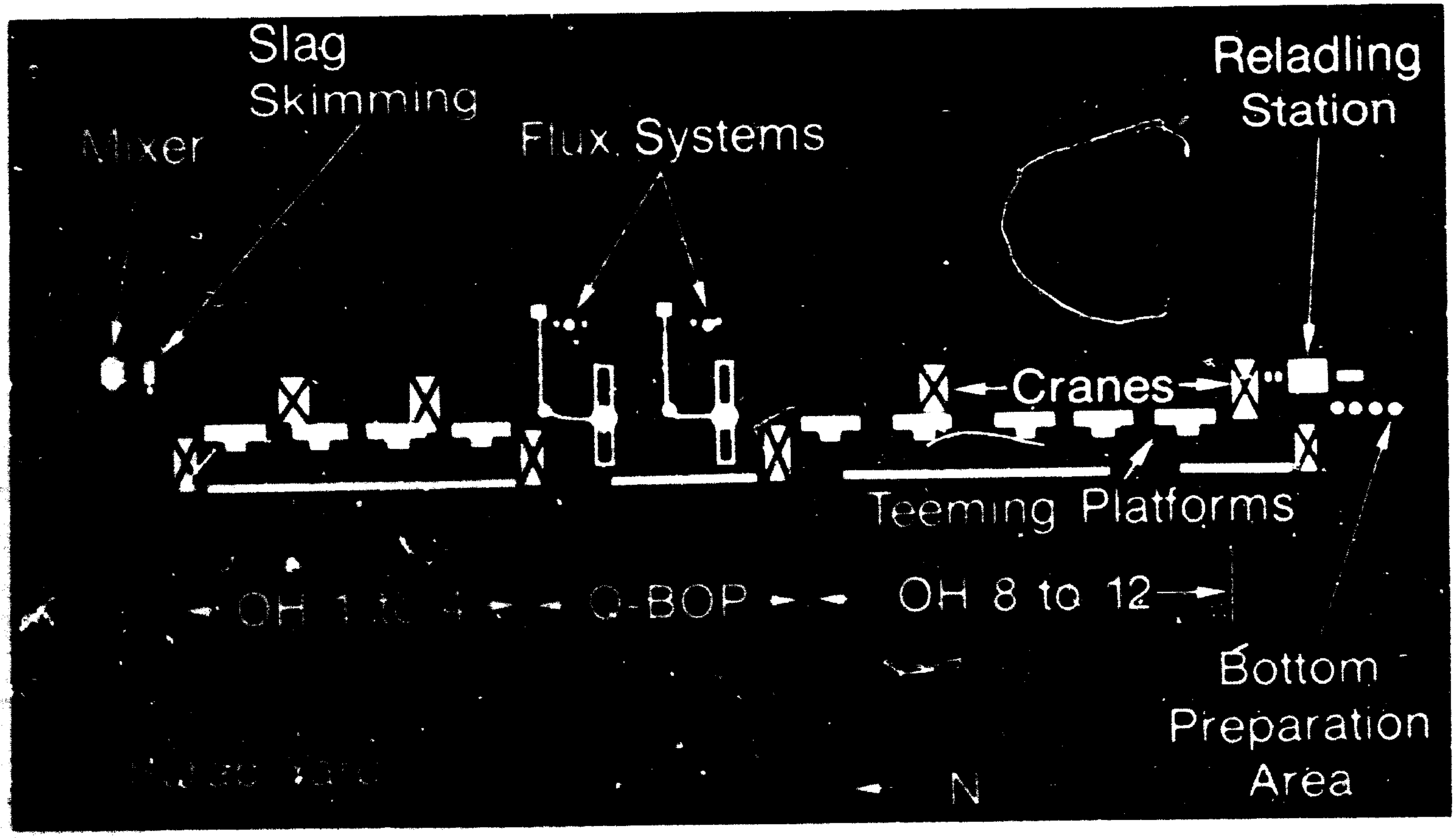

Fig. 8 - Installation of Q-BOP in No. 1 Open-Hearth Shop at Fairfield Works

The No. 1 open-hearth shop at Fairfield Works consists of twelve 230-ton furnaces. The entire steelmaking capacity of this shop will be replaced by two 200-ton Q-BOP furnaces. The Q-BOP furnaces and auxiliaries are being installed in the present open-hearth building at the site of No. 5, 6, and 7 open hearths which have been dismantled, Figure 8. During construction, eight of the nine remaining furnaces are being operated with the other being used as a spare.

