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AISI - DOE DIRECT STEELMAKING PROGRAM

Annual Report

for

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ANNUAL TECHNICAL REPORT
AISI - DOE DIRECT STEELMAKING PROGRAM

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SUMMARY

The Direct Steelmaking Program has completed the fifth year of research and development since cost-share funding was provided by the Department of Energy (DOE). The program has been budgeted through Fiscal 1993 for \$58,878,000, of which 77% (\$45,336,000) has been funded by the federal government. Pilot plant trials with the third, pressurized vessel with its offgas tempering, cleaning, and dust re-injection system began in July, 1993, about six weeks behind schedule but within budget, and twelve trials were conducted through November, 1993. Progress was made toward defining a four-year demonstration program for a 350,000 tonne-per-year ironmaking plant with two years required for design and construction and two years for demonstration operation.

For this one-year reporting period, one patent application has been filed for a smelting process with improved productivity and an application for an improved lance is in preparation. Three Invention Disclosure Documents were also filed. Six talks were given at three conferences, and nine papers were published in metallurgical journals. Many other papers have been accepted for publication and should appear in the next reporting period. A topical report on batch and continuous processes for refining hot metal to steel is now in press with the DOE and should be available shortly through the National Technical Information Service.

A program involving 19 trials with the pressurized vessel has been established, of which 12 were conducted in this reporting period. The remaining trials, including a final 36-hour endurance run with wustite pellets and a 72-hour endurance run with hematite, are scheduled within the next few months. Because of the complexity of the pressurized vessel, the lock-hopper feed systems, and the offgas cleaning and dust re-injection system, and because of difficulties in tapping due to poor slag fluidity, routine, stable operation was only achieved after about the tenth trial. With the medium-volatility coal used in the first 10 trials, good postcombustion (30 to 40%) was achieved after optimizing oxygen lance design and operation.

Good process control has been achieved which demonstrates that the process models developed for control truly reflect the actual operating conditions. Despite no satisfactory sensor for slag height (the radar device of last year's report has proven unsuitable), the process is well controlled based on information from the gas analysis system for hood and for stack gases and from intermittent sensor lance sampling. The solid, gaseous, and liquid effluents from the process are all within environmental guidelines.

A draft proposal for a 350,000 tonne-per-year demonstration plant program, independently funded by AISI and based on the Mannesmann Demag Pre-engineering Study mentioned in the last annual report, has been reviewed with several steel companies interested in

providing a host site. To date, one steel company has submitted an ironmaking demonstration plant proposal to the DOE.

To complete the commitment to study the refining of hot metal to steel, and thereby to meet the overall commitment to develop a process or a series of processes to produce steel directly from ore and coal, an eight-person task force was assembled in the spring of 1993, with Professor Fruehan of Carnegie Mellon University (CMU) as chairman. The task force examined trough refining processes, posthearth refining coupled to the smelter, electric arc furnace refining, the IRSID continuous refining process, and the energy optimizing furnace and compared these with the basic oxygen furnace as a base case. The report was submitted to the DOE in November.

Laboratory programs in support of the Direct Steelmaking Program were conducted at CMU, McMaster University, Praxair, and North American Refractories Company (NARCO). CMU personnel studied the reactions of the combustion products, CO_2 and H_2O , with iron-carbon droplets, slag foaming, and hot-metal desulfurization. McMaster personnel studied and modeled heat transfer through the refractory lining at representative levels in the lining, studied lance design, and worked closely with pilot plant personnel on lance design and operating procedures to improve the degree of postcombustion and heat transfer to the process. Praxair personnel also worked extensively with pilot plant and McMaster personnel on lance design and operating practices. In addition, they developed a neural net program for prediction of foam height and developed specifications for an oxy-fuel burner for the forehearth that would satisfy each of the three distinct operating regimes required for the forehearth. NARCO personnel conducted laboratory studies on fused lime-graphite brick as a replacement for magnesia-graphite brick, on high heat conductivity ram mixes for use in the water-cooled stove area, and on the resistance to slag attack of a variety of candidate refractory materials.

TASK 7 - BUDGET, PATENTS, TALKS, AND PUBLICATIONS

Budget

The Direct Steelmaking Program has completed the fifth year of research and development since cost-share funding was provided by the DOE. The program has been budgeted through fiscal 1993 for \$58,878,000, of which 77% (45,336,000) has been funded by the federal government.

Patents

An application for a patent for Mark Schlichting's invention, "Fuel and Oxygen Addition for Metal Smelting or Refining Process," was filed in July and amended in October.

