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"Hot Metal Without Coke Ovens"

KR Process Test
Using
Domestic Raw Materials

United States Steel Corporation

and

Minnesota Department of Natural Resources

May 22, 1985

Summary

The KR Process is a two-stage, coal-based ironmaking process that is believed to be in an advanced stage of development. However, at least one test was needed to learn more about the KR Process and to determine how the process would perform with domestic raw materials. Accordingly, the States of Minnesota and West Virginia, the United States' Bureau of Mines and Department of Energy, and the American Iron and Steel Institute sponsored a KR Process test using domestic raw materials - iron-oxide pellets from Minnesota and low-volatile coal from West Virginia. This test was conducted between October 28 and November 12, 1984, in the Korf Engineering - Voest-Alpine owned 60,000-tonne-per-year KR pilot plant located in Kehl, West Germany.

Data taken during the test were examined and used to prepare material and energy balances for the process. Based on these analyses and on observations made during the test, the following significant results can be reported.

1) Process operability was excellent during the 14-day test period; no process-related outages occurred.

2) The process is controllable and it responded well to control adjustments implemented by the operators.

3) Except for a higher percentage of silicon (average of greater than 2%), the hot metal produced was similar to that produced in a blast furnace. Although the brevity of the test precluded an attempt to lower the silicon, there is little doubt that a lower silicon metal can be routinely produced. The tap-to-tap silicon variability was generally better than that of the blast furnace. The sulfur content of the hot metal averaged less than 0.025 percent which was very low for a coal-based process and was less than anticipated prior to the test.

4) Despite high heat losses and high coal losses due to fines loss, the pilot plant operated for 55 consecutive hours with a coal rate as low as 1060-kilograms-per-tonne of hot metal (kg/thm) [2120 lb/THM]. For the West Virginia coal tested, the estimated coal rate for a commerical-sized plant is about 830 kg/thm (1660 lb/THM).

The tests were quite successful and further development of the KR Process should be encouraged. Additional development work is required to provide answers to questions on scale-up and performance of the process with lower rank and higher sulfur coals. Some of these questions could be addressed via tests in the Kehl pilot plant if it is modified for better control of raw materials and for improved data acquisition. However, it is believed that the most prudent path is the construction of a 300,000-tonne-per-year KR demonstration plant.

Introduction

In September 1984 U. S. Steel (USS) Research, acting as the technical representative of the American Iron & Steel Institute (AISI) received a professional services contract from the Minnesota Department of Natural Resources (DNR) to monitor and report on a KR Process (a developing coal-based ironmaking process) test using domestic raw materials. A 14-day test using Minnesota iron-oxide pellets and West Virginia low-volatile coal was conducted from October 28 to November 12, 1984, in a 60,000-tonne-per year KR pilot plant owned by Korf Engineering (KE) and located in Kehl, West Germany. This report contains background information regarding the KR test including the motivation for the test, the test sponsors, the raw materials used and the results of the test.

Technical Background

Much research effort was expended worldwide in the 1950's and 1960's to develop new ironmaking and/or direct steelmaking processes. These processes were claimed to be better than conventional processes (blast furnace for ironmaking and open hearth and basic oxygen processes for steelmaking). Many of these new processes failed for technical reasons while others were shelved for economic reasons primarily because of the tremendous performance improvements that occurred in blast-furnace operations. Steel companies are again showing renewed interest in the development of new ironmaking processes that challenge the blast furnace. Motivation for this interest includes the need to find a process with lower investment and operating costs and fewer environmental problems than the traditional coke-oven/blast-furnace route to hot metal.

The blast furnace, shown in Figure 1, has for over 100 years been the major source of hot metal for steel production in an integrated steel plant. It is an efficient, complex countercurrent thermochemical reactor that produces liquid hot metal (iron) from iron-oxide materials, flux (limestone and/or dolomite) and coke. The solid raw materials are charged into the top of the furnace and preheated air is blown into the bottom through water-cooled nozzles (tuyeres). The air reacts with carbon in the coke producing heat and carbon monoxide (CO). The CO along with other combustion gases rises up through the shaft reducing (removing oxygen from) the iron oxide. The metallic iron formed and gangue (silica and flux materials) are melted near the tuyeres producing liquid hot metal and slag which collect in the hearth and are periodically removed (tapped). Modern blast furnaces are as large as 45 feet in diameter and produce in excess of 10,000 tonnes of hot metal per day.

As previously noted, the major impetus behind the development of new ironmaking processes is the search for a process that requires less capital than conventional practices. Much of the capital problem is related to the production of metallurgical coke. Consequently, although there are significant differences in the developing processes, a common objective is to minimize or eliminate the need for coke. Therefore, most of the processes are primarily coal and/or electricity based. Another commonality found in the new processes is that they generally consist of two stages - a prereduction step and a gasification, final reduction and melting step. Technical evaluation and plant visits led the sponsors to believe that the KR Process was in an advanced stage of development and that tests using domestic raw materials were necessary to obtain a better assessment of the process.