The installation of the Q-BOP in the open-hearth building permits the utilization of existing cranes for scrap handling, charging, and teeming. In addition, most of the other auxiliary equipment in the shop can be used for the new Q-BOP.

Hot-metal handling facilities will be the same as in the open-hearth shop with the exception of the transfer ladles, which will be modified with nose spouts to facilitate the charging of the Q-BOP furnaces. Scrap will be loaded at the present scrap yard to the north of the shop and transported to the furnace area with mobile scrap carriers.

An injection system at each furnace will be used to add all slag-forming fluxes through the tuyeres in the furnace bottom. Oxygen, natural gas, and nitrogen will be supplied to the furnace tuyeres with the type of gas blown and the blowing rate determined by the furnace position.

Conversion of the Gary Works No. 2 BOP Shop to Q-BOP

The absence of a high-bay furnace aisle also means that even a greenfield Q-BOP shop can be constructed at a considerably lower cost than a comparable BOP shop. When U. S. Steel decided to install Q-BOP in the No. 2 BOP shop under construction at Gary Works, the high-bay shop already had been erected; however, the anticipated savings in operating costs from a shorter heat time and a higher yield justified the shop being completed with the Q-BOP process.

The three BOP furnaces in the No. 2 BOP shop at Gary Works had been designed to replace the more than 30 furnaces in the three existing open-hearth shops. The facility was scheduled for start-up in late 1972. Early in 1972, when it was decided to complete the shop with Q-BOP furnaces, much of the BOP-shop construction already had been completed. The scrap, charging, and furnace aisles had been installed, the open-hearth charging and teeming-aisle buildings were being modified, flux-addition bins were installed in the furnace aisle of the high-bay building, and the BOP furnace shells were being fabricated in the shop.

