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Recovery of Iron, Carbon and Zinc from Steel Plant Waste Oxides using the AISI-DOE Postcombustion Smelting Technology

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Events Leading To This Process Development

In November 1988, the American Iron and Steel Institute (AISI) and the United States Department of Energy (DOE) began a collaborative program to define an energy-efficient and environmentally-friendly technology for the production of hot metal for steelmaking directly from coal and iron ore pellets, without incurring the high capital costs and environmental problems associated with traditional coke and blast furnace technology. The five year $60.3 million research and development program, including pilot plant operations, laboratory research, and an independent study of the results, confirmed the technical feasibility of the postcombustion smelting technology developed for this purpose.

In April 1994, an alternative opportunity was sought to demonstrate this new technology, without waiting until existing ironmaking capacity needed to be replaced. Recycling and resource recovery of steel plant waste oxides was considered to be an attractive candidate. To assess this alternative, a ten-month, cost-shared $8.3 million program was initiated to test the production of hot metal from steel plant waste oxides using the new technology.

The waste oxide recycling trials, completed in December 1994, were highly successful, and it was decided to proceed immediately with a feasibility study for a demonstration plant producing 250,000 metric tons per year (mtpy) of hot metal from 500,000 mtpy of waste oxides. The rising costs of landfill disposal, the value of the hot metal that would be produced by smelting the waste oxides, and the overall environmental improvement argued strongly for the next step. The feasibility study indicated that the capital cost for a plant processing 500,000 mtpy of steel plant waste oxides would be $70 million with a profit potential of $30 million. The results of the waste oxide recycling trials, and the subsequent feasibility study are presented in this paper.

Process Description

The process flowsheet used at the pilot plant is shown in Figure 1. Coal/coke breeze and iron ore pellets/waste oxides are charged into the smelting reactor. The waste oxides are either agglomerated into briquettes (1 inch) using a binder or micro-agglomerated into pellets (1/4 inch) without the use of a binder. The iron oxides dissolve in the slag and are reduced by carbon to produce molten iron. The gangue oxides present in the raw materials report to the slag. Coal charged to the smelter is both the fuel as well as the reductant. Carbon present in the waste oxides is also used as the fuel/reductant resulting in a decrease in the coal requirement. Oxygen is top blown through a central, water-cooled, dual circuit lance. Nitrogen is injected through tuyeres at the bottom of the reactor for stirring purposes. The hot metal and slag produced in the smelting reactor are tapped at regular intervals through a single taphole using a mudgun and drill system. The energy requirements of the process are provided by (i) the combustion of carbon to carbon monoxide, referred to as primary combustion and (ii) the combustion of CO and H_2 to CO_2 and H_2O, known as postcombustion.

Dust laden gases exit the pressurized smelter and pass through a hot cyclone where most of the carbon, and much of the iron present in the dust are captured and returned to the process. The gas exiting the cyclone is quenched and the remaining solids are removed as a sludge. The zinc and lead present in the steel plant waste oxides report to the sludge. The alkalis and halogens report to the contact water system. The quenched gas has considerable fuel value, and can be used as a partial replacement for natural gas, or desulfurized coke oven gas.

The system is entirely enclosed, so that it is virtually pollution free. The only release to the atmosphere is from the combustion of the export gas. This gas contains sulfur, hydrocarbons, and nitrogen oxides at levels which do not create environmental concerns.

Thus, from the smelting of steel plant waste oxides the following products are made: (i) carbon saturated hot metal which can either be pigged/granulated, or used in the electric arc furnace (EAF) or the basic oxygen furnace (BOF), (ii) slag that can be used in construction applications, (iii) offgas containing considerable

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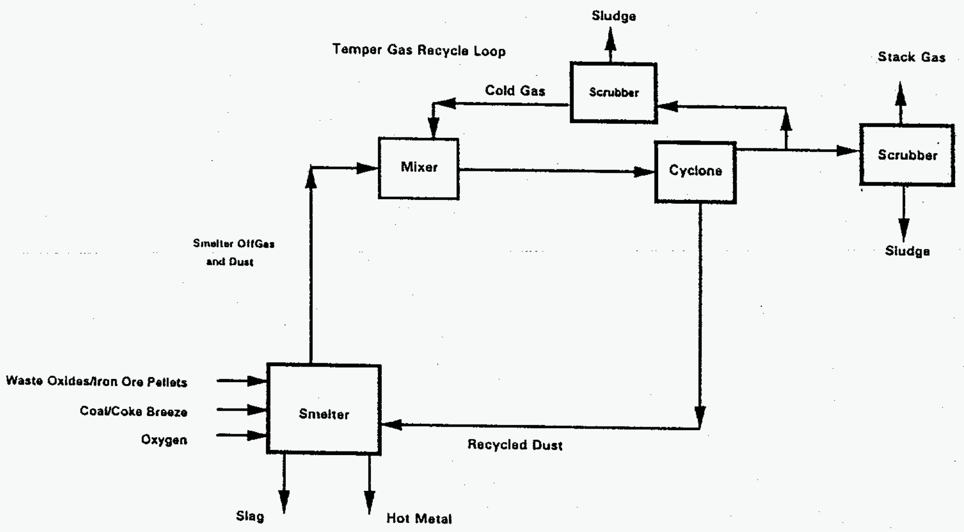
fuel value, which can be used in slab reheating furnaces, or for steam generation, and (iv) sludge with high levels of zinc, which can be used by the zinc producers as a feedstock.