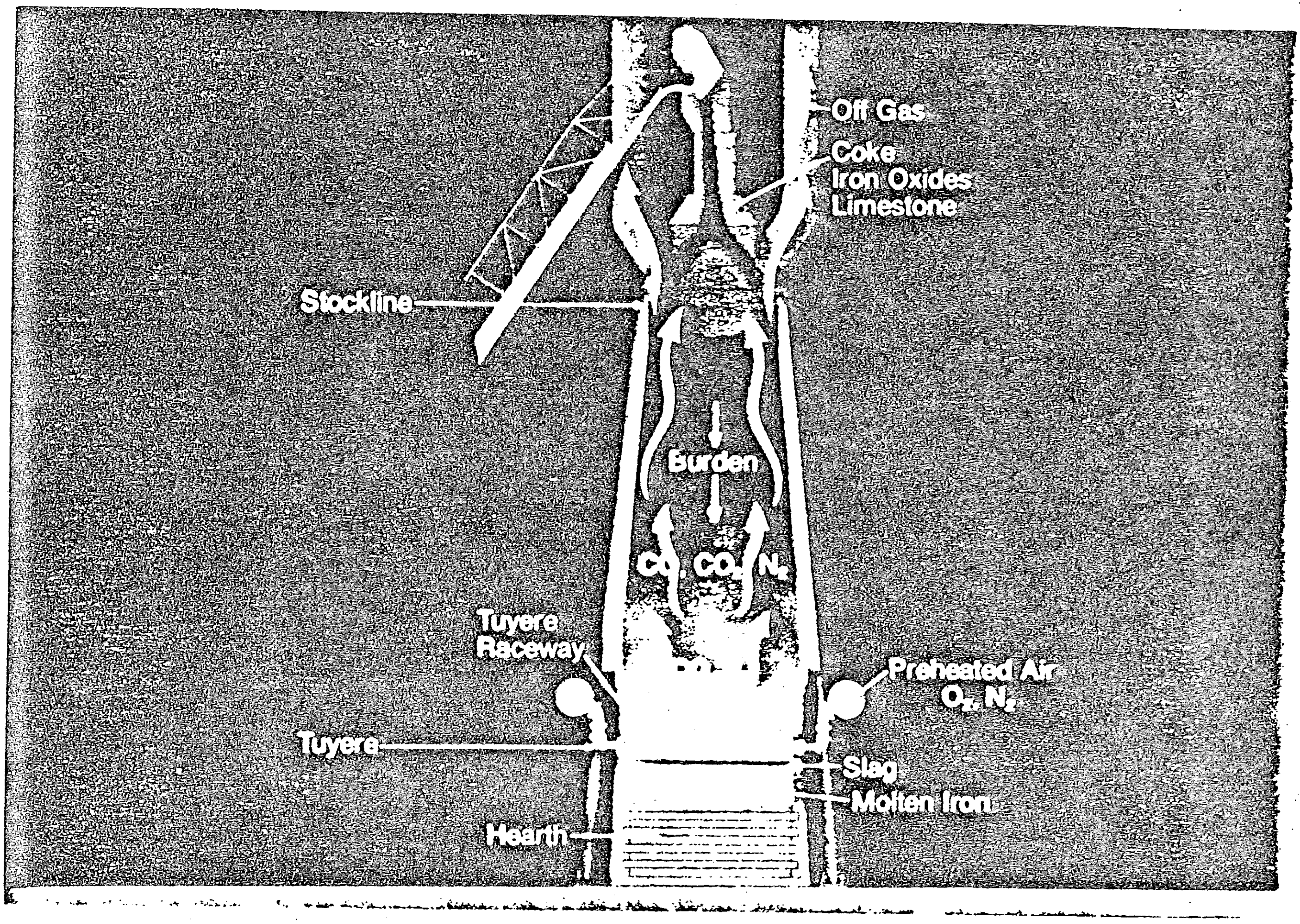


FIGURE I. BLAST FURNACE PROCESS

KR (Coal Reduction) Process

Process Description

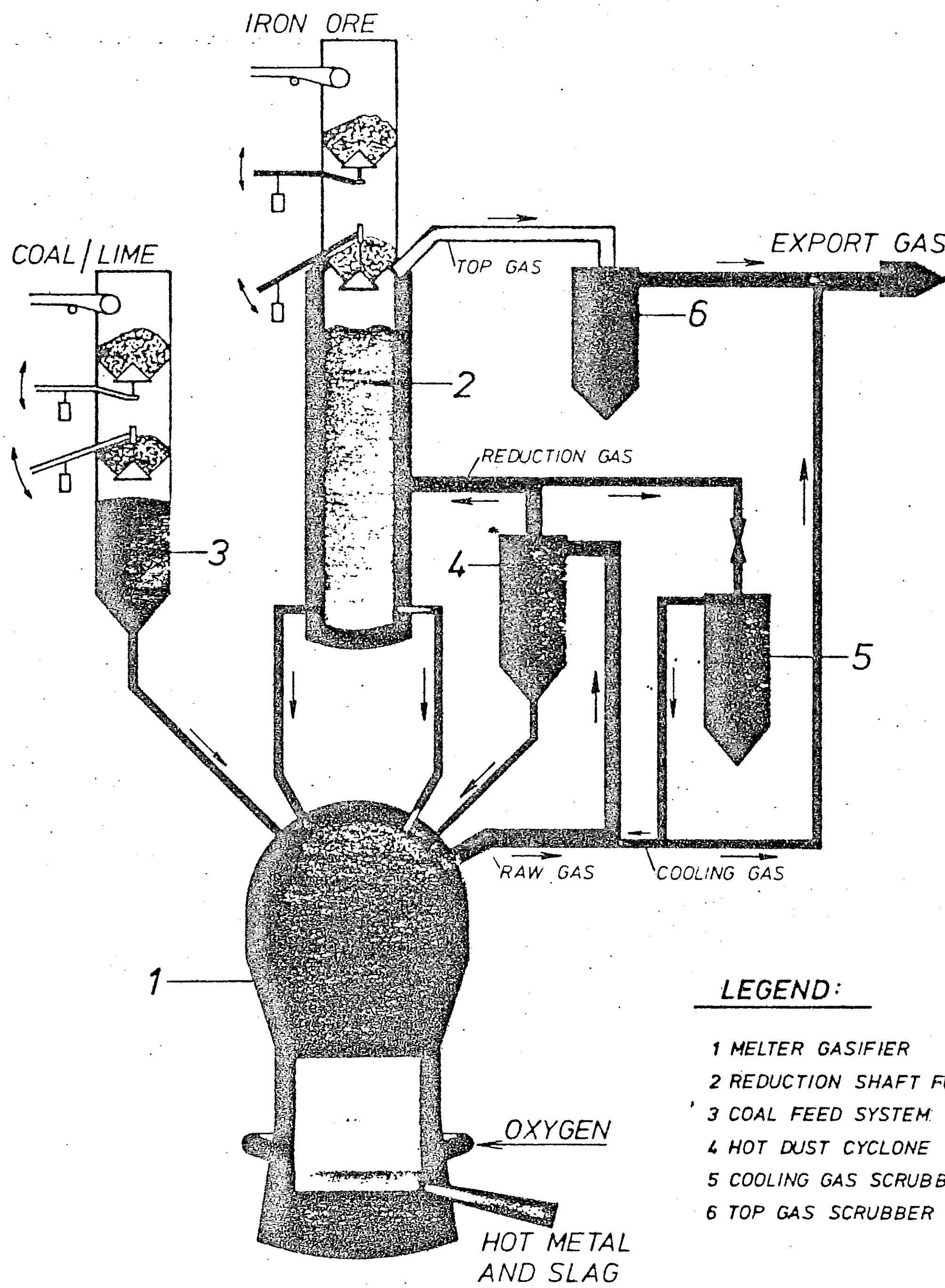
The KR Process, shown in Figure 2 which is the subject of this report, is being developed by Korf Engineering (KE) a subsidiary of Voest-Alpine (VA). The company's goal to use low-grade coal, without expensive preparation, in a quasi-fluidized bed to produce liquid iron while supplying the gas necessary for the reduction of iron oxides. The process is divided into two reactors, a reduction shaft furnace and a melter gasifier.