A parallel application for a patent for Mark Schlichting's invention, "Lance for Fuel and Oxygen Injection into Smelting or Refining Furnace," is in preparation.

Three Invention Disclosure Documents were filed during the reporting period.

Talks

"Planning for the 400,000 Tons/Year AISI Ironmaking Demonstration Plant" by Egil Aukrust for the Pittsburgh Coal Conference, Pittsburgh, PA, September 23, 1993.

"Desulfurization of Bath Smelter Metal" by L. B. McFeaters and R. J. Fruehan for the 1993 ISS-AIME Ironmaking and Steelmaking Conference, Dallas, TX, March 28 - 31, 1993.

"Kinetics of the Reaction of H₂O Gas with Liquid Iron" by T. Nagasaka and R. J. Fruehan for the 1993 ISS-AIME Ironmaking and Steelmaking Conference, Dallas, TX, March 28 - 31, 1993.

"Planning for the 400,000 Tons/Year AISI Ironmaking Demonstration Plant" by Egil Aukrust for the 1993 ISS-AIME Ironmaking and Steelmaking Conference, Dallas, TX, March 28 - 31, 1993.

"Experimental Investigation of Interaction Rates of Iron Oxide Particles with Molten Iron-Carbon-Slag Systems" by G. G. Krishna Murthy for the TMS-AIME Annual Meeting, Denver, CO, February 21 - 25, 1993.

"Investigation of Heat Transfer Characteristics of Molten Slags" by G. G. Krishna Murthy for the TMS-AIME Annual Meeting, Denver, CO, February 21 - 25, 1993.

Publications

Farley, J. M., and Koros, P. J., "The AISI-DOE Direct Steelmaking Process - Raw Materials Requirements," *MINExpo International '92 Session Papers*, November, 1992, pp. 203 - 224.

McFeaters, L. B., and Fruehan, R. J., "Desulfurization of Bath Smelter Metal," *Metallurgical Transactions B*, Volume 24B, June, 1993, pp. 441 - 447, and 1993 Steelmaking Conference Proceedings, Volume 76, pp. 671 - 677.

Nagasaka, T., and Fruehan, R. J., "Kinetics of the Reaction of H₂O Gas with Liquid Iron," 1993 Steelmaking Conference Proceedings, Volume 76, pp. 713 - 721.

Aukrust, Egil, "Planning for the 400,000 Tons/Year AISI Ironmaking Demonstration Plant," 1993 Ironmaking Conference Proceedings, pp. 341 - 346.

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Gou, H., Iron, G. A., and Lu, W.-K., "Mathematical Modeling of Postcombustion in a KOBM Converter," *Metallurgical Transactions B*, Volume 24B, 1993, pp. 179 - 188.

Krishna Murthy, G. G., Sawada, Y., and Elliott, J. F., "Reduction of FeO Dissolved in CaO-SiO₂-Al₂O₃ Slags by Fe-C Droplets," *Ironmaking and Steelmaking*, Volume 20, 1993, pp. 179 - 190.

Krishna Murthy, G. G., Hasham, A., and Pal, U. B., "Reduction Rates of FeO in CaO-SiO₂-Al₂O₃-X Slags by Fe-C Droplets," *Ironmaking and Steelmaking*, Volume 20, 1993, pp. 191 - 200.

Mourao, M. B., Krishna Murthy, G. G., and Elliott, J. F., "Experimental Investigation of Dissolution Rates of Carbonaceous Materials in Liquid Iron-Carbon Melts," *Metallurgical Transactions B*, Volume 24B, 1993, pp. 629 - 637.

TASK 10 - DESIGN AND CONSTRUCTION OF GAS CLEANING AND TEMPERING LOOP

The design of the gas cleaning and tempering loop was completed in 1992, and site preparation was completed in January, 1993. Structural, mechanical, and electrical work continued on schedule throughout January, February, and March, with initial commissioning beginning in April.

The entire facility was completed, pressure tested, sealed, and ready for operation by mid-May, 1993. During commissioning of the third smelter, some additional minor modifications were made, and actual usage started with the first smelter trial on July 8, 1993.

Some further modifications have been made as the trials proceeded. These have primarily involved the recycle of the dust captured in the cyclone to the vessel and the control of secondary combustion in the offgas.

TASK 11 - CONSTRUCTION OF THE PRESSURIZED SMELTER AND OPERATION OF THE COMBINED SMELTER AND OFFGAS SYSTEM

Construction

Site preparation for the third, pressurized smelter began in January, 1993. All the major components had been ordered, and delivery took place during the first quarter. Construction proceeded on schedule through mid-April when problems arose during the installation and testing of the copper cooling panels in the upper area of the vessel. The removal and repair of these panels caused a two-week delay.