Figure 1 : AISI-DOE Pilot Plant Flowsheet



Pilot Plant Equipment

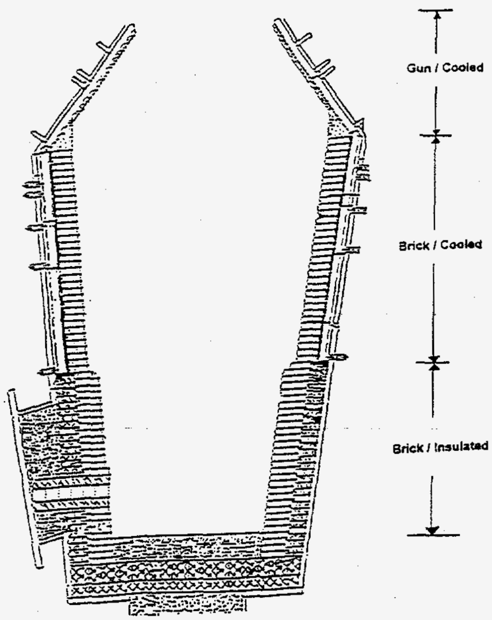
The pilot plant was located in Universal, Pennsylvania at a facility made available by United States Steel. Figure 2 shows a schematic of the vessel with the stave cooled and insulated refractory sections. A mix of the top charged raw materials entered the vessel on diametrically opposite sides through a double lockhopper arrangement. At any given time, material was charged to the vessel from only one feed hopper. Finer materials such as coal, blast furnace (BF) dust, BOF dust, and smelter dust were pneumatically injected into the slag.

The water-cooled cone and hood (not shown), at the top of the vessel, were coated with gunnite material, and frozen slag. The vessel was lined with refractory up to the cone. The refractory in the free space (upper barrel) was backed by water-cooled copper staves. Additional staves were later added to extend the stave-cooled region into the slag zone (mid barrel). Below the stave-cooled region, the refractory bricks were backed by an insulating safety lining.

The taphole was located at approximately the fifteen metric ton (mt) metal line. Casting was conducted every 90-120 minutes. Metal and slag samples were taken at cast. A sub-lance was used to measure metal temperature, and slag height as well as obtain slag and metal samples. The offgas exiting the smelter was analyzed by two Perkin-Elmer mass spectrometers. The gas samples were obtained from the duct prior to the cyclone as well as from locations after the cyclone. The offgas was continuously analyzed for CO, CO_2, H_2, H_2O, N_2 and Ar. A gas chromatography unit was used to measure the levels of sulfur bearing gases such as H_2S, COS, SO_2, and CS_2. The NO_x and total hydrocarbon content of the offgas were also monitored.

The gas exiting the smelter was dust laden as it traveled through the duct. Nitrogen used for the oxygen lance seal and raw material charging mixed with the smelter gas in the duct. In the mixing chamber, prior to the cyclone, smelter gas was tempered by a controlled amount of cold recycle gas. As the tempered offgas passed through the cyclone, much of the dust was removed. This dust was either collected and weighed in boxes or reinjected into the smelter after temporary storage in a silo. The dust discharged from the cyclone was sampled at regular intervals. The relatively cleaner gas exiting the cyclone was split into two streams. These streams were quenched separately with the smaller stream being used for tempering the gas entering the cyclone. The sludge from the scrubbers was sampled regularly. The gas exiting the main scrubber was burnt in the flare stack.

Figure 2: Smelter Schematic showing Refractory and Stave-cooled regions



Raw Materials

The steel plant waste oxides smelted at the pilot plant were BF dust and sludge, BOF dust and sludge, and rolling mill (RM) sludge. The charging system used for the recycle trials was originally built for iron ore pellets and could not be used to charge the waste oxides directly. Therefore, the waste oxides were agglomerated into briquettes using molasses and cement as the binder. The BF dust/sludge, BOF dust/sludge and RM sludge were obtained from integrated steel producers. The composition of the agglomerated waste oxides used in the pilot plant trials is shown in Table 1. In integrated steel mills, a mixture of the generated BF/BOF/RM waste oxides can have a zinc content up to about 3.5%. This was the case in agglomerates A, B, C, D1, and D2. In EAF steelmaking, the zinc content of the dust can be as much as 25%. In agglomerates E1 and E2, the zinc level of EAF steelmaking dust was simulated by the use of zinc calcine. In some trials, dry BF and BOF dust were directly injected into the slag. The chemical composition of the agglomerates smelted is shown in Table 2.