The reduction shaft is cylindrical and contains no interior structures. A unique feature of the reduction shaft is the discharge system which allows solid direct-reduced iron (DRI) to remain near reduction temperature (approximately 1600°F). The major components of this system are six screw feeders spaced equidistantly around the shaft which operate on a ratchet system permitting precise weighing. After leaving the screw feeders, the DRI, which is metallized to over 95 percent, drops down chutes into the melter gasifier.

In the melter gasifier, hot DRI at 1600°F is melted by the excess heat generated from the combustion of coal. The coal (particle size up to about 1-1/2 in.) is charged into the top of the melter gasifier where it contacts gas heated to a temperature of over 1800°F. The coal is quickly dried and devolatized. This reaction occurs so rapidly that most of the coal bursts forming char which falls into the fluidized bed where it is gasified by oxygen injected radially through tuyeres located near the base of the melter gasifier.

After preliminary cleaning in hot cyclones and temperature adjustment with cool recirculated gas, the hot gas generated in the melter gasifier is conveyed directly to the reduction shaft where it reduces the lump ore or pellet feed. The top gas from the reduction shaft and the excess gasifier gas not required for reduction represent valuable energy by-products of the hot-metal production. This export gas has a minimum heating value of approximately 180 Btu per standard cubic foot (Btu/scf). Maintaining control of the temperature in the gasifier hood guarantees production of high-quality reducing gas that contains about 95 percent CO and hydrogen (H_2), about one percent methane and trace amounts of nitrogen.

Little heating of the DRI takes place in the top of the gasifier, because the retention time is very short. The velocity of the descending DRI is reduced considerably in the fluidized bed resulting in additional heat transfer because of the extreme temperature difference between the DRI and the fluidized bed. The DRI is then melted directly in front of the oxygen tuyeres.



LEGEND:

1 MELTER GASIFIER
2 REDUCTION SHAFT FURNACE
3 COAL FEED SYSTEM
4 HOT DUST CYCLONE
5 COOLING GAS SCRUBBER
6 TOP GAS SCRUBBER

KR-PLANT

BASIC FLOW SHEET

FIGURE 2

The coal rate for this process will vary depending upon the coal rank but will be about 1700 pounds per ton of hot metal (lb/THM) for a high rank coal. The export gas available at this coal rate will be about 5 million Btu per ton of hot metal (MMBtu/THM) after fuel is used to produce the 0.75 ton of oxygen (tons O_2/THM) required for the process.

Like any new iron and steelmaking process, the KR presents a unique challenge for refractory-water-cooling containment systems in those critical areas that are subject to high temperatures, corrosive liquids and turbulent reducing gases. Although relatively brief periods of operation during test campaigns have indicated directions for refractory system designs, the economic viability of KR may well depend upon achieving long refractory life and attendant acceptable maintenance and replacement costs. Demonstration of refractory lifetime can only be accomplished in a large, commmercial-size plant that can be operated for long periods of time.

KR Background

The KR Process was developed by the Korf group based on small-scale tests conducted in 1975 to 1978. The early work indicated that the process might become commercial, but that a relatively large pilot plant would be required to further demonstrate the technology. The company designed a pilot plant with a nominal capacity of 8 tonnes per hour, but the high cost of building and operating such a plant forced the organization to seek funding and cooperation from other sources.

In 1979 VA agreed to purchase 49 percent of the KR Process, and a pilot plant was constructed at Kehl, West Germany, next to the Korf-owned Badische Stahlwerke. The pilot plant, which was completed in 1981, is located on about four acres of land. The major process units are a melter gasifier with an inner diameter of 3.5 metres (m) [11.5 ft] and a height of about 10 m (32.8 ft), and a reduction shaft with an inner diameter of 2 m (6.6 ft) and a height of 15 m (49.2 ft) mounted above the melter gasifier.