Further delays occurred when the entire system was tested at twice the anticipated operating pressure. Both some major and much minor reworking was required, with the net result that start-up was delayed until July 8, 1993, some six weeks behind the original schedule but within budget.

Subsequently, modifications have been required for the lock-hopper pressurized feed systems, the water-cooling system, and the Level 1 and Level 2 computer-control systems. More recently, other changes have been made to simplify and stabilize the furnace tapping process and to permit the re-injection of fines captured in the cyclone.

Operation

Trials

Twelve trials were conducted in the period from July 8, 1993, to November 18, 1993. The plan calls for a total of 19 trials with the last two being 36-hour and 72-hour endurance runs to be conducted in 1994. Ten of the twelve trials were conducted using a coal of medium volatility, about 22 to 23%. Toward the end of the tenth trial, transition was made to a high-volatile coal, about 37 to 38%, that was also used in the last two trials.

By the tenth trial, most of the modifications cited above under Construction had been implemented, and controlled stable operation was routine.

Because the smelting reduction mainly takes place in the foamy slag, and is proportional to the FeO content of the slag, it is important to know the volume of the slag as well as its FeO content for good process control. The radar foam height detector mentioned in the last annual report has proven unsatisfactory as a foam-height detector. Fortunately, the process model can predict the slag volume, although it is a function of many variables, and these predictions, calculated in real time, are used for process control.

Perhaps the most significant result from the twelve trials is that the process model works and that it can be successfully used as the basis for process control. Its success confirms that the process is well understood and that the model can be used for scale-up purposes.

Because the model requires the offgas composition as input, much of the success of the model is due to the accuracy and reliability of the offgas analysis system. Smelter offgas is sampled both in the offtake hood and in the duct after the hot cyclone. Samples are taken constantly through heat-traced lines and are either vented or presented to two mass spectrometers. Dual filters with back-flush features are provided for each line with automatic back-flush cycles. The heat-tracing is important to prevent condensation of water vapor in the lines prior to analysis so that the true degree of postcombustion can be calculated.

Slag

Considerable problems have been experienced in tapping slag from the smelter and in runner cleanup following a cast. The slag used in the process has a high lime-to-silica ratio of about 1.2 and is saturated with MgO to minimize dissolution of the magnesia lining. This slag has a tendency to freeze in the tap hole and in the runner. Physical changes were made in tap hole length and insulation to minimize the heat losses. The diameter of the tap hole has also been increased, and the mud gun has been remounted to facilitate closing the tap hole. These changes have largely eliminated the slag tapping problem.

Gas Conditioning Loop

The pilot plant does not have a prereduction shaft furnace but was designed with a gas conditioning loop to simulate the loop that must be used to condition the smelter gas before it can be used in a prereduction shaft furnace. Such conditioning involves controlling the gas temperature as well as removing some of the dust and alkalis contained in the smelter offgas. This is accomplished by passing part of the gas exiting the cyclone through a scrubber. The cooled gas then is mixed with smelter offgas in a mixing chamber located before the cyclone to control the gas temperature. Several changes have been made in this system to obtain proper operation.

Cyclone Dust Re-injection

The dust collected by the cyclone has ranged from 100 - 400 kg/hr, depending on the carbon source. For the process to be viable, the iron and carbon in this dust must be recovered by re-injection into the smelter. Re-injection of this dust into the slag has been practiced during the last two trials. Re-injection rates of 400 kg/hr have been achieved for several hours of operation.

However, dust re-injection is complicated by stops in the process, during which time re-injection must also be stopped. During these stops, slag has a tendency to build up on the re-injection tuyere which decreases and/or stops the dust re-injection. During forthcoming trials, it is planned to increase the re-injection rate to match the dust collection rate in the cyclone and to develop an operating procedure to deal with stops in operation.

Improved Process Heat Efficiency

For the first 11 trials, the water-cooled hood on the smelter was not insulated, resulting in heat losses of from 1.2 to 2.2 giga calories per hour (Gcal/hr). During the vessel reline after trial 11, it was decided to insulate the hood with 3 to 4 inches of gunned refractory to increase the duct temperature sufficiently to allow operation of the gas loop at design conditions. Prior to installing this insulation, the high heat losses resulted in a low duct temperature precluding the operation of the recycle system to provide a simulated shaft furnace gas at a temperature of 900 C. In trial 12, the insulation in the hood increased the duct temperature to as high as 1200 C, permitting operation of the recycle system at design conditions although the cyclone temperature was higher than the design of 900 C because of problems in getting adequate gas flow in the recirculating loop. This has subsequently been resolved. The insulation also decreased the heat losses to 0.5 to 1.0 Gcal/hr for a saving in process heat of 0.2 to 1.2 Gcal/hr.