Table 1 : Composition of Agglomerated Waste Oxides

Agglomerate	BF Dust	BF Sludge	BOF Dust	BOF Sludge	Rolling Mill Sludge	Zinc Calcine	Zn level (%)
A	40	40	20	0	0	0	0.67
B	40	20	20	0	20	0	0.7
C	22.5	22.5	20	35	0	0	0.81
D1	25	25	50	0	0	0	1.27
D2	25	25	50	0	0	0	3.48
E1	0	0	70	0	0	30	21.09
E2	15	15	30	0	0	40	24.56

Table 2 : Chemistry of Agglomerated and Injected Waste Oxides

	Agglomerate A	Agglomerate B	Agglomerate C	Agglomerate D1	Agglomerate D2	Agglomerate E1	Agglomerate E2	Injected BF Dust	Injected BOF Dust
SiO2	7.82	6.41	5.5	8.77	5.56	3.5	4.17	6.69	1.88
Al2O3	2.11	1.99	2.37	2.2	1.32	0.92	1.05	1.66	0.27
CaO	13.63	12.78	12.18	18.84	11.73	9.22	8.87	5.23	16.88
MgO	1.25	1.47	1.35	2.4	1.74	1.39	1.4	1.44	4.81
FeO	6.18	10.49	9.42	6.92	7.27	5.16	5.04	7.63	6.33
Fe2O3	49.5	46.87	50.67	44.75	55.7	50.46	39.98	45.37	58.82
Fe metallic	1.42	0.89	1.21	1.38	1.1	0.79	0.5	1.03	1.21
Na2O	0.13	0.19	0.27	0.024	0.1	1.11	0.227		0.03
K2O	0.53	0.58	0.46	0.13	0.23	0.33	0.281		0.02
ZnO	0.83	0.87	1.01	1.58	4.33	26.85	30.57		6.56
PbO	0.079	0.062	0.11	0.029	0.023	0.036	0.029		
C	15.87	16.19	12.57	10.31	9.61	1.79	6.93	27.3	2.63
S	0.45	0.43	0.34	0.41	0.31	0.75	1.01	0.35	0.07
Cl	0.3		0.23		0.14	0.2	0.2		
F	0.25		0.25		0.35	0.088	0.15		
Total Fe	40.88	41.85	44.01	38.09	45.74	40.13	32.41	38.72	47.31
Total Gangue	24.81	22.65	21.40	30.21	20.35	15.03	15.49	15.02	23.64

Smelter Operation

A typical trial began with the charging of about 13 mt of hot metal, melted overnight in an induction furnace, into the smelter. The charging hole was closed, following which an oxygen test was conducted. Thereafter, oxygen blowing began and smelter operation continued until the trial objectives were met. Smelter operation during a trial typically lasted for about 12 hours. The first hour was used for slagmaking, while the next two hours involved the smelting of hematite pellets. By this time, the offgas system was sufficiently heated to allow the input of waste oxides containing zinc, lead, alkalis, and halogens such that their deposition in the offgas ducts, and cyclone did not occur. When the addition of waste oxides was terminated, smelter operation was continued with hematite pellets, and the "finishing practice" was adopted. The vessel was drained and allowed to cool before it was inspected.

Stable operation of the smelter was maintained by controlling the raw material addition rate, lance height, and the oxygen blowing rate. The material addition rates were adjusted using energy and materials balances for control of hot metal temperature and slag FeO. The typical oxygen blowing rate, after the start-up period, was 5500 Nm^3/h. The aim hot metal temperature was in the 1475-1575 °C range. The slag FeO was controlled to below 5%, and was typically in the 2-5% range.

Figures 3 and 4 illustrate smelter operation for trials with coke breeze and medium volatile coal (23% VM) respectively. The main operating parameters affecting stable operation of the smelter are depicted. Figure 3a shows the measured postcombustion degree (PCD) of the offgas in the duct. The PCD, defined below, determines the amount of heat generated in the smelter and, for a given fuel, is affected by the lance height, blowing practice, and char weight.

Figure 3: Example of smelter operation with coke breeze, agglomerate C, hematite pellets and smelter dust reinjection

Figure 3a: Postcombustion degree

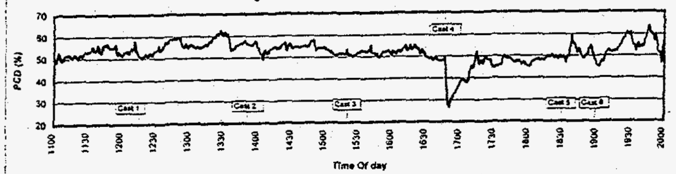


Figure 3b: Material feed rates

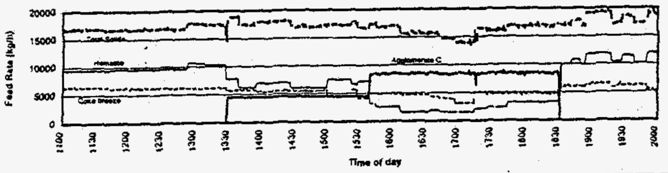


Figure 3c: Hot metal Temperature and Slag FeO

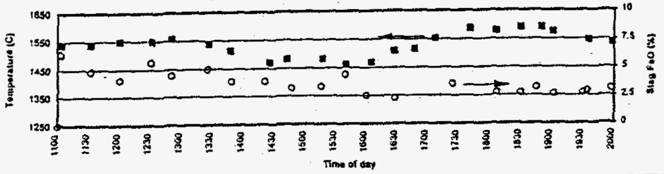


Figure 3d: Heat losses to water-cooled circuits

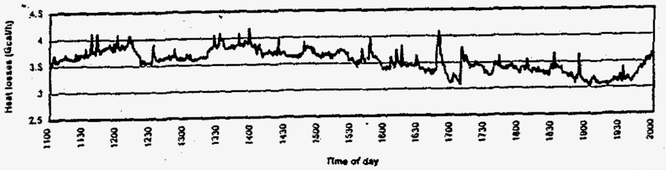


Figure 4: Example of smelter operation with medium volatile coal, agglomerate D2, hematite pellet and blast furnace dust injection