Regular campaigns began in 1981. The following tests were run prior to the test of United States raw materials.

Year	Operating Time, days	Materials
1981	1 in June	Anthracite & Saar coal; no ore
1981	1-1/2 in June	Anthracite & Saar coal; sponge iron
1982	(3 tests) 5-15 days each	Anthracite & Saar coal; South African ore
1983	(1 campaign) 8 weeks	South African coal, lignite coke, sinter, lump ore, Swedish pellets

In 1983 KE took over responsibility for the KR Process from the Korf group. In the same year VA purchased 100 percent of the KE stock. The firm decided to market the process worldwide and began an intensive campaign to publicize what had before been a somewhat confidential operation.

The license area for KE includes Western Europe, North and South America, and Africa. VA has the license for the Eastern block countries, Asia, and Australia. KE intends to offer turn-key installations of the KR Process and has just signed a contract with ISCOR of South Africa to construct a 300,000 tonne per year KR plant. This plant will begin operation in 1988.

Test Organization and Sponsors

The DNR along with others believed that the KR Process would be commercialized and realized that further domestic interest in the KR Process would depend upon how the process operated with domestic raw materials. Therefore, in July 1984, the DNR approached the AISI and others soliciting financial support for a KR pilot-plant trial using domestic raw materials. After several months of effort, support for a KR test became a reality largely as a result of efforts by the DNR.

Test sponsors and their approximate contributions are listed below:

State of Minnesota-DNR	$270,000
DOE	100,000
United States Bureau of Mines	100,000
AISI	70,000
State of West Virginia - Coal Development Authority	50,000

These contributions were used primarily for purchase and delivery of raw materials. KE contributed about $280,000 to this test by covering plant operating expenses such as oxygen and manpower.

Raw Material Selection

Selection Process

The DNR, acting as Project Manager, contracted with USS to supply iron-oxide pellets and a low-volatile coal for the KR test. About 3500 tonnes of Minnesota acid pellets from USS's Minntac plant were shipped to Germany for the test. These pellets were of excellent quality and are typical of the pellets produced domestically and used in blast furnaces for the production of hot metal. Based on conversations with KE, it was mutually agreed that a relatively low-volatile coal would provide the best performance in the KR Process. Accordingly, about 2600 tonnes of West Virginia low-volatile coal from the Pocahontas No. 3 Seam was obtained and shipped to West Germany.

Chemical and Physical Properties

The 3500 tonnes of pellets were reclaimed from the Minntac pellet stockpile at Duluth and loaded in the Transocean Pearl on September 29, 1984. The vessel departed Duluth on October 4, 1984. The pellets were sampled as reclaimed at 300-ton intervals using an automatic sampling system.

The 14 samples taken during loading were combined and chemical, physical, and metallurgical tests were run on the composite sample. All test values fell within current Minntac pellet specifications. The data are shown on Table I.

A. T. Massey Coal Sales was contracted to supply the West Virginia coal for the test. About 2600 tonnes of washed, low-volatile stoker coal nominally sized at 1-1/4 by 1/4 inch from the Pocahontas No. 3 Seam were obtained and loaded in the Breekant at Norfolk, Virginia, on October 6, 1984. A composite sample taken during loading was sent to the USS Technical Center for analysis. Results of this analysis are shown in Table II.

Liquid oxygen, liquid nitrogen and fluxes were obtained from suppliers in Germany. The analyses of the flux materials are shown on Table III.

TABLE I

KR TEST PROGRAM
DATA ON MINNTAC PELLETS

Chemical Analyses, % (dry)

Fe	65.3	Na_2O	0.023
FeO	0.32	K_2O	0.018
SiO_2	5.68	TiO_2	0.018
Al_2O_3	0.23	V_2O_5	0.0085
CaO	0.35	CuO	0.0009
MgO	0.32	ZnO	0.0018
MnO	0.11		
P_2O_5	0.05		

Screen Analyses

Size	Before Tumble Wt %	Before Tumble Cum Wt %	After Tumble Wt %	After Tumble Cum Wt %
+5/8 in.	0.1	0.1	0.1	0.1
-5/8 +1/2 in.	5.2	5.3	4.6	4.7
-1/2 +3/8 in.	84.6	89.9	82.2	86.9
-3/8 +1/4 in.	8.6	98.5	9.5	96.4
-1/4 in. +4 M	0.5	99.0	0.3	96.7
-4 +28 M	0.3	99.3	0.3	97.0
-28 M	0.7		3.0	
	100.0		100.0	

Q Index = 94.95

Moisture Analyses

Average of 14 increments	3.20%
Standard Deviation	0.82%
Standard Deviation of Mean	0.22%

TABLE I (Continued)

KR TEST PROGRAM
DATA ON MINNTAC PELLETS

Compression Tests

Average Compression (60 pellets)	503 pounds
Standard Deviation	186 pounds
Standard Deviation of Mean	24 pounds
Percent Minus 200 Pounds	3.3

Low-Temperature Breakdown Tests

	% +6.3 mm	% -6.3 +3.15 mm	% -32 Mesh
Test No. 1	90.1	5.5	2.0
Test No. 2	88.3	5.8	2.7
Average	89.2	5.6	2.4

ISO Reducibility dR/dt_{40}

Test No. 1	0.82
Test No. 2	0.78
Average	0.80

TABLE II

KR TEST PROGRAM
WEST VIRGINIA COAL DATA

Proximate Analysis

Moisture	3.5
Ash	9.2
Volatile Matter	14.9
Fixed Carbon	75.9

Sulfur

Total	0.60
Organic	0.56
SO_4 (S)	<0.01

Ultimate Analysis

Moisture	3.50
Carbon	83.09
Hydrogen	4.00
Nitrogen	1.11
Chlorine	ND
Sulfur	0.60
Ash	9.17
Oxygen (by dif.)	2.03