Refractories

The design of the refractory lining for the third vessel was based on experience with the first vertical vessel and the second (horizontal) vessel. Special attention was paid to reducing lining and shell stresses, based on finite element analysis, and to providing the best cooling for the magnesia-graphite brick used in front of the copper stove coolers in the upper part of the vessel. The initial lining was replaced after the tenth trial.

Used magnesia-graphite brick from the uncooled areas showed no cracking and showed similar wear mechanisms to prior campaigns. Brick from the stove-cooled areas showed less wear. Retention of metallic phases and less oxidation of the brick provided obvious evidence of the steeper temperature gradients.

The second lining of the vessel includes trial panels of a large-crystal MgO product.

Environmental

An environmental assessment of the process indicates that it will meet local, state, and federal guidelines. The solids are hot metal, slag, and sludge which can be sold or disposed of normally.

It may be possible to recycle the sludge after appropriate dewatering.

The water effluent meets guidelines. The chemical oxygen demand is low, less than 10 mg/l; the NH_3 is also low, increasing from an inlet value of about 7.6 mg/l to an outlet value of about 13 mg/l, also low; and the total organic carbon is less than the detectable limit of 1 mg/l.

The gas effluent contains about 5 ppm NO_x which is much less than that from normal combustion and total hydrocarbons are about 50 ppm equivalent methane, well under guidelines.

TASK 12 - STUDY FOR IRONMAKING DEMONSTRATION PLANT AND FOR STEELMAKING PROCESSES

Basic Study of the Ironmaking Process

Mannesmann Demag completed a basic study of the AISI ironmaking process in October, 1991, independently confirming the promise for the process established by the AISI analysis of the pilot plant program. This was reported in the annual report of two years ago.

Basic Study of the Direct Steelmaking Process

AISI proposed, and DOE approved, the creation of a task force to prepare a basic study on both batch and continuous processes for refining hot metal to steel. The task force was chaired by Professor R. J. Fruehan of Carnegie Mellon University and was composed of representatives from steel industry research laboratories as well as steel-plant engineering and process-engineering consultants. The task force examined trough processes such as COSMOS, WORCRA, and the Bethlehem continuous process, posthearth refining coupled to the smelter, electric arc furnace processes, the IRSID continuous steelmaking process, and the energy optimizing furnace.

A confidential report was issued to the AISI Committee on Technology in September, 1993, along with recommendations for proposed research programs.

The report has been revised for publication and is currently going through the publication process that will make it available from the National Technical Information Service some time in 1994.

350,000 tpy Ironmaking Demonstration Plant

Mannesmann Demag completed a confidential pre-engineering study for a 350,000 tpy ironmaking demonstration plant in November, 1992, that was used as a basis for discussions with steel companies who might be interested in hosting and providing a site for such a demonstration plant. The study was reported on in the last Direct Steelmaking Program Annual Report.

AISI independently funded the preparation of a proposal for a four-year, 50-50 cost share program for AISI to manage the design, construction, and demonstration operation of a 350,000 tpy ironmaking plant at a host site. Subsequently, AISI decided that it would be inappropriate for AISI as an industry trade association to commit to management of the program. Rather, AISI would make the technology available to steel companies interested in proposing such a demonstration program and would undertake to provide a cadre of experienced scientists and engineers to assist the host company with the cooperation of the member companies employing them.

To date, one member company has submitted a proposal to the DOE, and several other member companies are actively developing a consortium to submit a proposal.

TASK 13 - LABORATORY RESEARCH PROGRAMS

Carnegie Mellon University

Kinetics of Reactions and Reaction Models

A series of process reaction models has been developed by AISI Direct Steelmaking with the aid of CMU for controlling the rate of reduction of the iron oxide and the amount of char in the vessel. These models require fundamental information on the rates of several chemical reactions. Previous work examined the reduction of FeO in slag by char and carbon in iron and the oxidation of char by CO₂ and H₂O. The current work examined the rate of the reactions of H₂O and CO₂-H₂O gases with carbon in iron and the rate of reaction of simulated volatiles (CH₄ and C₂H₆) with liquid iron.