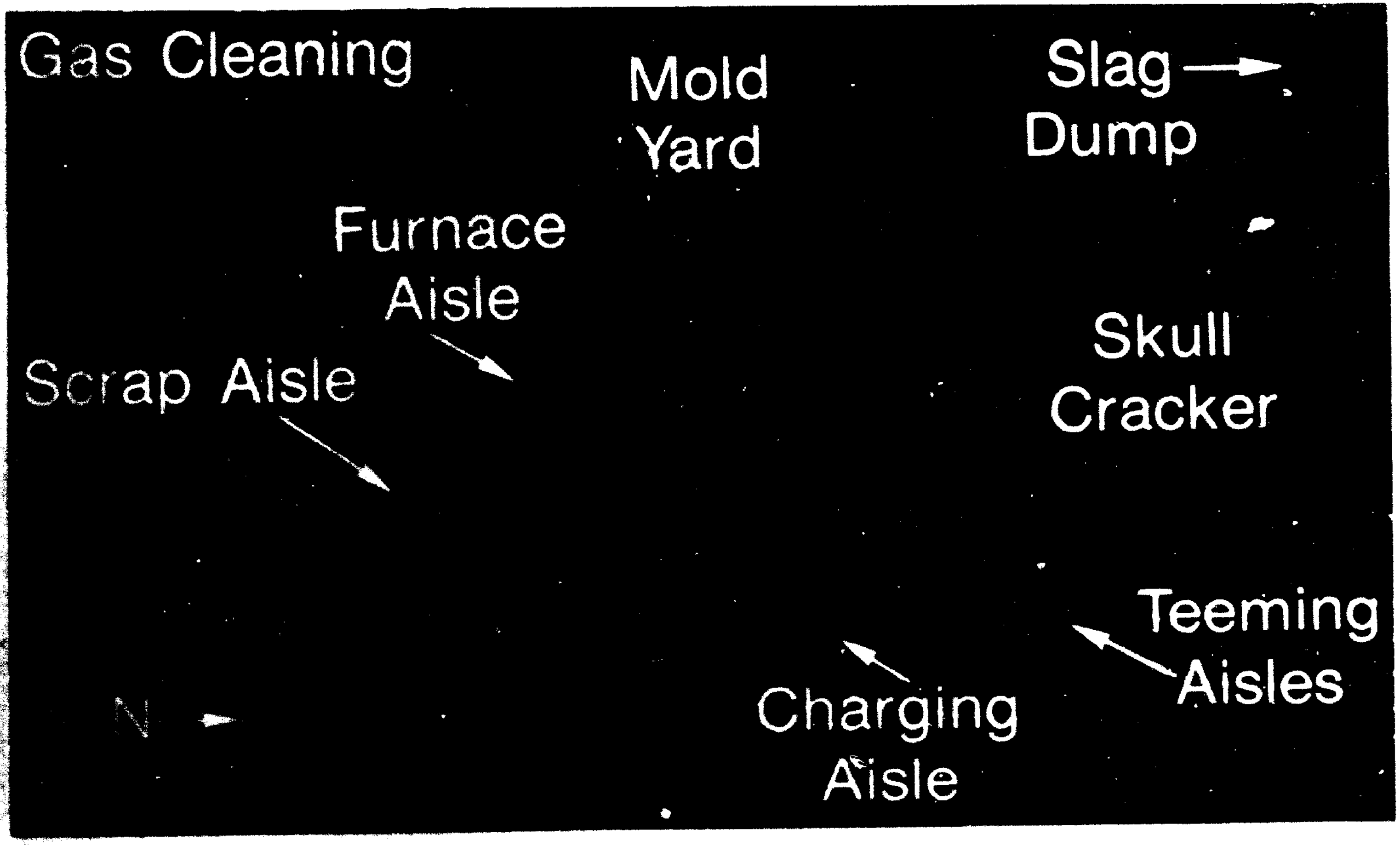

Fig. 9 - Conversion of Gary Works No. 2 BOP Shop to Q-BOP

The most obvious alteration necessary was the adaptation of the furnace shells to bottom blowing. The bottom of each furnace was cut off to allow the insertion of a refractory-lined plug containing the tuyeres. Additional piping was supplied to provide oxygen, nitrogen, and natural gas to the tuyeres. A pneumatic-injection system was installed for powdered lime; however, the existing flux-addition bins were to be used for other fluxing materials. The hood-cooling and gas-cleaning systems were modified and an enclosure was installed around each furnace to capture fumes evolved during furnace-rotation periods. An area for bottom makeup was needed and spare bottoms were required. Additional instrumentation also was supplied for the new systems.

Primary operating functions are concentrated in five parallel working aisles in the Gary No. 2 Q-BOP shop, Figure 9. Adjacent areas contain the mold yard, skull cracker, and slag dump to service the shop.

Scrap Handling

Two overhead magnet cranes unload scrap from railroad cars in the east aisle of the shop. The scrap for each heat is loaded into one of five 2500-cubic-foot scrap boxes on one of three scrap transfer cars. The transfer car and scrap box rest on a track scale which displays the desired and actual scrap weights for the crane operator. Because the Q-BOP can melt heavier scrap than the BOP, a higher scrap density is possible, and the scrap can be loaded quicker than for a BOP. The scrap transfer car moves the loaded scrap box to the charging aisle just west of the scrap aisle where the scrap is charged to the furnace. The two spare scrap boxes also are stored in the charging aisle.

Hot-Metal Handling

Hot metal is received from two 1300-ton mixers in the north end of the charging aisle. The hot metal for each heat is weighed as it is poured into a transfer ladle for charging into the Q-BOP furnace. A skimming station has been completed where all blast-furnace slag and kish are removed.

Furnace Aisle

The furnace aisle houses the ladle- and flux-additive bins as well as numerous storage areas. Each furnace is enclosed in a housing with sliding doors. The doors are closed to enable collection of fumes except while the furnace is charged, Figure 10.

