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ENERGY CONSERVATION AND PRODUCTIVITY IMPROVEMENTS IN STEEL PLANTS

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Abstract—The purpose of this paper is to review applications of modern computer technology to energy conservation and productivity improvements in continuous reheat furnaces and soaking pits of steel plants.

1. REHEAT FURNACES

A recent engineering study by Thermo Electron Corporation has identified major opportunities for increasing the energy efficiency and production rate of existing continuous slab-reheat furnaces. Under terms of a contract with ISCOR, South Africa's national steel company, engineers from Thermo Electron and its Holcroft-Loftus Furnace Division performed extensive analyses and measurements on nine large furnaces at ISCOR's Vanderbijlpark North and South Works to determine optimum strategies for cost-effective modernization of equipment, heating schedules, and operating practices.

In today's economic environment, older furnaces can be retrofitted with cost-effective modifications that could not have been justified in the past. Advances in the technology of materials, monitoring equipment, and control systems provide new opportunities for reducing cost and increasing both product quality and production rate.

An important tool used in the ISCOR study was Thermo Electron's computer model describing the heating process for slabs, billets, blooms, rounds, and other geometrical shapes processed in reheat furnaces. Field measurements taken by Holcroft-Loftus at the North Works showed excellent agreement with temperature profiles predicted by the computer model. The slab heating model was incorporated into a detailed energy balance model, which accounts for heat losses to the furnace walls, roof, hearth, openings, water-cooled parts, and flue gases. These comprehensive analytical tools permit parametric investigation of various potential changes in furnace design and operating practices.

A. Furnace model

The furnace model deals with heat transfer inside the material shape being heated, with coupling of the shape to the furnace environment, and furnace energy losses.

The workpiece is divided into nodes (shown in Fig. 1). It is assumed to be of unit thickness in the direction of travel through the furnace. Standard heat transfer relations are written for the bulk of the slab, and the interaction of the slab with the furnace is described by specifying the boundary conditions for the surface nodes. A radiative network connection, a conduction heat-transfer element, and a convection heat-transfer element are necessary for energy to reach the boundary of the workpiece. The model can represent heating conditions for the slab when the top and bottom zones of the furnace are operated at different temperatures. Thermal effects of the water-cooled skid rails supporting the slab are also taken into account, thus allowing the prediction of skid marks on the underside of the slabs.

Temperature dependent material properties, i.e. thermal conductivity, specific heat, and variations in surface emissivity, are provided as input data. Radiative heat transfer is calculated using a network based upon simplified shapes having exact solutions to the generalized view factor integral formulation.

B. Optimization studies

The total furnace firing rate can be lowered by reducing the furnace temperature profile at a lower push rate, i.e. at a reduced production for the same slab thickness and hearth coverage (slab area). For a given furnace with maximum hearth coverage and specific slab

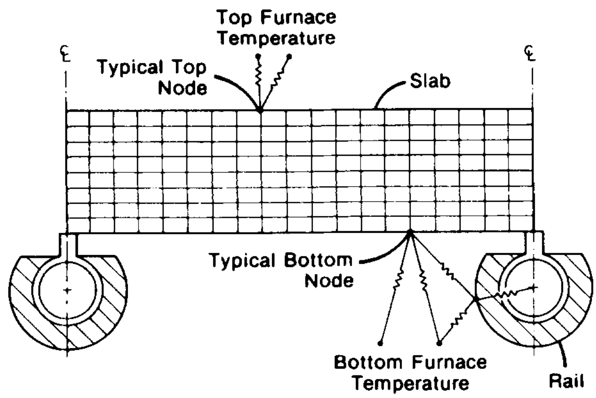

Fig. 1. Workpiece nodes and boundary conditions with skid rails for slab heating model.

thickness and material properties, there is a maximum production rate consistent with acceptable furnace life and with the required slab temperature at discharge. If production in tons per hour is decreased either by reducing the push rate at a fixed slab thickness or by reducing slab thickness at a fixed push rate while maintaining hearth coverage, furnace temperature can be lowered.

Specific fuel consumption depends on the relationship between furnace temperature, production rate, and furnace heat losses. Reducing temperature will reduce specific fuel consumption initially as the push rate decreases, until an optimum value is reached. As the production rate is further reduced, the result will be an increase in specific fuel consumption due to the effect of furnace losses. Optimum furnace temperature means altering the profile to a minimum value consistent with maintaining the required discharge temperature. Excessive thermal head refers to maintaining the same temperature profile required for the maximum production rate. For a discharge temperature of 1300°C, the specific fuel consumption could range from 1.6 GJ/t at about 65% capacity to 1.72 GJ/t for maximum production.

Another possibility for reducing fuel consumption is to lower the final slab discharge temperature by reducing the furnace temperature profile. However, the rolling mill horsepower demand will increase, and product quality may be affected. For an ISCOR South Works furnace after retrofit, the calculated fuel consumption decrease is 6–8% for each 50°C decrease in slab temperature. Reduced slab discharge temperature can also result in greater production if the furnace temperature profile remains unchanged. On this basis, production rate is increased 8% for every 50°C decrease in slab temperature. This improvement, of course, must be weighed against possible adverse effects on down-stream operations, such as too low temperature for finishing. Adverse effects may be avoided by providing radiation shields at the roll table between the roughing mill and the finishing mill.

Of paramount importance to the rolling process is the skid mark or cold spot created on the bottom of the slab by the combined conduction and radiation effect of the water-cooled longitudinal skid rail. The rule of thumb in the past has been to provide 30–40 min of residence time on the hearth for temperature equalization in the slab. Since heat flow is only from the top, the slab leaves the soak zone with a temperature differential of about 30°C from top to bottom at the center line between the rails, and a greater differential at the point of rail contact.