Ash Mineral Analysis

SiO_2	55.98
Al_2O_3	29.97
Fe_2O_3	6.10
TiO_2	1.85
CaO	1.15
MgO	0.86
Na_2O	0.85
K_2O	0.87
P_2O_5	0.20
SO_3	0.95
Undetermined	1.22

Calorific Value

Gross	14230 Btu/lb
	33080 KJ/kg

Ash-Fusion Temperature (Reducing)

Fluid	2700+°F
	1480+°C

Free-Swelling Index 7

Grindability (Hardgrove Index) 91

Size (Lamberts Point)

Screen (Sq. Mesh)	Cum % On
2 in.	0.5
1-1/2 in.	2.9
1 in.	17.5
1/2 in.	70.8
1/4 in.	91.0
1/8 in.	92.8
14 Mesh	94.7
28 Mesh	95.6
48 Mesh	96.8
100 Mesh	97.8
200 Mesh	98.2

Ox. 99%

Rouhr Dilatation +30

Vitrinoids 72-75% Reactives

TABLE III

KR TEST PROGRAM
FLUX DATA

	Quartz	Coarse Dolomite	Fine Dolomite	Coarse Limestone	Fine Limestone
Fe_T	0.23	0.72	0.66	0.03	0.18
SiO_2	89.30	4.19	3.84	0.094	0.93
Al_2O_3	1.82	1.03	0.88	0.05	0.25
CaO	1.19	29.0	28.8	56.0	54.5
MgO	0.14	19.8	20.1	0.20	0.43
MnO	0.015	0.070	0.054	0.012	0.043
P_2O_5	0.040	0.042	0.044	0.008	0.012
S	0.04	0.13	0.12	0.02	0.02
Na_2O	0.49	0.22	0.18	0.004	0.013
K_2O	1.89	0.41	0.37	0.005	0.031
TiO_2	0.055	0.089	0.097	<.01	0.013
BaO	0.033	0.009	0.012	0.017	0.019
Cr_2O_3	0.004	0.003	0.004	0.001	0.002
C	0.24	11.79	12.00	11.75	11.85
CW	0.40	0.46	0.46	0.50	0.28
FW	0.042	0.081	0.078	0.039	0.017
LOI	1.07	44.15	44.58	42.8	43.2

Size Range

Quartz	1-3 mm (approximate)
Coarse Dolomite	11-16 mm
Fine Dolomite	2-4 mm (approximate)
Coarse Limestone	8-15 mm (approximate)
Fine Limestone	0.5-2.5 mm

Pilot-Plant Description

The following is a brief discussion of the KR pilot-plant facilities.

Raw-Material Handling

Raw materials (iron ore and coal) are unloaded from barges at a dock a few kilometres from the pilot plant. These materials are transported by dump truck to the storage area of the pilot plant where they are stored on a gravel base. The material handling facilities are very limited which precludes blending of the segregated sizes formed in loading, unloading and stocking. Moreover, it is very difficult to obtain representative samples of materials as they arrive or are consumed at the plant. The fluxes are stored in bins on a concrete pad with wooden dividers and a concrete back wall.

A front-end loader reclaims raw materials from the stockyard and loads the feed hoppers. There are four hoppers, one each for coal and ore and two for fluxes. If required, additional materials are charged by preblending on the ground or by forming alternate layers in the feed hoppers. The hoppers are mounted on load cells. Vibratory conveyors deliver desired weights of materials to a common belt that feeds a bucket elevator which lifts alternately coal and ore to the top of the pilot plant. A separate lift is not made for the fluxes as these materials are metered from the bins onto the common belt while feeding the bucket elevator with either ore or coal. The materials are mixed at transfer points.

The iron-ore material including any coarse fluxes are diverted at the top of the bucket elevator through a chute into the blast-furnace-type bell charging system of the shaft furnace. The coal and finer-sized fluxes load through a similar system connected to a pressurized coal feed hopper. Screw feeders transport coal from the bottom of this pressurized vessel into steeply sloping pipes which feed into the melter-gasifier. Although two coal screw feeders are installed, only one is used.

Liquid O_2 and liquid nitrogen (N_2) are trucked to the plant and stored in cryogenic tanks. A large battery of air economizers provides the vaporization capacity of the plant under usual conditions. However, in colder weather personnel are assigned to purge frost and ice from these devices. The O_2 enters the plant through a main metering orifice and then flows to the tuyeres and dust burners. The nominal flow for the campaign was 3750 normal cubic metres per hour (Nm^3/h) (2830 scfm). The N_2 is used to pressurize the coal feed hopper, and provide purge gas to prevent hazardous gas leakage and safe emergency shutdown.

Shaft Furnace - Design and Operation

Except for the methods of feeding iron ore (as mentioned previously) and withdrawing the DRI, the shaft furnace design approximates a scaled-down Midrex configuration. The shaft which is 2 m (6.6 ft) in inner diameter performs oxygen removal and iron metallization in a reduction zone about 7.5 m (24.6 ft) in height above the tuyeres needed to inject hot reducing gas. Another 7.5-m-high zone below the tuyeres provides extended residence time and assists in the carburization of the DRI. In that regard, KE stresses the importance of cementite (Fe_3C) formation which precludes reoxidation of iron in front of the oxygen tuyeres of the smelter and assures low iron-oxide (FeO) concentration in the slag. The total residence time in the shaft furnace is nine to ten hours.