Reactions of H₂O and H₂O-CO₂ with Iron Carbon Droplets

In the smelting processes the offgases from the primary reactions are H₂ and CO. In order for the process to be energy efficient, the offgases are postcombusted to CO₂ and H₂O. However, these gases will react with iron carbon drops, reducing postcombustion and reoxidizing iron. For example:

(1)

(2)

Similar reactions occur for CO₂. For CO₂ the kinetics are reasonably well known but not for H₂O or H₂O-CO₂ mixtures.

The kinetics of reaction were measured from 1673 - 1873 K as a function of sulfur in the metal. The rate decreased significantly with sulfur content as shown in Figure 13-1. Sulfur is surface active and retards the rate by covering the available reaction sites.

Experiments were also conducted using H₂O-CO₂ and Ar-CO₂ gas mixtures. Previous work on the rate of the reaction of CO₂ was extended to higher CO₂ pressures. The rate for CO₂-H₂O gas mixture could be predicted from the individual rates for CO₂ and H₂O as shown in Figure 13-2. The calculated line is for the assumption that the rates are simply additive. These results indicate the reactions occur independently in parallel.

A simple model was developed to predict when iron is oxidized rather than carbon. When the carbon content reaches a low value, mass transfer of carbon to the surface is slower than the rate of dissociation of H_2O or CO_2 . Typical results of the calculations and experimental results confirming the results are in Figure 13-3 where the critical carbon content is the concentration at which iron is oxidized rather than carbon. The results indicate that the carbon level must be extremely low before iron is oxidized rather than carbon.

Rates of Volatiles Reaction with Iron

Coals contain significant quantities of volatiles (10 - 45%). For the process to be energy efficient, the volatiles must be used in the process. One possible method of more efficiently using the volatiles is to inject them into the metal. Therefore, experiments were conducted to measure the rates of reaction of simulated volatiles (CH_4 and C_2H_6) with liquid iron. The rates were measured as a function of sulfur content and temperature. The results for CH_4 are shown in Figure 13-4. The rate decreases with sulfur content, indicating chemical kinetics are influencing the rate. The results of these studies are being used to assess the potential benefits of injecting coals into the metal as opposed to simply drop-charging them into the slag through the top of the reactor.

Slag Foaming Studies

Previously CMU developed the concepts required to evaluate slag foaming in the smelting process. The work concentrated on normal bath smelting slags which contain less than 5% FeO. Work was conducted with slags higher in FeO. Also, the previous work was at lower temperatures than experienced in smelting. In the two-zone smelter, the FeO content in the oxidizing zone will be higher; therefore, experiments were conducted with higher amounts of FeO and higher temperatures. Typical results in terms of the foaming index are shown in Figure 13-5. The models based on the fundamental properties to predict the foaming index previously developed could predict the present results reasonably well. It was concluded that the foaming index for any slag composition can be predicted reasonably well using these models.

Desulfurization of Smelter Metal

Equipment was built and operated to determine the metal and reagent compositions for the most effective desulfurization of smelter metal. Lime (CaO) is the least expensive reagent and resulfurizes according to the following reactions:

(3)

(4)

If aluminum is added, the reaction is:

(5)

Reaction 3 is generally slow, and smelter metal does not contain silicon. Therefore, the objective of the study was to determine the amount of Si or Al required to achieve good desulfurization. Also, CaF_2 in the flux is required to provide fast reactions; the amount of CaF_2 required was also determined.

The experiments consisted of melting 5 - 10 kg of simulated smelter metal in an induction furnace under an oxygen atmosphere. Additions of FeSi or FeAl and FeS were made once the temperature of interest was obtained and an initial sample taken. About 100 - 150 grams of desulfurization flux was then added. Samples were taken as a function of time to determine the rate of desulfurization.

The effect of the amount of silicon in the metal on the rate is shown in Figures 13-6 and 13-7 respectively. The effect of CaF_2 is shown in Figure 13-8. In addition, the effect of particle size, temperature, and stirring was also determined. A reaction model based on liquid phase mass transfer controlling the rate was developed. The rate constant (k_s) is defined from the following relationship:

(6)

$$\ln \left(\frac{\%S}{\%S_0} \right) = -k_s t$$

The rate constants as a function of Al and Si content are shown in Figure 13-9.

Based on the results, the following recommendations concerning desulfurization of the smelter metal were made:

1. There should be 0.1% Si above that required for desulfurization in the metal. For example, to remove 0.1% S, according to reaction (2), requires about 0.1% Si; therefore, there should be 0.2% Si prior to desulfurization.

2. There should be 8% CaF_2 present, and the temperature should be above the CaO-CaF eutectic ($\sim 1400^\circ\text{C}$).
3. The CaO particles should be greater than 1.5 mm diameter to avoid agglomeration.