Figure 2 shows the temperature profile in a 24 cm thick slab as it enters the soak zone after 3 hr in the furnace. Figure 3 shows the temperatures at 4 hr as the slab is discharged from the furnace. The computer model shows a temperature differential of 30°C at the rail between the top and bottom surfaces at the time of discharge. Temperature of the top surface at the rail is 15°C lower than the top surface between the rails.

Temperature measurements were performed at ISCOR's North and South Works, using

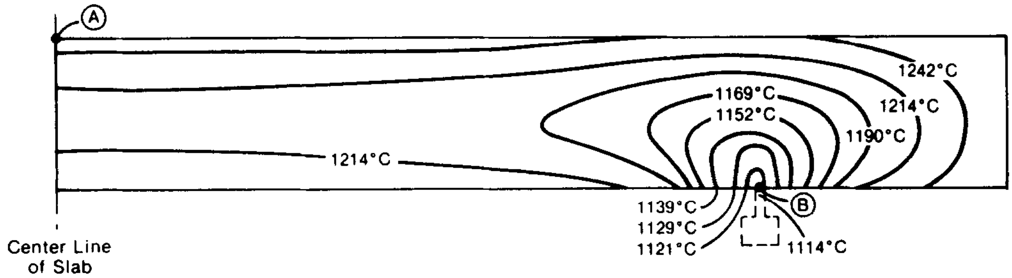

Fig. 2. Computer generated isotherms for slab at 3 hr (end of heating zone).

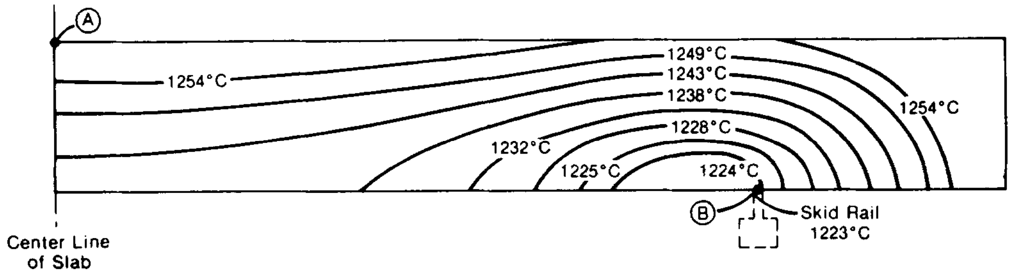

Fig. 3. Computer generated isotherms for slab at 4 hr (end of soak zone prior to discharge from furnace).

radiation pyrometers outside the furnace and trailing thermocouples embedded within the material being heated. For each of these sets of measurements, the actual furnace temperatures were used as input to the computer model, and a time-temperature history for specific locations on or within a slab was calculated. As shown in Figs. 4 and 5, the correlation between actual and calculated temperature histories is extremely good. These comparisons demonstrate the accuracy of the computer model and provide a high degree of confidence in analyses of furnace modifications and operating strategies aimed at reducing energy consumption and raising productivity.

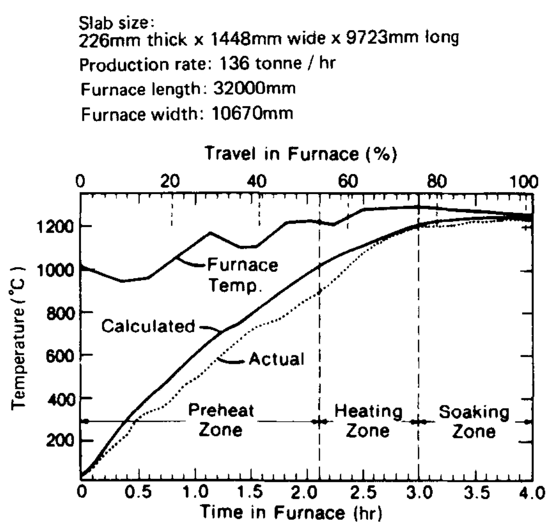

Fig. 4. Top surface of slab at center line. Calculated and measured temperatures vs time.

The energy balance of the furnace was used to study the effects of furnace modifications, component additions, and operating procedure changes on energy consumption. Because flue gases represent the major losses in reheat furnaces, considerable effort was devoted to the question of optimum air preheat, i.e. recuperation, and other factors associated with

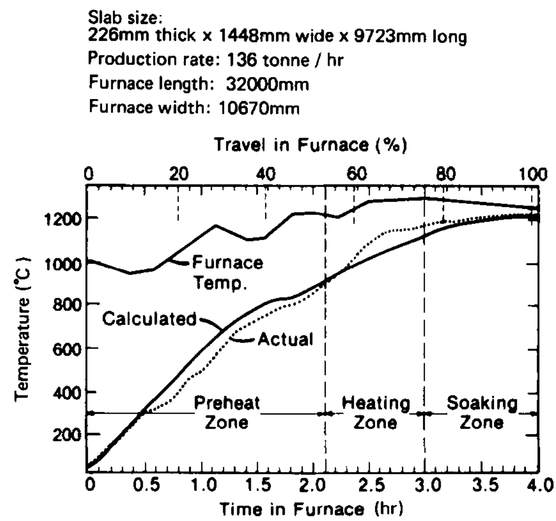

Fig. 5. Bottom surface of slab at skid rail. Calculated and measured temperatures vs time.

fuel combustion. Figure 6 shows the calculated effects of fuel gas composition and degree of recuperation for one of the older South Works furnaces. Specific fuel consumption in these furnaces can be lowered by 10% by employing high temperature recuperators (465°C vs the present 270°C). Another 5% saving is obtained by changing from mixed gas fuel (57% coke-oven and 43% blast-furnace gas) to 100%, higher heating value coke-oven gas. Overall, the thermal efficiency of the furnaces can be raised from an initial value of 45% before improvements to 53% after improvements.