The heat loss of the gas stream from the smelter limits bustle pipe temperature (distributor pipe feeding hot gas to the tuyeres) to about 750°C (1382°F). At this temperature, the hot reducing gas and the exothermic reduction and carburization of the iron by CO gives about 820 ± 20°C (1508 ± 36°F) in the hottest zone of the shaft. Prior to discharge, the DRI cools to 650 to 750°C (1202 to 1382°F).

Six pneumatically-operated water-cooled screw feeders which are installed on the circumference of the shell discharge volumetric increments of hot DRI and fluxes from the bottom of the shaft furnace. Each of the screw feeders connects to a feed pipe leading to the smelter.

Melter/Gasifier (Smelter)

Design

The smelter is a pressure vessel originally designed for 16 bars pressure (about 16 atmospheres). Both the top and the bottom of the steel shell are dome shaped. The smelter has a cross-section area of about 10 square metres (m^2) [107.6 ft^2] in the lower portions comprising the hearth and fluidized bed. The fluidized bed zone is about 2.5 m (8.2 ft) high. The elevation of the tuyeres above the taphole is 1.7 m (5.6 ft). The upper or solids disengaging zone of the smelter expands to about 20 m^2 (215.3 ft^2). This part of the smelter is usually referred to as the dome.

High-purity O_2 is injected through 12 tuyeres spaced equally around the lower circumference of the smelter. The tuyeres and related ancillary cooling equipment are similar to the usual blast-furnace design. The flame temperature is 2700 to 3000°C (4892 to 5432°F) in the raceway created by the O_2 injection.

A falling film of water cools the dome and sidewalls of the melter-gasifier. Water sprays cool the bottom. Various other members utilize water channels.

The smelter has four devices employing a radioactive isotope of cobalt (Co^{60}) to detect the level of the fluidized bed. The level indicators also measure the intensity of the radioactive signal and therefore can provide some indication of bed-level at intermediate positions. The lowest level indicator contains fail-safe circuitry which automatically shuts off the O_2 and purges the smelter with N_2 should the bed level decrease below this critical level.

Operation

During operation of the melter-gasifier, the coal particles enter the dome and encounter temperatures of 1000 to 1100°C (1832 to 2012°F). The coal releases volatile matter and, according to KE literature, shatters into smaller particles. The charred coal then forms a fluidized bed in the region above the tuyeres. The gas generated by the combustion of C with O_2 exerts a lifting force on the particles of the bed. The upward flowing gases carry some sensible energy from the raceway to the upper portions of the smelter.

Use of low-rank coal with high-volatile matter, high moisture, and low-fixed carbon adversely affects the operation. The volatiles lower the dome temperature and preclude cracking of the higher molecular weight material. The tar formed under these conditions will carry over to the shaft furnace and the gas cleanup equipment.

Gas Handling and Fines Recirculation

To prevent accretion of fused particles in the two gas pipes (offtakes) from the melter-gasifier, the hot gas is quickly cooled to 850 to 950°C (1562 to 1742°F) by water-cooled members and by the immediate injection of cold recycle gas. The cooler gas is then directed to two hot cyclones. The KR Process is similar to any fluidized bed process in that a heavy fines circulation load exists. Therefore, equipment is installed to recycle the fines to the melter-gasifier. After the cyclones, the parallel gas streams are joined. Part of the gas is then diverted to a variable throat venturi scrubber and a cooling tower. This gas has a heating value of about 280 Btu/scf.

Equipment similar to that used on the melter-gasifier off-gas scrubs and cools the top gas from the shaft furnace. The bypass gas mixes with this cold gas and the combined stream flows past a butterfly valve which completes the pressure control scheme. The top gas before mixing has a heating value of about 180 Btu/scf.

Orifice meters determine the flow of melter-gasifier off-gas, cold recycle gas, bypass gas for pressure control, and the shaft-furnace top gas. The pilot plant flares the fuel gas derived from the excess smelter gas and shaft-furnace top gas.

Data Acquisition and Sampling

In addition to measurements of flows, temperatures, and pressures discussed above, temperatures are measured at various locations in the refractories of the melter-gasifier. The flow of N_2 is also determined by an orifice meter.

During operation, samples of DRI, slag, metal and fine material are transported to the chemical laboratory of the adjacent Badische Stahlwerke.

Continuous gas analyzers measure the components of the smelter off-gas and the shaft-furnace top gas. The major components are CO, carbon dioxide (CO_2) and H_2. In addition, methane (CH_4) is determined in the smelter gas. A thermal conductivity analyzer determines H_2 while infrared analyzers are used for the other components.

The KE operators recorded temperatures, gas flows, and gas analyses from the various strip chart recorders on a two-hour schedule.

Test Program

Test Objectives

The major objective in running the test was to determine how the KR Process performs with good quality domestic raw materials. Data from extended periods of operation would provide an opportunity to assess the stability and operability of the process and to determine how the process responds to changes in operating parameters. Such information is required in order to assess the technical and economic viability of any process.

Test Chronology

Figure 3 is an operating chart prepared during the test which shows the test chronology, information on hot-metal composition and other important operating data. This figure is useful in discussing how the test was conducted.

At 10:00 a.m. on October 28, 1984, the ore charge to the shaft was changed from 100 percent Sishen ore (from South Africa) to a 50 percent mixture of Minntac pellets and Sishen ore. Nine hours later, the ore charge was switched to 100 percent Minntac pellets. This transition was accomplished smoothly. At 10:30 p.m. on the same day, the coal charge was changed from a mixture of one-third anthracite/two-thirds Australian coal to 100 percent West Virginia coal. Following the change to U. S. raw materials, there was a dramatic increase in hot-metal temperature and silicon content. By 4:30 a.m. on October 29, 1984, the percent silicon in the hot metal had exceeded 3 percent and the hot-metal temperature had increased to nearly 1600°C (2912°F). These changes were attributed to oversize coal which prevented the fluidized bed from operating in a normal manner. The KE engineers speculated that large-size coal particles were dropping to the base of the gasifier causing it to operate like a packed bed instead of a fluidized bed.