A model for continuous desulfurization was developed. It was shown that the final sulfur level [% S_f] is related to the initial sulfur level [% S_o]; the specific feed rate (F) and the rate constant for desulfurization k

(7)

$$F = \frac{\text{metal feed rate}}{\text{Reactor capacity}}$$

(8)

$$[\% S_f] = \frac{F[\% S_o]}{F + k}$$

Based on this model, the optimized process for desulfurization was defined with regard to metal composition, temperature, reactor size, metal feed rate, flux composition, and amount of flux.

Figure 13-1

The rate of dissociation of H_2O on Fe as a function of sulfur and temperature.

Figure 13-2 Effect of p_{H_2O} in $\text{CO}_2\text{-H}_2\text{O}$ gas mixture on the rate of decarburization.

Figure 13-3 Relationship between the critical carbon content and P_{H_2O} as a function of sulfur content in the metal.

Figure 13-4

The effect of temperature and sulfur content on the rate of reaction of CH_4 with liquid iron.

Figure 13-5 Effect of temperature on foaming index for a slag containing 48%CaO, 32%SiO₂, 10%Al₂O₃ and 10%FeO.

Figure 13-6

The effect of Si content on the rate of desulfurization of carbon saturated iron at 1450°C using CaO-10%CaF₂.

Figure 13-7

The effect of Al content on the rate of desulfurization of carbon saturated iron at 140° C using CaO-10%CaF₂.

Figure 13-8 The effect of %CaF₂ in the slag on sulfur removal at 1450°C.

Figure 13-9

Rate constants for desulfurization at 1450°C using $\text{CaO-10\%CaF}_2$ as a function of Al or Si content.

McMaster University

Modeling and Computation of Heat Transfer at the Hot Faces of Working Lining of the Smelter

In the AISI Direct Steelmaking process, the amount of heat transferred at the hot face of the working lining of the vessel is required to close the process heat balance and to evaluate the process heat transfer efficiency. A one-dimensional, un-steady state heat transfer model and the corresponding computer code have been developed at McMaster University to calculate the temperature profile within the refractory wall and the heat transfer rate through the refractory hot face in the AISI pilot plant smelter.

The inner surface (hot face) of the refractory wall in the vessel is in contact with either the liquid metal, slag, or the high temperature gases. In un-steady state, part of the heat which is transferred through the hot face will be accumulated inside the refractory, and the rest will be lost to the atmosphere through the vessel shell. The aim of the heat transfer calculation is to determine the temperature profile and gradient inside the refractory, especially in the vicinity of the hot face, so that the amount of the total heat transferred through the hot face can be determined at any time during operation.

The refractory wall is divided into a number of zones along the vertical direction, and the heat transfer calculation is carried out at each zone. The main assumptions made in the modeling are:

- The refractory wall is cylindrical at each zone, and the expansion angle of the vessel at each zone is ignored.
- Heat transfer is one dimensional, that is, only occurs in the radial direction.
- The refractory is considered to be a continuous and homogeneous solid phase.

The partial differential equation for describing one-dimensional, un-steady state heat transfer by conduction is:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) \quad (9)$$

and the heat transfer rate is determined by:

$$\dot{q} = -k \frac{\partial T}{\partial r} \quad (10)$$

where:

T: temperature (°C)
t: time (s)

r: radial coordinate (m)
 ρ : density (kg/m^3)
 c_p : specific heat capacity ($\text{kcal/kg/}^\circ\text{C}$)
 k: heat conductivity which is temperature dependent
 ($\text{kcal/s/m/}^\circ\text{C}$)

Equations (1) and (2) are to be solved numerically by Finite Difference Method (FDM).

A computer program using Microsoft Fortran has been written to solve the differential equation. Two thermocouples are buried in the working lining at each zone at the same vertical level but at different radial distance. Temperatures are read in certain time intervals. At each reading, the instantaneous temperature profile inside the refractory and the heat transfer rate through the hot face of the refractory are calculated. The measured temperatures are used as the boundary conditions, and the previous calculated temperature values are used as the initial conditions in the computation. The thermal conductivities of the refractory materials involved in the calculation are temperature dependent. Before the temperature calculation, the local thermal conductivities are calculated based on the previous calculated temperature values.

This program has been integrated into the process heat balance computation program, and the computed results have been used for the process heat balance calculation and for the on-line process control.

As an example of the use of this program, calculated temperature profiles inside the refractory at a particular time are shown in Figure 13.10 and calculated temperature and heat flux at the hot face are shown in Figure 13.11.