Another major source of heat loss is the water-cooled skid pipe and support system, particularly in older furnaces where there is likely to be significant loss of insulation. A parametric study of the effects of insulation loss on water-cooled skids indicated a 5% fuel saving for each 10% improvement in insulation coverage.

Wall and door losses represent only about 2–4% of total furnace heat input and, therefore, were not subjected to parametric model analysis. Typically, the wall losses can be cut in half using new lightweight refractories. These materials also reduce heat storage by as much as 80%, thereby decreasing the required heatup and cooldown time and thus resulting in greater furnace availability.

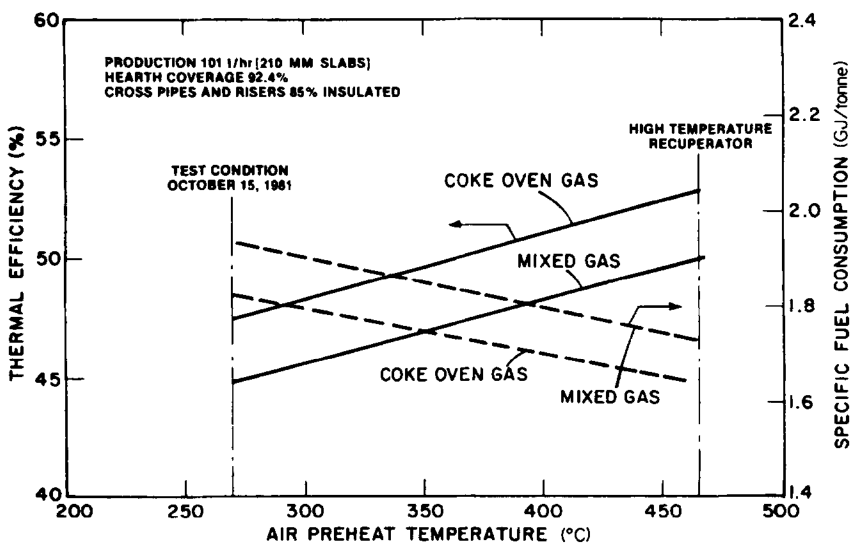

Fig. 6. Effect of air preheat and fuel type on specific fuel consumption.

The effects of hearth coverage and production rates were investigated for a wide range of conditions. For any given hearth coverage and furnace geometry, there is a unique relationship between the minimum specific fuel consumption and production rate. This fuel consumption is found by carrying out an energy balance using the optimum furnace temperature profile obtained by successive iterations of the slab heating model.

A patented new Holcroft-Loftus system for improving both production rate and product quality in continuous pusher-type reheat furnaces is the skid alternator. In this system, the stationary skids are extended over the entire length of the furnace. The alternator helps to improve temperature uniformity of the slabs by periodically raising the slabs in the soak zone out of contact with the skid rails along which they travel through the furnace. The controlled raising and lowering of the lift rails in the soak zone is coordinated with the extraction of slabs from the furnace and the pushing of slabs within the furnace. The system reduces or eliminates skid marks without the need for a soak hearth, and increases bottom side slab temperature. Thus, the time required for a slab to reach the desired uniform rolling temperature is decreased. Maximum production rate of the furnace is increased by 18% relative to the conventional refractory soak zone hearth. Additional benefits from elimination of the soak hearth are greater furnace availability, reduced maintenance costs, and reduced mechanical damage to the bottom of slabs.

Figure 7 shows the effect of the skid alternator compared to a conventional-type refractory hearth soak zone. The temperature at the skid mark increases more rapidly, thereby shortening the required soak time. The initial drop in skid-mark temperature differential at each alternator cycle results from the radiation shadow projected by the alternator mechanism. The lift mechanism consists of an open structure of rails and supporting members extending only through the soak zone.

Parametric graphs of specific fuel consumption versus production rate and hearth coverage for modified North Works furnaces are shown in Figs. 8 and 9. The modifications include use of refractories, increased air preheat, and improved insulation (Fig. 8) plus the skid alternator (Fig. 9). In both Figs. 8 and 9, the curve that connects the points of maximum production rate at varying hearth coverage, and the curve corresponding to 100% hearth coverage are the operating limits for the improved furnace. The optimum furnace temperature profile and, hence, the firing schedule for the burners, varies as a function of production rate. The region to the right of the dashed line in Fig. 9 represents the improvement achievable by the use of the skid alternator.

The improvements identified by Thermo Electron for ISCOR's furnaces are applicable to many existing mills throughout the world. Each plant will present a unique set of problems, which may lead to variations in the detailed design. However, the overall approach for increasing reheat furnace productivity will follow the general plan outlined above. Particularly attractive is the use of the skid alternator system in the furnace soak zone. This innovation not only increases output but also enhances product quality by overcoming some of the inherent shortcomings of pusher-type slab reheat furnaces.