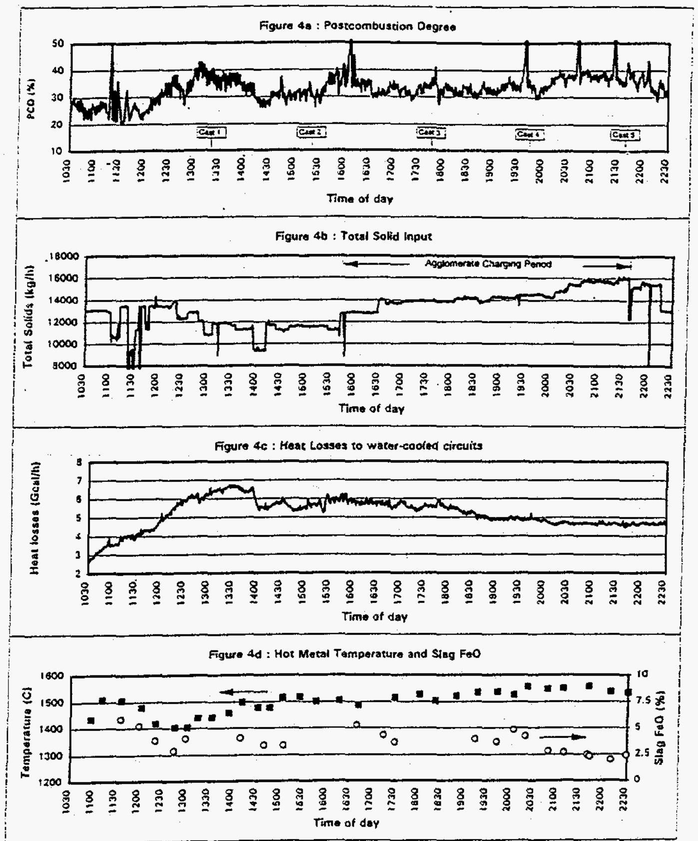


Figure 4a : Postcombustion Degree

Figure 4b : Total Solid Input

Figure 4c : Heat Losses to water-cooled circuits

Figure 4d : Hot Metal Temperature and Slag FeO

Excess carbon retained in the slag, referred to as char, is produced by the devolatilization of coal.

$$PCD = \frac{(\%CO_2 + \%H_2O)}{(\%CO + \%CO_2 + \%H_2 + \%H_2O)} * 100 \qquad (1)$$

As can be seen from Figure 3a, the PCD ranged from 50-60% except for a brief period when it decreased to 25%. This was due to excessive amount of slag being cast resulting in a high char-to-slag weight ratio which is detrimental to the PCD. The situation was corrected within 30 minutes by decreasing the fuel rate for a short period as shown in Figure 3b. The recovery in such a short time period is characteristic of the smelting process.

Figure 3b depicts the material addition rates. The total solid input rate was mainly in the 16-18 metric tons per hour (mtph) range. Agglomerate charging was conducted at two levels. The measured hot metal temperature and slag FeO are illustrated in Figure 3c. The hot metal temperature ranged from 1460 °C to 1590 °C. The slag FeO level was below 5% for most of the trial. The heat losses to the water-cooled circuits, shown in Figure 3d, ranged from 3-4 Gcal/h. Figures 4a through 4d illustrate operating parameters with medium volatile coal.

The results obtained during the waste oxide trials were reproducible. The main process parameters such as the postcombustion degree, heat losses to the water-cooled circuits, offgas temperature in the duct, dust composition and rate, hot metal and slag chemistry, and the total solids input rate were predictable for a given oxygen blowing rate and fuel type. The process was operated using rigorous energy and materials balances, and the results obtained at the pilot plant were in close accord with these calculations.

As stated earlier, smelter operation during a trial lasted about 12 hours and individual periods within a trial lasted up to 5 hours. The stability of operation over this period was considered sufficient to draw interpretive results from the data gathered. In this regard, it is worthwhile to review the response time of the smelting reactor. The smelting reactor responds very rapidly to changes made in the operating parameters. The mean residence time for FeO in the reactor is about 3 minutes. The residence for the gas is of the order of 1 second. The process responds to changes in the blowing rate, material feed rates, and lance position in a matter of seconds, and reaches stability in a few minutes. The low response time is a result of enhanced rates of heat and mass transfer, and chemical kinetics due to the high temperatures and the fact that phenomena are occurring in the liquid state.