Oxygen Lance Design

The mathematical model developed at McMaster for describing the oxygen jet combustion in the CO-H_2 atmosphere and the jet penetration inside the foaming slag was used to aid in the design of the oxygen lance and its control strategies in the AISI third smelter (reference H. Gou, Z. Du, G. A. Irons, and W-K. Lu, "Entrainment and Post Combustion in Oxygen Jets Under Steelmaking and Smelting/Reduction Conditions," submitted to Transactions of ISS, April, 1993). Based on the specific operation conditions, the model predicts the oxygen jet trajectory, temperature, velocity, and composition changes in the vessel. When the jet reaches the liquid slag, the jet momentum will allow it penetrate into the slag, depending on jet and slag properties. The jet penetration depth is related to the bath stirring, reduction reaction rate, and heat transfer efficiency of the vessel and is a very important parameter in the lance design and operation control.

The model is an attempt to determine this distance based on the fundamentals of multi-phase fluid mechanics and combustion reaction kinetics. The calculated results gave the plant engineers useful references and guidance.

FIGURE 13.10

Temperature profiles inside refractory. TCW5 is the refractory zone in contact with gas phase and TCW2 with slag phase.

FIGURE 13.11

Calculated hot face temperature and heat flux at TCW2-the refractory zone in contact with slag phase.

Praxair, Inc.

Praxair, Inc., has continued providing technical support in 1993 to the AISI Direct Steelmaking Program in the following areas:

Pilot Plant Operation

Assistance has been provided to various pilot plant activities, such as preparation for the third smelter start-up, pre-trial and post-trial analyses, and some on-line computer analyses during the third smelter trials, etc.

O₂ Lance Design & Blowing Practice

Oxygen lance practices in the first smelter and corresponding results were studied and summarized. Based on the learning from the pilot plant smelter trials, recommendations for O₂ lance design and corresponding blowing practice have been made to AISI. The O₂ lance design is specified in terms of primary and secondary O₂ flow rates, jet orientation, velocity, and number of primary and secondary nozzles. Five sets of lance design parameters have been specified to date. The first two lance designs were for the third smelter start-up trials with a relatively low O₂ flow rate, aiming to facilitate the start-up operation and to achieve a moderate PCD. They were used in the first seven trials (Trials 1 - 7) of third smelter experiments. The third and fourth sets of lance designs were for a relatively high O₂ flow rate, aiming to achieve a high PCD. They were used in Trials 8 - 12 of the third smelter experiments. The fifth set of lance designs was aimed at obtaining the optimum design, based on information from the prior trials.

Neural Nets for AISI Direct Steelmaking

A preliminary effort was carried out to assess whether neural nets could be developed to predict foam height, degree of postcombustion (PCD), and vessel heat loss as a function of various process parameters in the direct steelmaking process, such as oxygen rate, lance height, ore rate, etc. Unlike mathematical models, neural nets do not need algorithms; they learn the relationships between inputs and outputs from sets of data. They are generally easier to develop than mathematical models and can provide accurate numerical results.

Data on the horizontal vessel (Trials 9 - 20) were provided by AISI. They were filtered to discard incomplete and/or incorrect data sets and then divided into two sets: a training set on which the nets were trained and a test set on which the predictions of the nets were tested for accuracy. Figure 13.12 is an example showing the accuracy with which the nets could predict foam height from the data provided. The R² value is 0.92 for the training data set and 0.76 for the test set. Similar results were obtained for PCD and vessel heat loss. After training, a sensitivity analysis

was conducted with the neural nets to quantify the effect of changes in various process parameters on the foam height, PCD, and vessel heat loss. The nets gave reasonable trends which agreed with current process understanding and provided quantitative estimates of the effect on foam height and PCD.

Forehearth Burner

An oxy-fuel burner is needed to meet the forehearth energy requirement if a forehearth is used for the third smelter at the pilot plant. The operating requirements of the forehearth burner have been identified, and operating conditions have been defined. The forehearth burner will operate in three modes, i.e., (i) preheating mode for forehearth preheat at ambient pressure; (ii) maximum firing mode for fast heating/melting at 1.8 bars; and (iii) submerged firing mode for steady state energy supply at 1.8 bars against forehearth heat loss and for energy supply to recover from process upsets. Praxair, Inc., has proposed to AISI to supply such an oxy-fuel burner and the associated control system which satisfies the defined burner operating requirements.