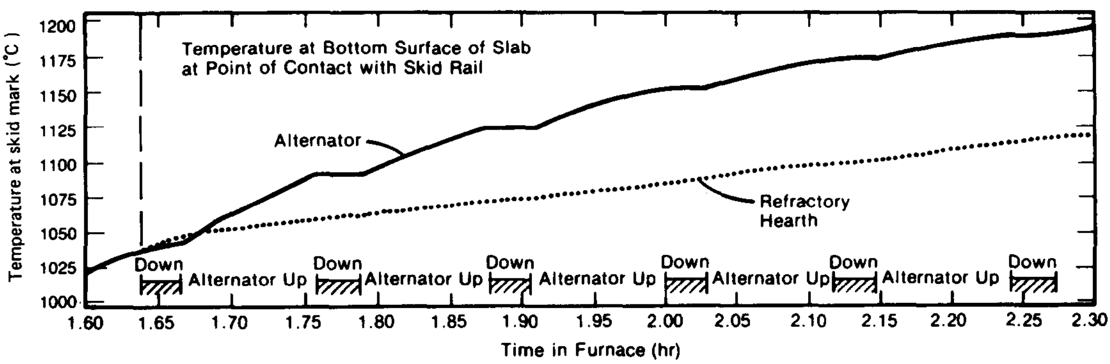

Fig. 7. Comparison of slab temperature–time histories for conventional refractory hearth and skid alternator systems.

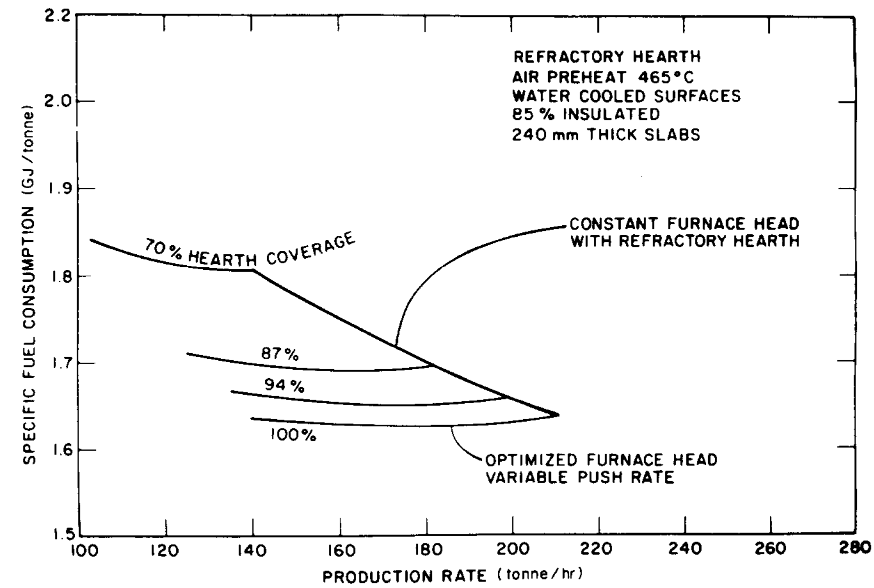

Fig. 8. Specific fuel consumption as a function of production rate for varying hearth coverages and push rates at ISCOR North Works without skid alternator.

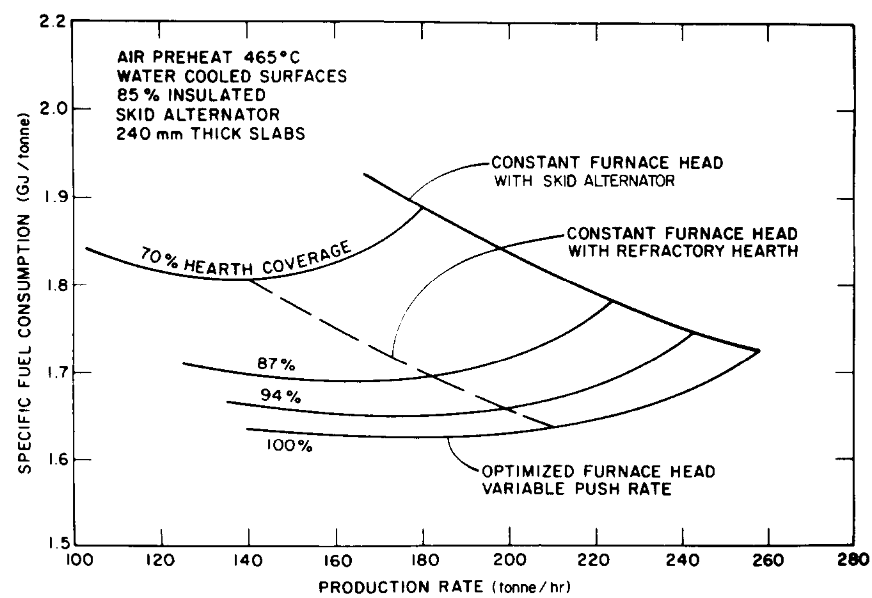

Fig. 9. Specific fuel consumption as a function of production rate for varying hearth coverages and push rates at ISCOR North Works with skid alternator.

2. SOAKING PITS

The Holcroft-Loftus Company has been selected by the Timken Company to supply a completely integrated computer control system for eight Loftus soaking-pit, ingot-reheating furnaces. The furnaces will be installed at the new Timken Faircrest Steel Plant in Canton, Ohio. This plant will be fully automated and will produce high alloy steels for bearings and other high-performance applications. It will be operational by the middle of 1985. Holcroft-Loftus will provide all the hardware and software for the computer system, as well as system engineering and installation. The system will provide complete control of the process and logic functions of the soaking pits, as well as supervisory control of the furnaces utilizing a combination of the ARMCO Inc., Cylindrical Equivalent Model

(CEM™) of ingot thermal behavior, and the Holcroft-Loftus Hierarchical, Interactive, Adaptive, Real-Time, Computer Control (HIARCC™) system of supervisory interface, which will communicate with the steel melting, rolling, and higher level management control systems.

Control of the furnace process and logic functions will be through computer and programmable controllers. These functions will include temperature, fuel–air ratio, pressure, cover control, and combustion monitoring. Information will be displayed on video terminals for the furnace and crane operators, and printers will provide hard copies of data and operating information. Alarms will inform the operators of out-of-range furnace conditions. Data on production, operation, and performance will be stored at the furnace system for a specified period and then transferred to the higher level plant computer system.