The operators changed the coal feed to about two-thirds West Virginia coal and one-third anthracite, changed the flux charge and made other process adjustments to get control of the process. The anthracite coal was smaller in size and improved the performance of the fluidized bed.

On October 30, 1984, a breakout in the spool piece leading from the melter-gasifier to the runner resulted in a 13-hour outage. This failure was caused by improper refractory installation. Following repair the coal charge was changed back to 100 percent West Virginia coal which had been screened to minus 35 mm (1.38 in.) to provide more normal operation of the fluidized bed. Just when the process appeared to be coming under control, an electrical failure of the lowest level probe caused an automatic shutdown of the plant. Unfortunately, some mistiming of nitrogen

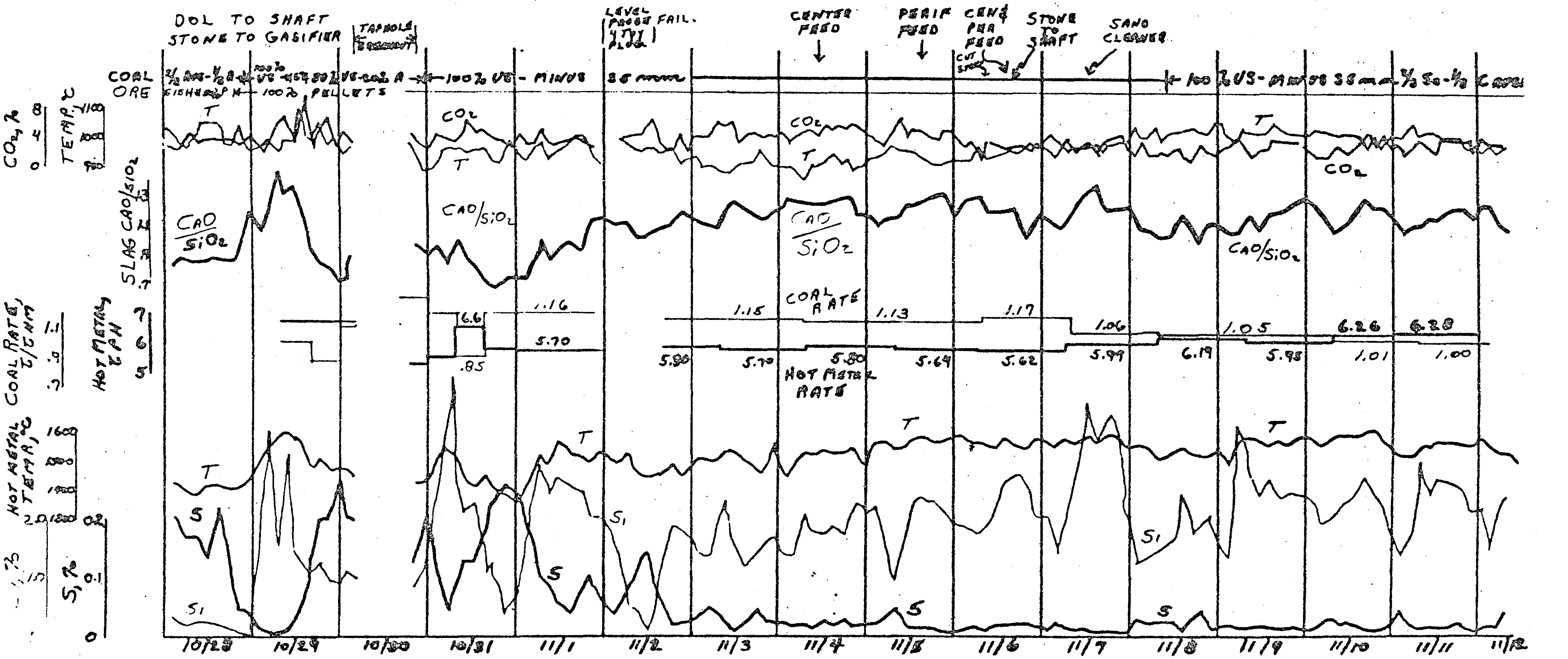


FIGURE 3

flow resulted in the plugging of four tuyeres with slag. This resulted in a total downtime of about four hours.

Following the start-up and after opening the plugged tuyeres on November 2, 1984, the plant operated continuously for a total of nearly 10 days until it was shutdown normally on November 12, 1984 in preparation for other test work. During this time, the plant operated smoothly and a number of tests regarding the feed location for reduced pellets and fluxes were conducted. Also during these ten days, extended periods of stable operation were obtained.

Test Results

The test using West Virginia low-volatile coal and Minnesota iron-oxide pellets in the KR Process pilot plant in Kehl, West Germany, was quite successful. The following significant results and conclusions can be drawn based on (1) observations made during the test, (2) analyses of the data collected during the test, and (3) material and energy balances on the pilot-plant operation.

1) Process operability was excellent during the 14-day test period. This conclusion is based on the fact that no process related plant outages were encountered. Downtime for other equipment problems took only about 5 percent of total test time.

2) The KR Process is stable, controllable and responsive to control measures taken by plant operators. (See Figure 4 for tap-to-tap hot-metal properties.) Controllability was demonstrated by the ease with which the plant was put back into production after a shutdown of about 13 hours. Furthermore, an intentional shutdown was conducted to demonstrate the ease with which the plant can be restarted.