Radiation Zoning Model

A radiation zoning model has been developed to study the radiative heat transfer in the head space of the third smelter and to answer "what if" type of questions. The model consists of four surface zones and one gas zone, representing the top foamy surface, top barrel, cone, vessel mouth, and free gas phase, respectively. Eighty-five cases, obtained by varying the values of eight process parameters (see Table I & II), were studied using the model. A correlation of non-measurable mouth radiant heat loss versus measurable cone radiant heat loss was established through the case study. It was found that the radiant heat loss correlation between the mouth and cone is almost linear (see Figure 13.13) for the parameter ranges studied.

TABLE I. Fixed Parameters and Their Values in the Model Calculation

Fixed Parameters	Their Values used in the calculation
Inner mouth diameter, d_4 , (m)	1.6956
Cone Height, h_3 , (m)	1.49
Top Barrel Height, h_2 , (m)	1.34
Emissivity of the top barrel refractory, ϵ_2	0.88 (NARCO data)
Emissivity of the cone gunning mix, ϵ_3	0.75 (NARCO data)
Equivalent emissivity of the mouth opening, ϵ_4	0.95

TABLE II. Variable Parameters & Their ranges in the Model Calculation

Variable Parameters	Their Ranges Used in the Calculation
Temperature of the top slag surface, T_1 , (C)	1600 - 2000
Temperature of the top barrel wall, T_2 , (C)	1500 - 1900
Temperature of the inner cone wall, T_c , (C)	1400 - 1600
Equivalent radiative temperature at the mouth opening, T_m , (C)	400 - 1100
Gas Temperature, T_g , (C)	1600 - 2200
Top barrel inner diameter, d_1 , (m)	2.83 - 3.13
Equivalent emissivity of the top slag surface, ϵ_1	0.4 - 0.8
Equivalent gas emissivity, ϵ_g	0.1 - 0.5

FIGURE 13.12

Radiative Heat Loss Mouth vs. Cone in PP #3

FIGURE 13.13

North American Refractories Company

NARCO explored the use of a fused lime-graphite brick as opposed to a magnesia-graphite brick for the smelter, a high heat-conductivity ram material for use between the magnesia-graphite brick and the water-cooled copper staves, and tested a wide variety of refractories for resistance to slag attack.

Fused Lime-Graphite Brick

Classic free energy of formation criteria indicate that refractories made with fused calcia (CaO) should be more stable than magnesia (MgO) type refractories in contact with carbon at high temperatures and might therefore provide longer life in the higher temperature postcombustion zone of the AISI smelter. Results of this study, however, indicate that the fused-lime actually enhanced the MgO-C reaction in brick made with lime contents from 15 - 65 percent. The fused-lime had poor hydration resistance, making it impossible to produce brick containing fine lime and causing lower strengths and faster oxidation for the brick made with coarse lime than for comparable magnesia-graphite brick.

No further work or field trials will be conducted on the fused-lime-bearing brick because its properties do not compare favorably with the magnesia-graphite brick now used in the smelter postcombustion zone.

High Heat-conductivity Ram Material

The third smelter vessel uses water-cooled copper staves in the cone and upper barrel. These staves are designed to allow operation without refractory, but it is desirable to maintain the brick in front of the barrel as long as possible to minimize heat losses. Because the life of the MgO-graphite brick in front of the staves will be extended by better cooling, it is important to maximize heat flow from the brick to the staves. For this reason, the properties and behavior of the high-conductivity ram mix used between the brick and staves is very important. Prior blast furnace experience has shown that this material can best be selected after simulated tests. NARCO has conducted such simulated tests using a water-cooled stove, the MgO-graphite brick to be used, and two types of ram materials which have proven particularly successful in blast furnace environments.

Temperature and heat flow measurements in a brick, ram, and copper stove system heated in the door of a gas-fired furnace have shown that the best results are obtained using a silicon-carbide-type ram material supplied by Carborundum Company. Thus, FURM 3 from Carborundum Company should be used in the third smelter.

Resistance to Slag Attack

Induction furnace slag tests conducted on a variety of refractories for the AISI smelter indicate that the best resistance is obtained using magnesia-graphite brick of the type now used in the third smelter. These results show that some improvements over the 10% graphite brick now used may be obtained using a 20% graphite product. Prior results have indicated promise for a similar brick made with large crystal magnesia. Trial brick of these two types of products have been included for trial in the current lining. An alumina-carbon-silicon-carbide brick also shows some promise but is more sensitive to high temperature than the magnesia-graphite brick. Other products tested, including dolomite brick, lime brick, SiC brick, Al_2O_3 - Cr_2O_3 brick, and MgO - Cr_2O_3 brick, gave lesser slag resistance.

Results show that various magnesia-graphite brick are the most promising for the AISI smelter and should continue to be evaluated.

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