The objective of the HIARRC supervisory control system will be to optimize furnace productivity and efficiency, and product quality through utilization of the CEM thermal model. The CEM is a real-time model of ingot thermal behavior from teeming to ready-to-roll. It will be used to project the location of the ingot solidification front, to determine optimum strip time, and to dictate the optimum soaking pit firing practice. The supervisory system will use the CEM in conjunction with data from the electric furnace, rolling mill, and management areas to determine the furnace operating practices necessary to meet the plant objectives.

Disruptions, due to scheduled or unscheduled delays, and changes in schedule will be accounted for in a manner that will minimize their adverse effect on overall furnace performance and product quality. Furnace operating data will be transmitted to the higher level management system computer so that they can be utilized in the overall plant production planning.

A. Ingot model

The heart of the HIARCC system is a mathematical model that represents the thermal behavior of ingots throughout the time period between teeming and ready-to-roll. It is a one-dimensional cylindrical equivalent model (CEM) that has been under development by ARMCO over the past decade, and that has been successfully applied to the operation of the Middletown, Ohio Works of ARMCO since May 1982. It has also been implemented at three other ARMCO plants in Houston, Tex., in Ashland, Ky and in Kansas City, Mo. Holcroft-Loftus has been licensed by ARMCO to market the CEM for use in soaking pit computer control systems.

The cylindrical equivalent model represents the thermal behavior of ingots accurately and yet consisely so that computer capacity and calculation time are minimized. It accounts for various ingot sizes, material grades, and charging patterns, and operates in real-time. It projects the location of the ingot solidification front, determines optimum strip time, and prescribes the optimum soaking pit firing practice. The model also accounts for temperature dependencies of conductivity, specific heat, diffusivity, and emissivity of the processed ingots. Moreover, it includes actual boundary conditions based on ingot size and pit loading for each pit charge.

Rimmed steels may be moved, stripped, and charged before they are completely solidified, and be rolled with a liquid center. For these, the model calculates the solidification front of the ingot, and specifies the strip time based on a predetermined standard. For killed steels, which may be neither moved nor stripped prior to complete solidification, the model predicts the earliest strip time, the in-mold cooling after solidification, and out-of-mold cooling after stripping.

Improvements in fuel efficiency and productivity derive chiefly from the large amount of sensible heat in the ingot at teeming, and the ability to improve scheduling. The sensible heat of molten steel is approx. 1.3 GJ/t. The required heat content of the steel for rolling is about 0.9 GJ/t. By proper scheduling of strip and charge times, a significant amount of the sensible heat can be retained in the ingot so that fuel consumption and pit residence time are reduced, and fuel efficiency and productivity are increased. The largest gains are achieved for rimmed steel ingots. Improvements are realized also for killed steel ingots because of the ability to predict the optimum strip time and to determine the best firing practice.

After charging, the model uses the expected pit time–temperature profile to calculate the heating rate and temperature profile throughout the ingot and, thus, predict the earliest rolling time as a function of surface and center temperatures, and percent solidification. If there are scheduled or unscheduled delays in the rolling cycle, or if the time from charge to scheduled roll is greater than the minimum heating time, a new time–temperature profile is implemented. Thus, an appropriate slower heating rate is achieved, and the ingots are ready to roll at the new rolling time. This feature minimizes fuel consumption.

At the end of the heating cycle, the model calculates the heat content of the ingot, and the thermal efficiency of the cycle. It also estimates the energy consumption at the start of a cycle. This permits the evaluation of operating options that impact on energy consumption.

The real-time operation of the model provides accurate and timely information about the thermal condition of the ingots to the supervisory control system. The effect of changes in the operating variables on the heating cycle are evident immediately so that proper action can be taken by the control system to insure optimum operation. The ability to predict ingot solidification allows the earliest possible charging of the ingots. Thus, the amount of heat retained from the melt shop is maximized. Utilization of this feature and the ability to predict the optimum heat-up cycle based on the actual time available for heating result in significant fuel savings. Rolling with a liquid center also improves the yield of rimmed steel ingots because it reduces over-roll losses. This is a significant cost saving, as well as an improvement in productivity.

The effect of in-mold and out-of-mold times on the energy content of the ingot as charged, and on fuel consumption are illustrated by the calculated results shown in Figs. 10–12. The model has been used to calculate pit residence time, energy content of the ingot when charged, and specific fuel consumption for three in-mold times, and for out-of-mold times ranging from 15 to 90 min. The assumed charge consisted of eight 1016 × 1245 mm 20-t ingots.

Figure 10 shows the required pit residence times. The 15-min time out-of-mold points

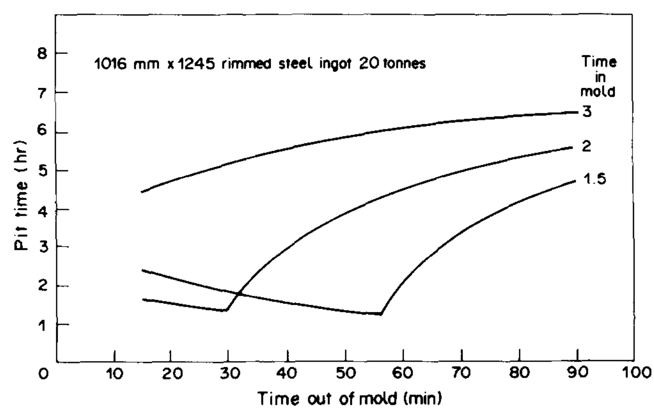

Fig. 10. Pit residence time vs time in and out of mold. Time in mold is in hours.

were calculated for general interest only. In most installations, delivery times from the stripper to the pits are larger than 15 min. All results for 30–90 min were solid at ready-to-roll except those corresponding to 1.5 hr in-mold and 30 min out-of-mold. The latter correspond to 95% solidification. For a short time in the mold, the corresponding curve has a knee. This knee shows the effect of liquid center in the ingot when charged. After charging in the hot pit, the ingot cooling rate decreases. Although this increases pit time, it also reduces fuel consumption.