Operating Results

Table 3 lists the operating results obtained with different fuels and waste oxides. Results for eight different cases are presented with the oxygen blowing rate being constant at about 5500 Nm^3/h. Cases 1 through 3 represent operation with coke breeze and hematite pellets with different types of dust injection. Cases 4 through 6 are for operation with coke breeze and different types of agglomerated waste oxides containing less than 3.5% zinc. Case 7 is for operation with medium volatile coal, agglomerate D2 (3.5% Zn) which represents a typical blend of North American steel plant waste oxides, and BF dust injection. Case 8 represents operation with coke breeze and a synthetic EAF dust agglomerate containing about 25% zinc.

The table lists the material feed rates, hot metal temperature, slag and metal chemistry, PCD and heat losses to water-cooled circuits, hot metal and slag production rates, and the fuel and oxygen rates for the various operating cases. Discussed below are some of the key operating results.

Postcombustion, Fuel Rate and Productivity: Up to 60% postcombustion was achieved with coke breeze as the fuel source. However, for most operating periods, the aim postcombustion degree was in the 50-55% range. The total solids input rate was about 17 mtph, and the hot metal production rate was about 5.9 mtph when operating with hematite pellets as the iron bearing feed. The fuel rate (wet basis) and oxygen rate were about 1060 kg/mt and 940 Nm^3/mt. The slag production rate was about 2.25 mtph.

For operation with agglomerated and injected waste oxides, PC levels of 50-55% were demonstrated with coke breeze as the fuel source. The total solids input rate was also about 17 mtph. However, the hot metal production rate was lower at about 5 mtph, while the slag production rate was higher at about 3 mtph for operation with agglomerated waste oxides compared to operation with hematite pellets. The fuel rate (wet basis) was lower and the oxygen rate was higher for operation with waste oxides.

As stated earlier, the agglomerates were prepared by briquetting using cement as the binder. The binder comprised about 10% of the

Table 3 : Waste Oxide Recycle Trials - Summary of Operating Results

1	Case Number	1	2	3	4	5	6	7	8
2	Top charge fuel type	Coke Breeze	Coke Breeze	Coke Breeze	Coke Breeze	Coke Breeze	Coke Breeze	MV Coal	Coke Breeze
3	Top charged agglomerate type	None	None	None	C	D1	D2	D2	E2
4	Injected dust type	Smelter	BF	BOF	Smelter	None	None	BF	None
5	Total oxygen flowrate (Nm3/h)	5509	5499	5479	5488	5476	5456	5479	5474
6	Top charge fuel rate (kg/h)	6278	5060	6081	4864	4775	4508	5490	5617
7	Top charge ore rate (kg/h)	9759	9161	8716	4387	3682	2451	1261	5874
8	Top charge flux rate (kg/h)	691	682	325	615	318	261	241	357
9	Top charge agglomerate rate (kg/h)	0	0	0	6484	8196	8567	6168	4241
10	Injected smelter dust rate (kg/h)	262	0	0	245	0	0	0	0
11	BF/BOF Dust injection rate (kg/h)	0	2421	1933	0	0	0	1480	0
12	Total Solid Input (kg/h)	16990	17324	17055	16595	16971	15787	14640	16089
13	Solids/Oxygen Ratio (kg/Nm3)	3.08	3.15	3.11	3.02	3.10	2.89	2.67	2.94
14	Metal temperature at start of period (C)	1546	1484	1582	1537	1590	1563	1516	1538
15	Metal temperature at end of period (C)	1537	1485	1553	1591	1558	1578	1557	1593
16	Slag CaO/SiO2 ratio	1.05--1.13	1.23--1.34	1.09--1.24	1.11--1.56	1.18--1.34	1.33--1.41	1.22--1.29	0.98--1.07
17	Slag FeO (%)	4.08--6.38	3.98--6.28	3.92--4.5	2.25--4.44	2.56--4.47	3.02--4.78	2.48--4.83	3.36--5.83
18	Hot metal carbon (%)	4.8			4.61--4.94	4.28	4.7--4.78	4.87--4.91	4.76
19	Measured Post-combustion degree in duct (%)	54.4	54	51.89	50.42	48.34	49.69	34.53	47.58
20	Total heat losses to water cooled circuits (Gcal/h)	3.72	2.99	4.7	3.57	4.7	4.98	4.97	4.75
21	System Pressure (kg/cm2 gauge)	0.6	0.6	0.65	0.59	0.65	0.6	0.58	0.6
22	Raw hot metal production rate (tph)	5.87	6.41	6.22	5.5	5.14	4.9	3.7	4.44
23	Raw slag rate production rate (tph)	2.26	2.54	2.36	2.85	3.7	2.7	2.3	2.27
24	Raw fuel rate (kg/t)	1058	790	979	876	930	921	1485	1264
25	Carbon from Agglom. and Inj. Oxides (kg/t)	11	103	8	161	158	159	263	64
26	Oxygen Rate (Nm3/t)	939	858	881	1006	1065	1113	1481	1233

agglomerate. This resulted in the agglomerate having a lower iron content and a higher gangue content as compared to hematite pellets. This is reflected in the lower hot metal production rate and higher slag production rate. Nevertheless, it can be concluded that the iron oxides present in the waste oxides were smelted and the iron was recovered.

The lower fuel rate obtained during operation with waste oxides as compared to that with hematite pellets was due to the presence of carbon in the waste oxides. The fact that the fuel rate was lowered demonstrates that the carbon in the waste oxides was used a fuel/reductant.