3) The KR Process is capable of producing hot metal with a quality similar to that produced in the blast furnace (see Table IV). Sulfur in the hot metal averaged less than 0.025 percent during the entire test period which was lower than expected. The silicon in the metal averaged greater than 2 percent which is higher than what is normally produced in the blast furnace. Because of time constraints no attempt was made to decrease the silicon content of the hot metal. However, there is little doubt that a lower silicon metal can be achieved.

4) The process operated with a coal rate as low as 1060 kg/thm (2120 lb/THM) despite high heat losses and high coal losses to the dust. For the West Virginia coal tested, it is estimated that the coal rate for a commercial-sized KR plant would be about 830 kg/thm (1660 lb/THM) which is slightly higher in most cases than the equivalent coal rate to hot metal via the coke-oven/blast-furnace route. At this projected coal rate, the export gas expected energy content is about 8 MMBtu/THM. However, if the gas is burned in a steam-driven power generator for the oxygen plant, the available export gas energy content would be decreased to about 4.6 MMBtu/THM which is less than 1 MM Btu/THM greater than that of the coke-oven/blast-furnace route.

Although the test was successful, many questions regarding scale-up and the performance of the process with lower rank and

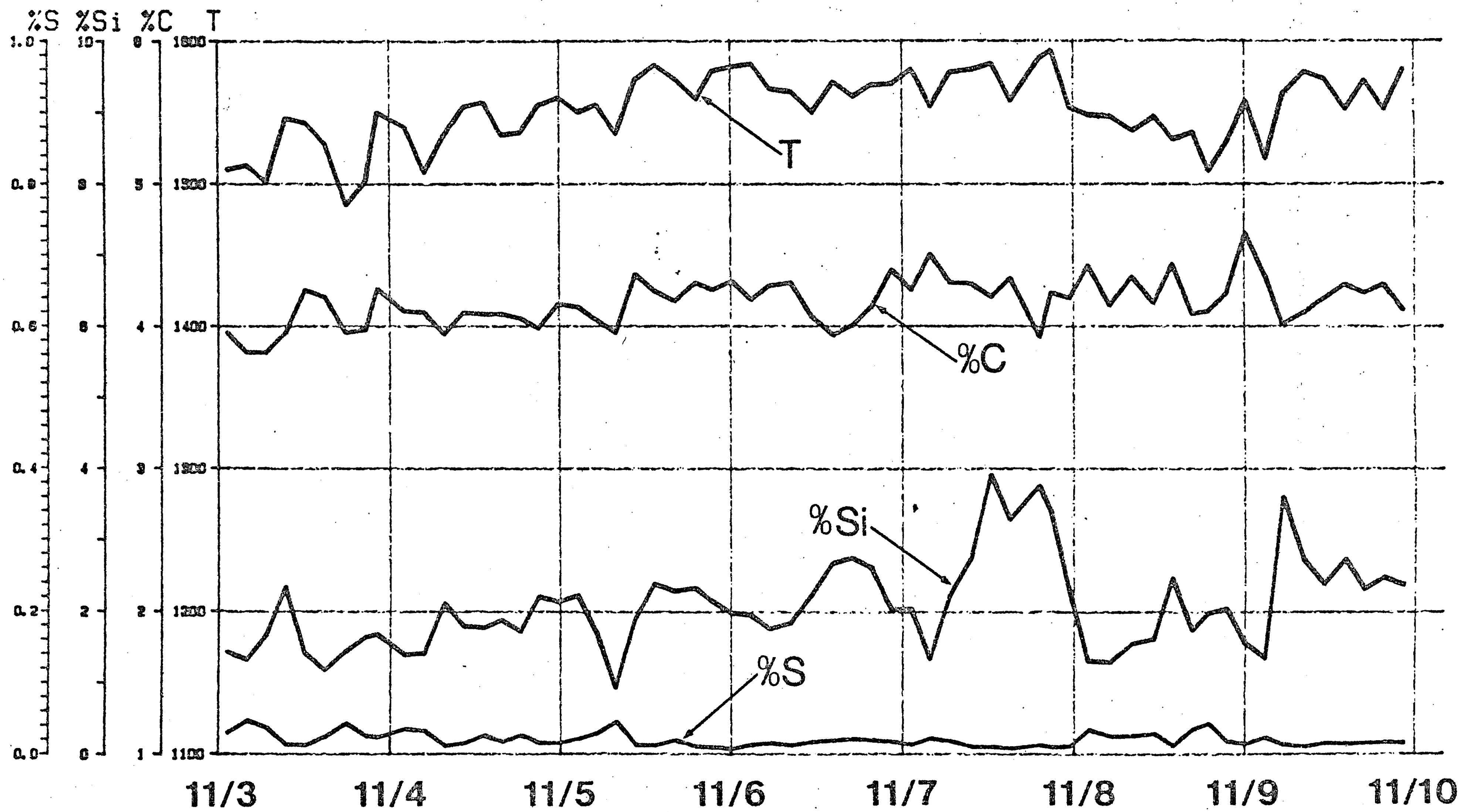


FIGURE 4 HOT METAL CHEMISTRY

higher sulfur coals need to be answered. Some of these questions could probably be addressed with tests in a modified pilot plant with improved control of raw materials charged to the plant, improved dust recovery, and better data acquisition.

Because it is believed that further development of the KR Process is warranted, and after considering all factors, the most prudent step would appear to be the construction of a 300,000 tonne per year demonstration plant.

Table IV

Hot-Metal Properties
20 Consecutive Taps

	Mean	Standard Deviation
Temperature °F/°C	2822/1550	45/25
% C	4.27	0.15
% Si	2.40	0.44
% S	0.021	0.009

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