Figure 11 shows the specific heat content of the ingot when charged vs time out-of-mold. This heat is given in GJ/t on the left-hand side scale, and as a percentage of the heat required for rolling, i.e. as a percentage of 0.9 GJ/t, on the right-hand side scale. These

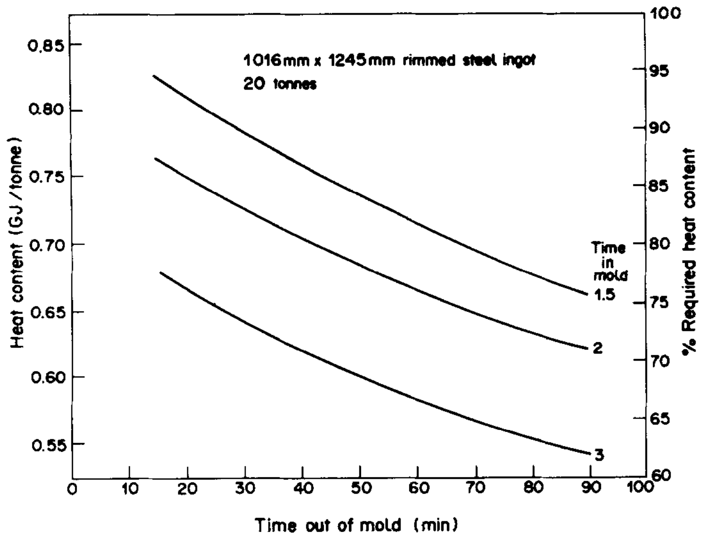

Fig. 11. Heat content of ingot when charged. Time in mold is in hours.

results confirm what has always been known—as total track time decreases, the heat content of the ingot at charge increases.

Figure 12 shows the specific fuel consumption based on the results in Figs. 10 and 11. The fuel consumption is from charge to draw for a 160 t heat and does not include delays or downturns. A monthly average fuel figure would be higher.

The cylindrical equivalent model has been in operation at the ARMCO Middletown, Ohio Works since May 1982. The bar chart in Fig. 13 shows the fuel consumption before and after the model was implemented. It is seen from this chart that the average monthly fuel consumption has been reduced by about 30%.

The computerized control system makes it possible to monitor and report the fuel consumption by various categories of pit charges. This, of course, provides a better insight into the operation of the soaking pits than the monthly average for all charges. Specifically, from January to April 1985 the fuel consumptions for three categories of pit charges from charge to draw were: (1) rimmed steel (liquid center), 0.3 GJ/t; (2) rimmed steel (not liquid center), 0.68 GJ/t; and (3) cold steel, 1.76 GJ/t.

The implementation of the CEM also resulted in improved productivity of the furnaces. It is estimated that the mill production is now achieved with 18 pits instead of the 32 that

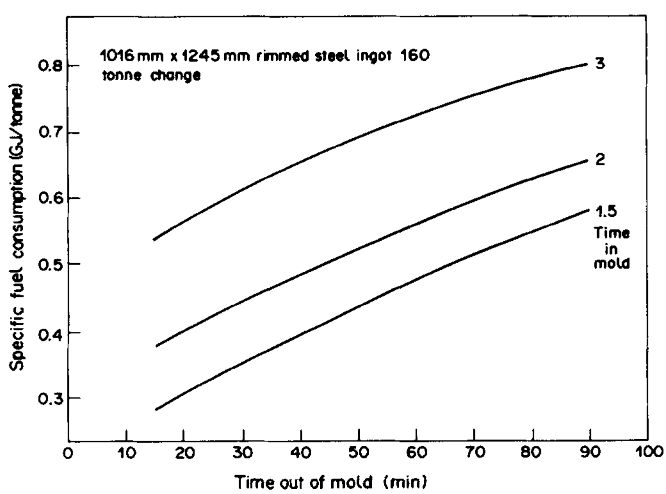

Fig. 12. Fuel consumption vs time in and out of mold. Time in mold is in hours.

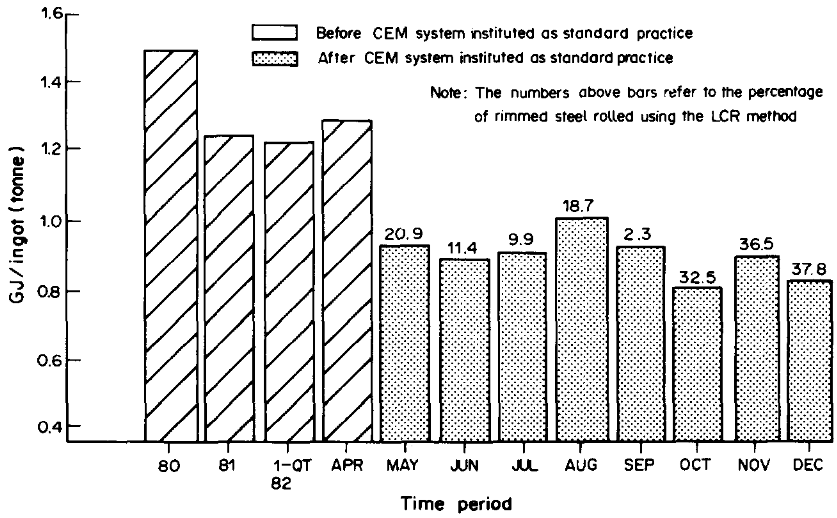

Fig. 13. Specific fuel consumption in soaking pits at Middletown, Ohio Works before and after implementation of CEM system.

were originally in use.