For operation with a medium volatile coal, average postcombustion levels of about 35% were demonstrated. PC levels of about 38% were demonstrated over shorter operating periods as shown in Figure 4. In these periods, the total solids input rate was similar to that for operation at 50% postcombustion with coke breeze. Injection of recycled dust from the cyclone, BF dust and BOF dust into the slag was successfully conducted in several trials. Injection rates of 2.5 mtph were achieved with BF and BOF dust. Under appropriate operating conditions, blowthrough of the injected waste oxides did not occur, and this was confirmed by the measured dust and sludge rates.

Smelting of synthetic EAF steelmaking waste oxides was also successfully demonstrated. Zinc inputs in excess of 1 mtph were used, and the results obtained showed that zinc and lead reported to the sludge.

As stated earlier, the hot metal production rate when operating with hematite pellets and coke breeze was about 6 mtph. The vessel volume up to the barrel-cone interface was about 24 m^3, resulting in a production intensity of 6 mt/(m^3 day). In the case of the direct ironmaking flowsheet, the iron feed to the smelter is preheated wustite. This reduces the thermal requirements in the smelter and production intensities in excess of 8 mt/(m^3 day) can be achieved with coke breeze as the fuel. This level of production intensity is about 3 times that of a blast furnace. Operation with high volatile coal and wustite pellets resulted in a hot metal production rate of 5.6 mtph. For a scaled-up, coal-based operation with preheated wustite, the anticipated production intensity is about 7 mt/(m^3 day) which is more than 2 times that of a blast furnace.

<u>**Heat Utilization and Thermal Efficiency:**</u> The heat losses and heat fluxes to the vessel walls were well quantified by direct measurement of the refractory and gas temperature and the temperature increase in the water-cooled circuits. Table 4 lists the heat fluxes and losses to various regions in the smelter vessel. The heat fluxes to the refractory regions with and without stave cooling, and the cone were estimated based on the exposed surface area in each zone. In Table 4, results for operation with stave-cooled panels in the upper barrel are shown along with those for operation when these panels were extended to the mid-barrel (belly coolers). For operation with the belly coolers, the total heat losses to the refractory, lance, and cone were 3.6-4.7 Gcal/h, as compared to 3.1-4.2 Gcal/h for operation without the belly coolers. The increase in heat loss was about 0.5 Gcal/h, and this is consistent with that calculated from a heat balance using actual hot metal temperature measurements. The heat flux to the stave-cooled refractory section in the upper barrel was estimated to be 0.04-0.05 Gcal/(h m^2). After the belly coolers were added, the average heat flux to the stave-cooled refractory section increased to about 0.06 Gcal/(h m^2). This was due to refractory wearing back to the copper staves in a narrow band in the slag region.

At the pilot plant, heat losses to the water-cooled hood played a crucial role during operation. These heat losses varied from 0.5 Gcal/h to 2.5 Gcal/h depending on the thickness of material coating them. The difference in the total heat losses shown in Figures 3d and 4c was a direct result of the smaller thickness of material coating the hood during the initial portion of the trial with medium volatile coal. The heat losses to the hood were decreased by lowering the lance and coating slag on the hood by splashing slag. A decrease in the hood heat losses did not result in an increase in the offgas temperature in the duct, and resulted in improved process thermal efficiency. The decrease in hood heat losses could be achieved because much of the contribution to the hood heat losses was from direct radiation as opposed to heat transferred from hot gases. It is important to consider these radiation losses when designing the smelter hood and offgas cooling system.

The total heat generated in the smelter during the waste oxide recycling trials was about 21.5 Gcal/h. This heat consists of contributions from the combustion of C to CO and CO and H_2 to CO_2 and H_2O respectively. . The process thermal requirements including those for the reduction reactions and other endothermic phenomena, and for raising the temperature of the produced hot metal, slag, offgas, and dust to the hot metal temperature was about 17 Gcal/h. The heat lost to the refractory, the water-cooled sections of the smelter, and the superheat in the offgas were estimated to be about 4.5 Gcal/h. Thus, the thermal efficiency of the process, defined as ratio of the energy utilized for the process requirements to that generated, was about 80%.

Previous work[1] has shown that the heat transferred to the smelter did not correlate to the cross-sectional area of the vessel. The correlation obtained between the heat transferred and the total slag volume suggests that heat transfer scales up volumetrically rather than with the reactor cross-sectional area.

Refractory Performance: As mentioned earlier, the smelter vessel was provided with stave cooling in the free board. Additional staves, in the slag zone, were added during the program to retard lining wear. The stave and refractory system were designed to provide a frozen slag layer on the inner surface of a stable brick lining under controlled conditions of slag composition and temperature. An invention disclosure has been submitted on this design which consists of special water-cooled copper staves and a combination of refractories, carefully selected for their heat transfer properties, supporting the frozen slag layer.[2] The formation of a stable brick thickness would provide improved lining life at reasonable levels of heat loss.