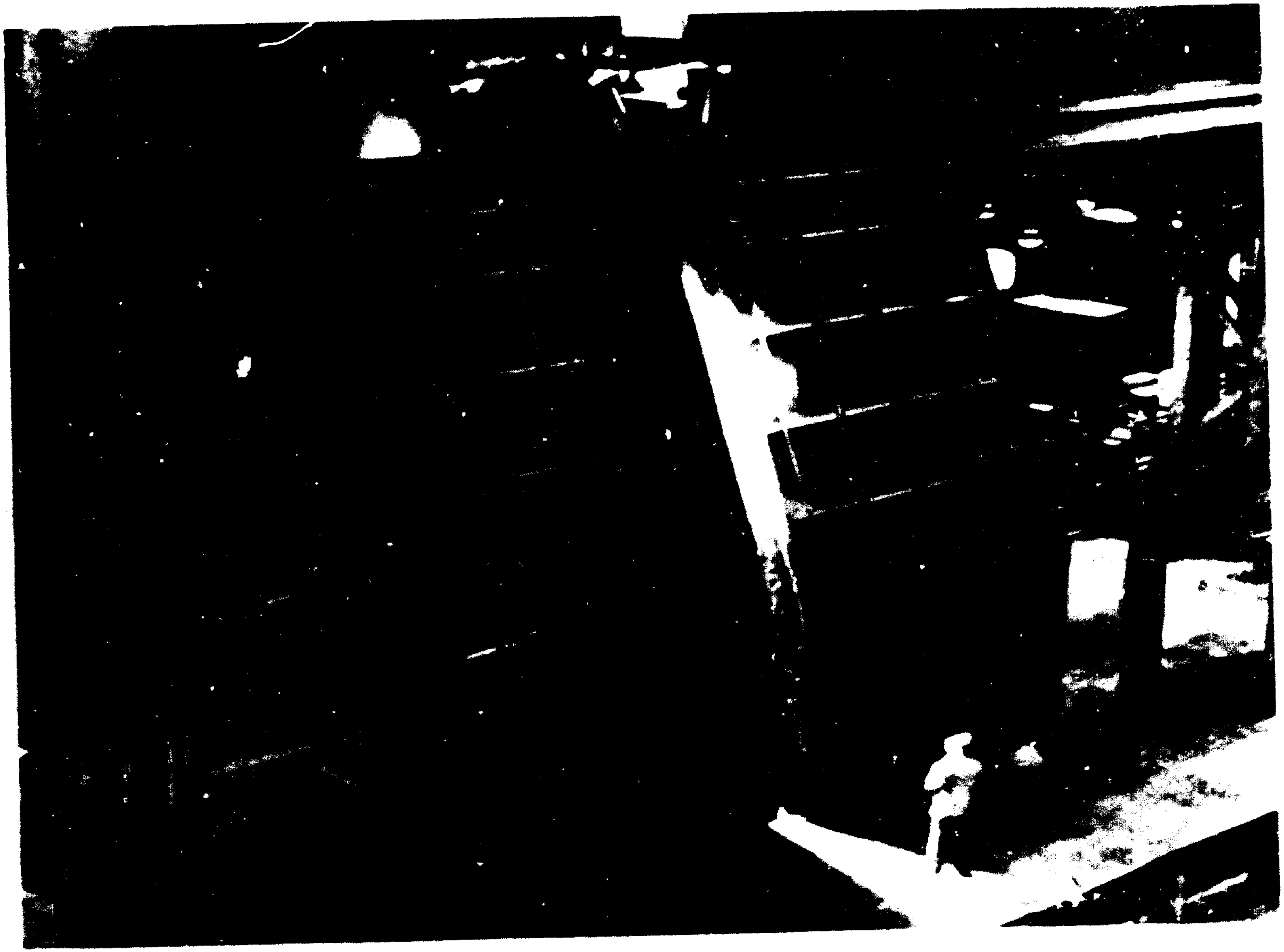

Fig. 10 - Q-BOP **furnace** during blowing, showing doors closed to permit collection of fumes

Gas Cleaning

The gas-cleaning system is designed to clean the gases from two furnaces blowing at the same time. The system consists of two triple-throat venturi scrubbers, a combination moisture separator and gas-cooling tower, and two induced-draft fans and is designed for 202,000 standard cubic feet per minute of dry gases. A water-cooled plate hood collects fumes from each furnace. Hood sprays cool the gas before it enters the quencher where further cooling occurs. The gas then enters a scrubber and a separator prior to entering the gas-cooling tower where its temperature is lowered to 110 F (45 C) or below prior to exiting through the discharge stack.

Lime-Injection System

Lime is delivered to an unloading house in 100-ton railroad cars. The lime is then transferred from a receiving hopper to an 1100-ton tank located to the north of the unloading building. From here the lime is pumped at a rate of 100 tons per hour to three in-shop intermediate bins located 166 feet (50 m) above ground level. The three intermediate bins hold approximately 140 tons of lime and are connected to a weigh tank by a short air slide. The weigh tank holds enough lime for one heat and can be filled in approximately 10 to 12 minutes. The three weigh tanks are interconnected by turntable valves to allow service to adjacent furnaces, thus providing operating flexibility in case of equipment malfunctions. The lime is injected from the weigh tank into the furnace with oxygen.