The bar chart in Fig. 14 shows the slabbing mill yield before and after the CEM implementation. The number at the top of each bar indicates the percent of rimmed steel rolled with liquid or hot center. The current yield improvement due to liquid center rolling is 1.7%. In addition, another 0.5% is realized due to reduced scale loss resulting from the shorter pit residence times. The monetary value of the 2.2% overall increase in yield is significant and, in general, much larger than the value of the fuel savings. For killed steels that cannot take advantage of liquid center charging or rolling, the gains are less.

B. The computer control system

The Holcroft-Loftus HIARCC is a hierarchical, interactive, adaptive, real-time, computer control system operating at several levels. Figure 15 is a schematic of four of these levels.

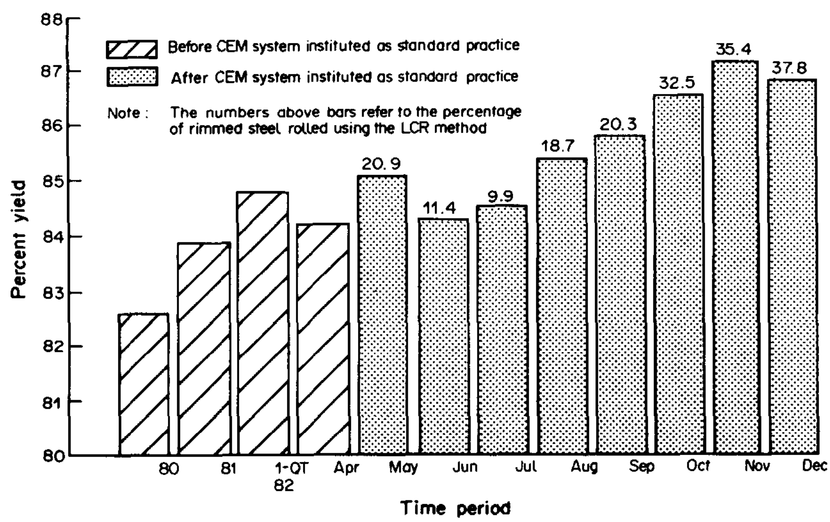

Fig. 14. Percent yield from ingot to slab at Middletown, Ohio Works before and after implementation of CEM system.

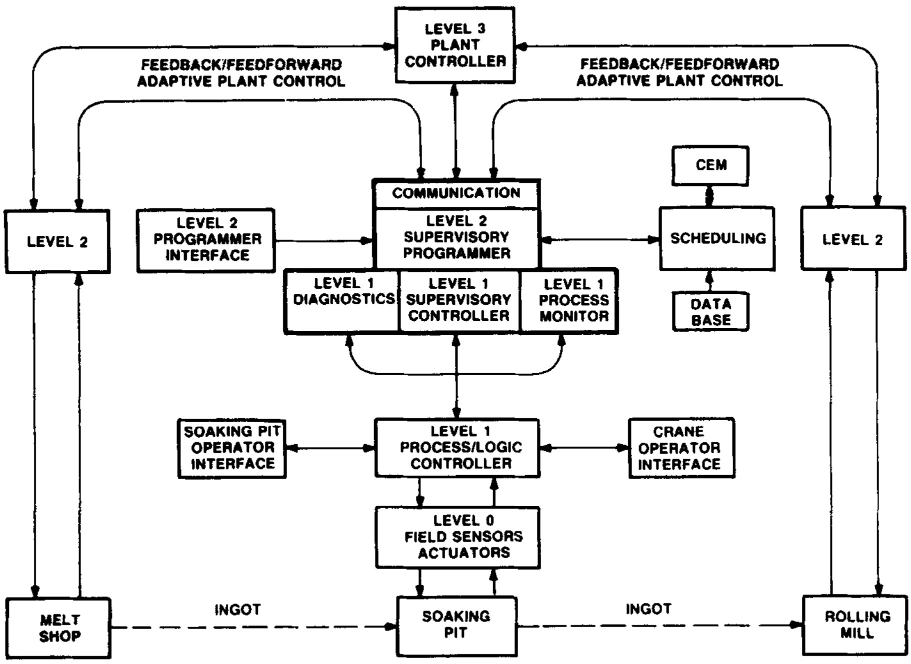

Fig. 15. Schematic of the hierarchical, interactive, adaptive, real-time, computer control system.