The actual residual thickness measured in the various areas of the vessel are shown in Table 5. The wear rate at the bottom of the vessel, i.e. the region in contact with the metal and lower slag, was found to be very slow. The residual thickness measured in the middle portion of the barrel ranged from 0-100 mm. The refractory was found to wear back to the copper panels in the upper slag region which is also the postcombustion zone. However, the copper panels supported a frozen slag layer in front of them and were not directly exposed. The residual refractory thickness in the middle slag region was up to 100 mm. The refractory thickness in the freeboard of the vessel stabilized around 150-175 mm.

Hot Metal and Slag Chemistry: Samples of the hot metal and slag were obtained using the sub-lance and during a cast. The hot metal was carbon saturated and contained more than 4.5% carbon. The silicon and aluminum levels in smelter hot metal are very low. The manganese content was less than 0.3% while the phosphorus content was typically about 0.03%.

The hot metal sulfur varied between 0.04% and 0.17%. This variation was a result of operation at slag CaO/SiO_2 ratios ranging from 0.9 to 1.6 and differences in the slag FeO and hot metal temperature. The hot metal tapped from the

Table 4 : Heat Fluxes to Different Regions in the Smelter

With Stave Coolers in Upper Barrel			
Region	Heat Loss (Gcal/h)	Area (m2)	Heat Flux Gcal/(h m2)
Refractory with Insulating Lining	0.9-1.2	30.35	0.03-0.04
Refractory with Stave Cooling	0.5-0.6	12.77	0.04-0.05
Cone	0.9-1.2	15.4	0.06-0.08
Lance (at 3 m)	0.8-1.2	4.8	0.17-0.25
Total	3.1-4.2		

With Stave Coolers in Upper and Mid Barrel			
Region	Heat Loss (Gcal/h)	Area m2	Heat Flux Gcal/(h m2)
Refractory with Insulating Lining	0.5-0.7	17.8	0.03-0.04
Refractory with Stave Cooling	1.4-1.6	25.52	0.055-0.063
Cone	0.9-1.2	15.4	0.06-0.08
Lance (at 3 m)	0.8-1.2	4.3	0.17-0.25
Total	3.6-4.7		

Table 5: Comparison of residual thickness in smelter lining

Area	Construction	Residual Refractory Thickness (mm)
Cone	Gun/Cooled	25-30
Upper Barrel	Brick/Cooled	150-175
Mid Barrel	Brick/Cooled	0-100
Lower Barrel/Bottom	Brick/Insulated	Very slow wear

smelter is desulfurized in the casting ladle to a final sulfur content of 0.04%. This desulfurization can accomplished because the smelter slag is not saturated with sulfur. Ladle desulfurization involves reduction of the oxygen potential in the slag and good slag-metal mixing. The ladle desulfurization technology was developed at the pilot plant, and the hot metal was desulfurized to below 0.04%. The sulfur path in the smelting process will be discussed in detail in a separate paper.[3]

As stated earlier, the CaO/SiO_2 ratio in the slag varied substantially depending on whether waste oxides were charged to the smelter. As can be seen from Table 2, the waste oxides had a high CaO/SiO_2 ratio. When operating with waste oxides, lime addition to the furnace was stopped, and the slag CaO/SiO_2 ratio was allowed to stabilize at a steady state value which depended on the type of agglomerate being used. The alumina content of the slag was less than 10% while the MgO content of the slag varied between 15% and 23%. Magnesite was charged to the smelter to maintain about 12-16% MgO in the slag. The FeO levels in the slag were controlled to below 5%, and the slag FeO was typically in the 2-5% range. The MnO and P_2O_5 content of the slag, when operating with waste oxides, were about 1.5% and 0.3% respectively.

The zinc oxide content of the slag was less than 0.1%. The zinc content of the hot metal was less than 0.01%. Based on the slag and hot metal production rates, it can be concluded that the amount of zinc retained in the hot metal and slag is much less than 1% of the zinc input to the smelter. A special blowing and material feeding practice was developed for the removal of zinc from the condensed phases when operating at high levels of zinc input as in the case of smelting of EAF dust.

The lead oxide content of the slag was less than 0.1% while the lead content of the metal was less than 50 ppm. The potassium and sodium oxide levels in the slag were less than 0.05% and 0.15% respectively. The chlorine and fluorine content of the slag were less than 0.01% and 0.05% respectively. The chlorine content of the hot metal was 40 ppm. It can be concluded that the levels of lead, alkalis and halogens in the slag and metal were small.

Smelter Dust

Part of the dust contained in the offgas exiting the smelter were captured in a dry form in the hot cyclone. The dust bypassing the cyclone was collected as a sludge. Samples of the cyclone catch, scrubber water and solids were collected. Since the rate of water flow was known, the sludge rate could be estimated from the dry weight of the solids, and the total weight of the samples.

Figure 5 depicts the amount of sludge as a percent of the material inputs. In Figure 5, the filled circles represent trials with coke breeze while the empty circles are for trials with medium volatile coal as the fuel. Smelter dust is defined as the sum of the cyclone dust and the smelter sludge. The total dust increased with increasing zinc oxide input to the smelter. This was because the zinc oxide charged to the smelter was reduced, and zinc vapor exited with the offgas. This zinc was collected as part of the solid sludge when the offgas was cooled and quenched. For operation with hematite pellets alone, the smelter dust was about 3% of the total solid input when coke breeze was used as the fuel source. With medium volatile coal as the fuel source, the total smelter dust was about 6% of the total solid input.