Teeming Facilities

Ladle-additive bins have been installed on the east and west side of each furnace to allow tapping on either side. Each heat is tapped into a ladle supported on a transfer car. The transfer car moves the ladle to one of two parallel teeming aisles.

Start-Up and Operating Experience With the Gary Works Q-BOP

To minimize start-up time, all operating and maintenance personnel involved in the start-up attended intensive training sessions. These sessions emphasized the mechanics of the process: the furnace with its removable bottom, the concentric tuyeres and their operation, the gas-control logic and the proper gases and flow rates required during each stage of the process, and finally the lime-injection systems and the precise lime-injection practice required for the specific product chemistry and available hot metal. These sessions, together with observations of the operation of the 30-ton pilot Q-BOP furnace, provided the experience for the Gary personnel as they processed the first 200-ton bottom-blown Q-BOP heat.

Operation began with a single furnace on a one turn per day basis. The operating periods were extended as more crews gained experience, until around-the-clock operations began. Before the end of the first quarter of 1973, hundreds of trial heats were made to explore the full range of carbon contents in the product mix. The steel produced is of excellent quality and meets specifications for the specific grades involved. Heats have been applied to structural plate, commercial and drawing quality sheet, aluminum-killed drawing-quality sheet, welded tube, pressure vessel quality, cold-drawn, and axle products. Experience to date indicates that there will be no difficulty in producing any grade in the Gary product mix.

Nitrogen contents are in good control and are maintained at very low levels, with nitrogen contents in the product ranging between 0.003 and 0.005 percent, the same as obtained in the BOP. Sulfur removal in the Gary Q-BOP has been consistent in meeting specification requirements as seen in Figure 11, showing sulfur levels in heats made during a representative day. Two-thirds of the heats had ladle sulfur contents of 0.020 percent or less, and the maximum level reached in any of the 34 heats was 0.023 percent sulfur. The sulfur content of the hot metal charged in these heats ran as high as 0.057 percent.

Phosphorus removal by the Q-BOP process in the Gary furnaces has been excellent. Analysis of a typical operating period, Figure 12, showed that for heats with a maximum of 10 points of carbon, over 90 percent contained less than 0.010 percent phosphorus. For carbon levels between 11 and 30 points, 47 percent of the heats had less than 0.010 percent phosphorus, and over 91 percent contained less than 0.020 percent phosphorus. For the higher carbon heats with between 31 and 50 points of carbon, 96.5 percent of the heats were below 0.020 percent phosphorus, with the remaining 3.5 percent below 0.025 percent phosphorus. Only five heats were made with carbon contents over 0.50 percent, and four of these were below 0.020 percent phosphorus and the other was below 0.025 percent phosphorus.

Lime usage in the Q-BOP is averaging 154 lb/ingot ton (77 kg/metric ingot ton) with some heats using as little as 140 lb/ingot ton (70 kg/metric ingot ton). This compares to 185 lb/ingot ton (92 kg/metric ingot ton) at Gary's No. 1 BOP shop for the same product mix.