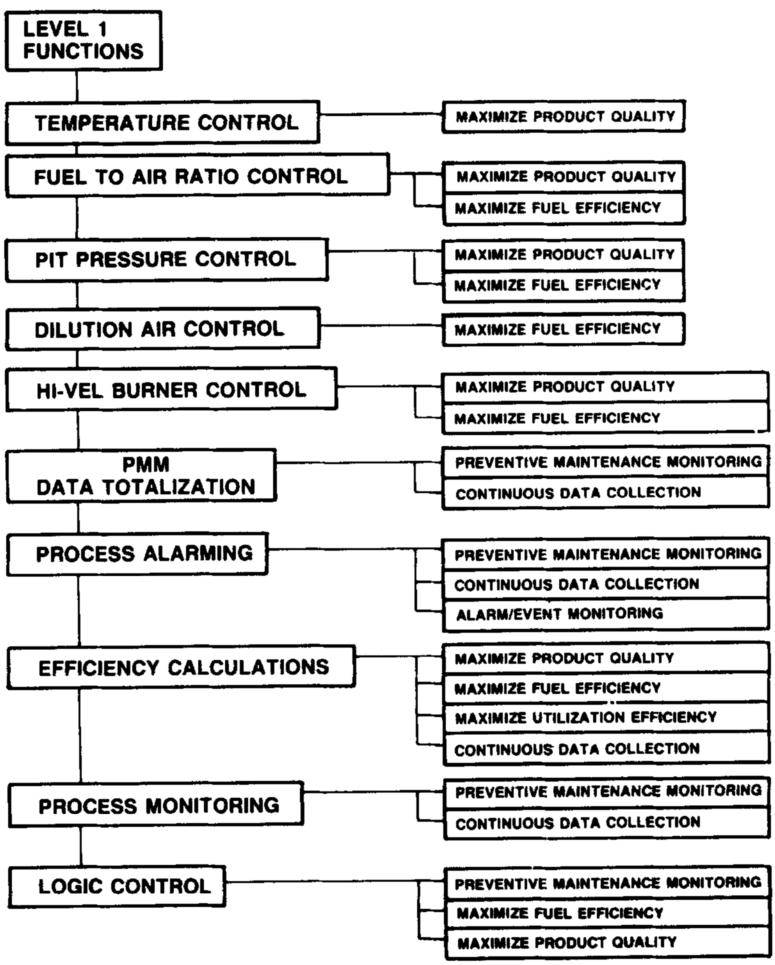

Fig. 16. Level 1 control functions and objectives.

Level 0 represents the sensors for process measurements and actuators for process control, such as thermocouples, orifices, transmitters, valves, and valve actuators. The sensors and actuators are located at the soaking pit. Level 1 consists of the various control functions, such as temperature and fuel–air ratio controls. Each of these functions contributes to the

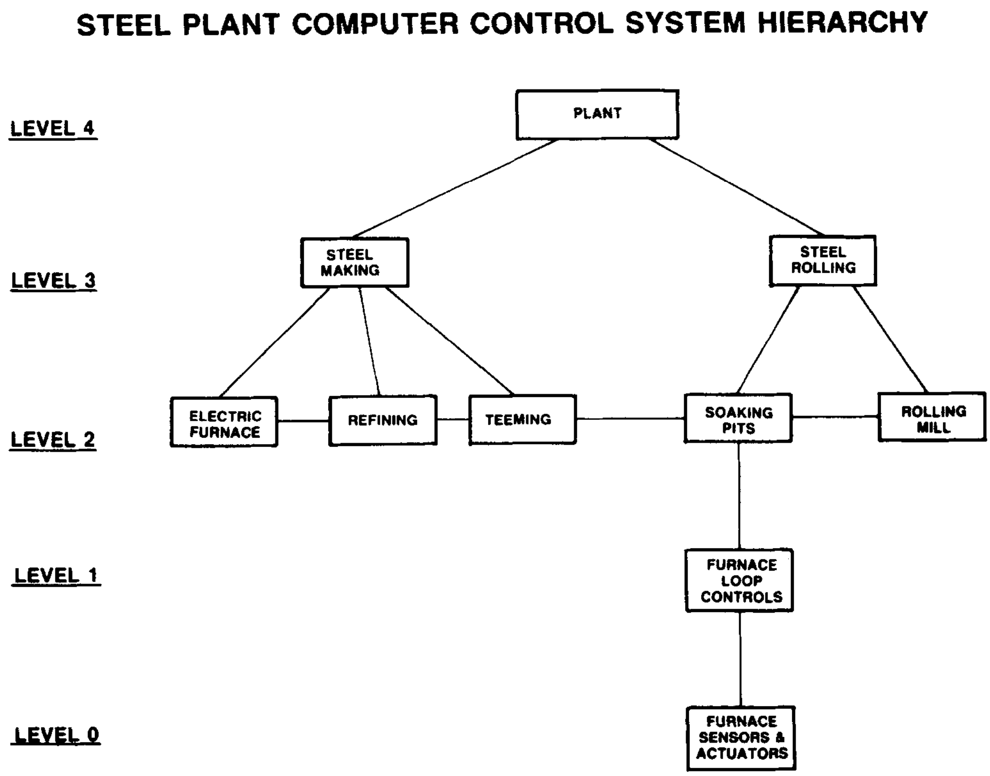

Fig. 17. Schematic of HIARCC Levels 1–5.

optimization of the operation as shown by the block diagram in Fig. 16. Level 2 is the supervisory machine and loop control that relates the operation of the soaking pit to the operations of electric furnaces, refining, teeming, and rolling. Level 3 refers to the controlled operation of the steel rolling department.

A second Level 3 system controls the steel making department. The plant operation is represented by the computer at Level 4, which controls all of the Level 3 operations. A schematic of the 5 levels is shown in Fig. 17. Each box represents a computer control system, and each interconnection a line of communication. Boxes for Levels 0 and 1 are shown only for the soaking pits even though they are present in the other processing areas as well.

A prime concern in any control installation is the accuracy of the model predictions. Because of the normal deterioration of pit refractories and equipment, such as thermocouples, errors may develop in the predictions as time goes on. By means of closely controlled rolling experiments for a range of ingot temperatures, and statistical analyses of the results, relationships between ingot temperature and roll force and roll torque can be developed. When the rolling results at the mill show a prescribed deviation from the expected relationships, the maintenance department is alerted, and the pits are checked for possible problems.

In conclusion, computer control systems, including mathematical modeling of heating processes, result in improved operations of reheat furnaces. In addition, by providing management with a better insight of the heating and scheduling processes, computer control systems permit the development of operating strategies that optimize efficiency, productivity, and quality.

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