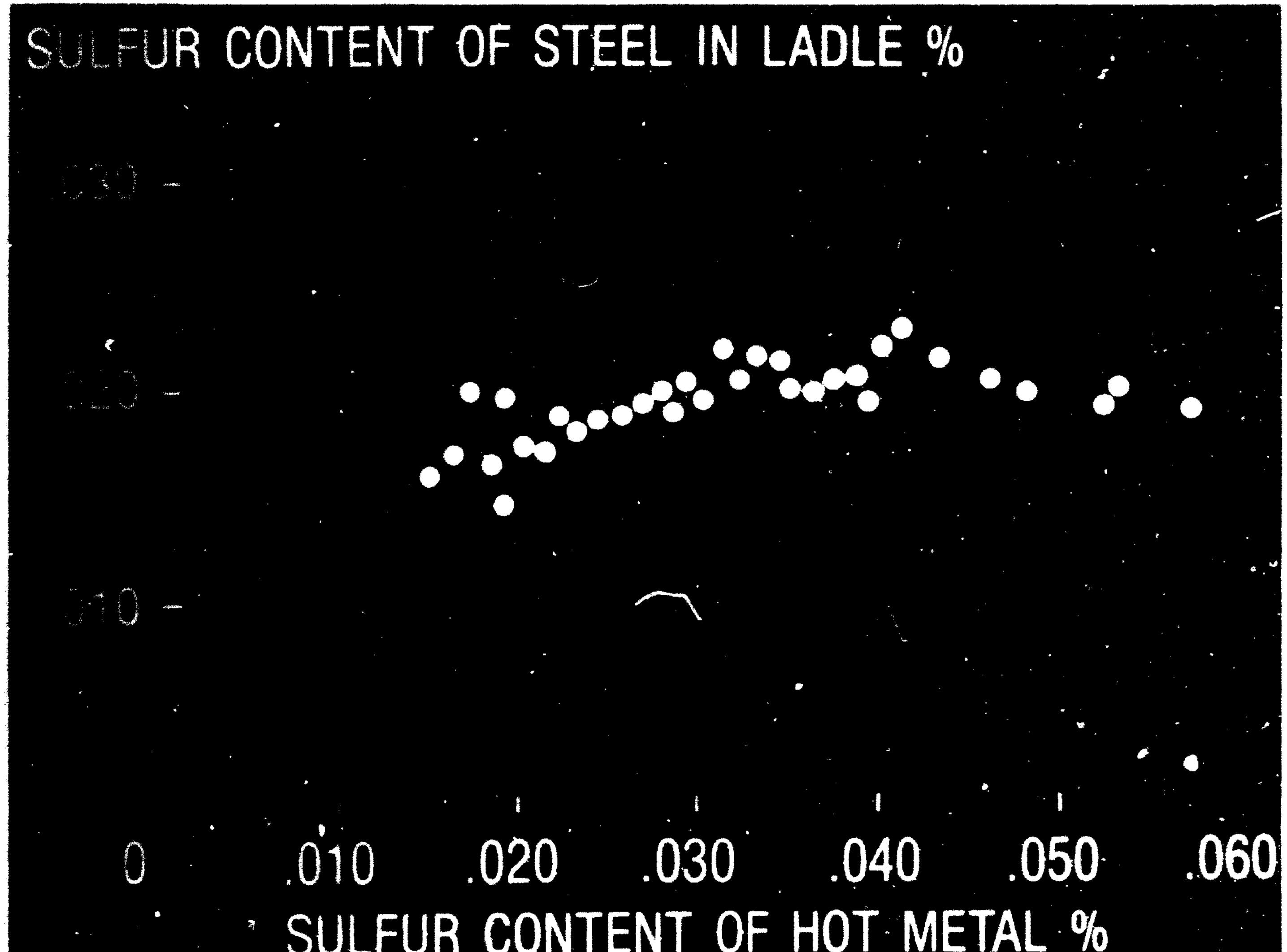

Fig. 11 - Sulfur contents in Q-BOP heats during representative day

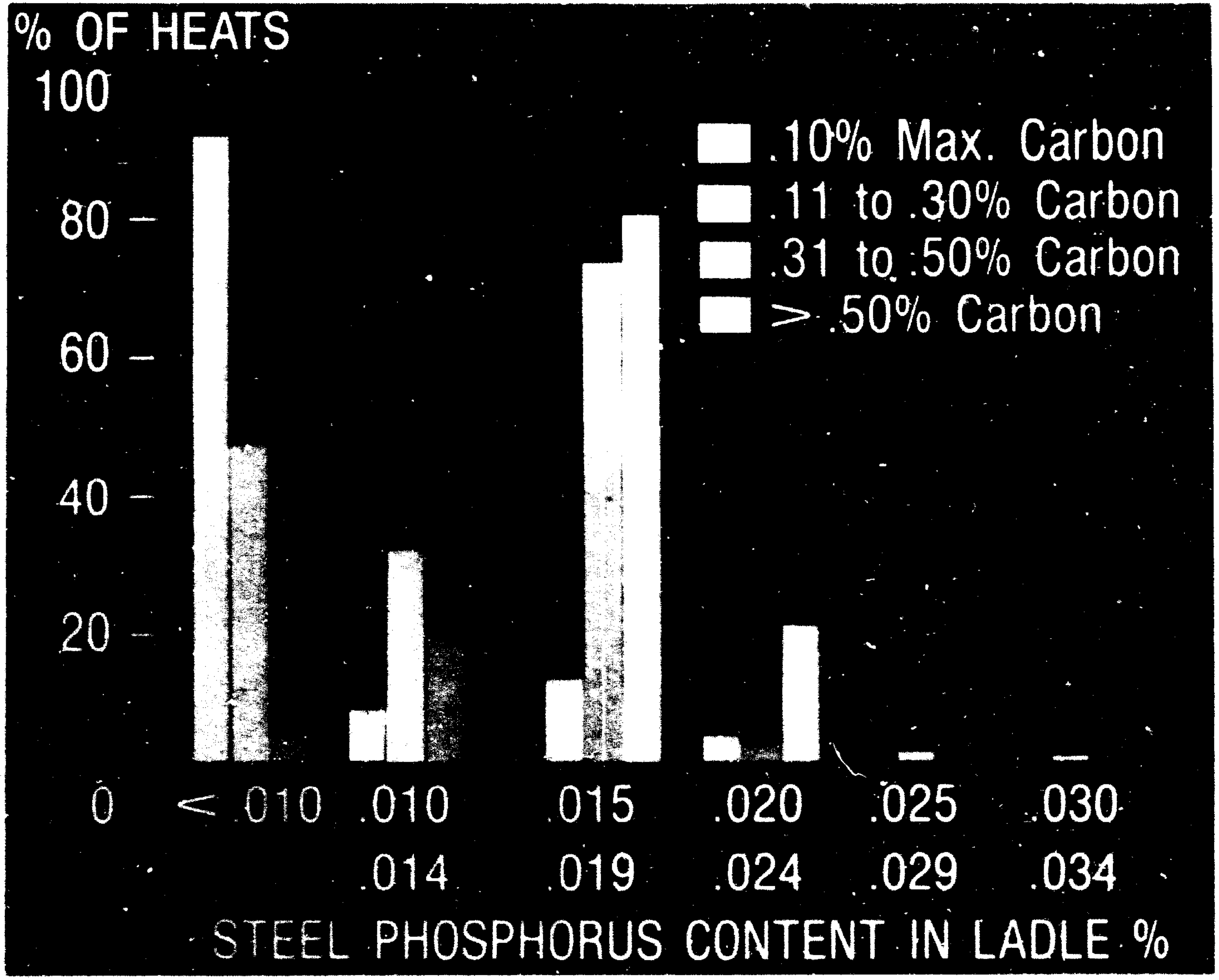

Fig. 12 - **Phosphorus levels in Q-BOF melts over a typical operating period**

The ultimate scrap-melting capability obtainable with the Q-BOP has not been realized yet because continuous operation has not been achieved in the shop. Scrap melting continues to improve as the shop approaches a continuous operation. Consumption of heavy scrap has been very good. Pieces of scrap weighing 5 to 25 tons are charged routinely, and scrap ingot molds weighing up to 10 tons have been melted during a standard operating period. Tap-to-tap times of 31 minutes have been achieved and the majority of heats made during a continuous operation have had tap-to-tap times under 41 minutes.

Indications are that yields from the Q-BOP are approximately 2 percent higher than the yields from comparable grades at the No. 1 BOP shop, and the molten steel from many heats exceeds 90 percent of the weight of the charged metallics.

Slag analyses indicate that prospects for a long lining life are good, and bottom-plug wear is improving as the shop operation becomes more continuous.

In general, the start-up has been smooth; the usual equipment and operating problems associated with bringing a new process on-stream are being systematically eliminated, producing a new performance plateau daily.

Conclusion

The Q-BOP offers many advantages over other steelmaking processes. The investment costs for a Q-BOP shop are lower than for a BOP on a greenfield site, and installation of the Q-BOP in an existing open-hearth shop can result in even greater savings of capital. High-quality steel can be produced and operating cost benefits realized because of the high speed, higher metallic yield, and greater scrap-melting capability possible with the Q-BOP.

U. S. Steel has made a major commitment in the Q-BOP at two steelmaking locations with the ability to produce some 8 million tons of raw steel annually. The first of these facilities is now in production at Gary Works, while the second is under construction at Fairfield Works. Extensive interest has been shown in this process, and USS Maxtech, a joint venture company being formed by our USS Engineers and Consultants, Incorporated, and Maxhütte, has active inquiries regarding the process from several major steel companies in eastern and western Europe, Japan, and South America. The start-up of the 200-ton Q-BOP furnaces at Gary has confirmed U. S. Steel's confidence in Q-BOP, and we are more enthusiastic than ever about the future of Q-BOP steelmaking.

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