The non-zinc dust, shown in Figure 5b, was calculated by subtracting the zinc oxide present in the total amount of smelter dust. The non-zinc dust as a percent of the total solid input was 2-4% for operation with coke breeze, and 5-6% with medium volatile coal. The variation of the non-zinc dust with the zinc oxide input was found to be in a relatively narrow range indicating that the total amount of carbon, iron, and gangue in the smelter dust were independent of the zinc oxide input.

The carbon dust as a percent of the fuel input is shown in Figure 5c. It ranged from about 6-9% with medium volatile coal while it was mostly less than 2% for operation with coke breeze. The carbon contained in the agglomerated or injected waste oxides was not considered as a part of the total fuel input in this estimation. If this were taken into account, the carbon dust, when operating with waste oxides, would be lower by up to 30% of the values shown.

Figure 5: Smelter dust, carbon and iron dust as a percent of the material inputs
(Open and filled circles are for operation with medium volatile coal and coke breeze respectively)

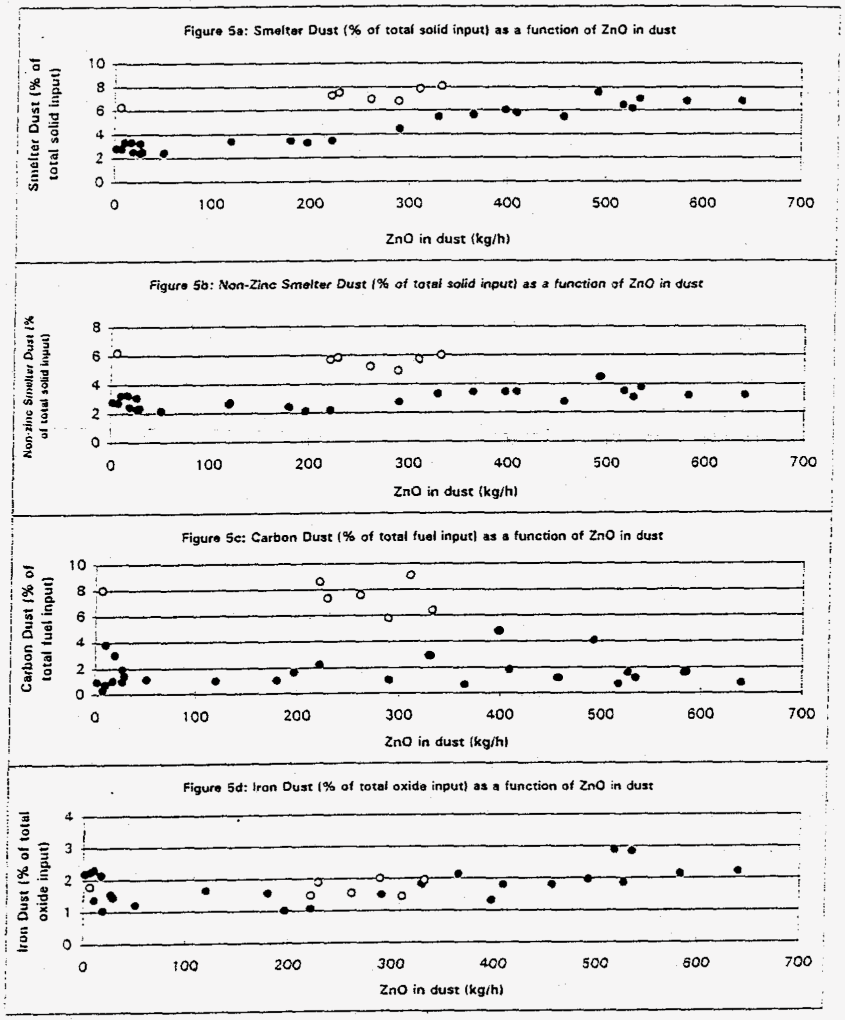


Figure 5a: Smelter Dust (% of total solid input) as a function of ZnO in dust

Figure 5b: Non-Zinc Smelter Dust (% of total solid input) as a function of ZnO in dust

Figure 5c: Carbon Dust (% of total fuel input) as a function of ZnO in dust

Figure 5d: Iron Dust (% of total oxide input) as a function of ZnO in dust

As shown in Figure 5d, the amount of iron in the dust was controlled to less than 2% of the total oxide input. Based on Figures 5b through 5d, it can be concluded that the non-zinc dust, carbon dust, and iron dust are independent of the zinc input to the smelter. The cyclone was found to be highly efficient for carbon removal. During operation with medium volatile coal, the cyclone captured more than 95% of the carbon dust. The cyclone efficiency with respect to iron was lower, and about 50% of the iron dust could be recovered in the cyclone when the amount of iron dust was less than 200 kg/h. For the gangue species, the cyclone efficiency ranged from 60-80%. More than 90% of zinc and lead entering the cyclone were not captured and reported to the sludge. The lower cyclone efficiency for iron, zinc and lead were a result of their smaller size.

Mechanism of Dust Formation: Microscopy studies, and size and chemical analysis of the cyclone dust and smelter sludge were conducted to determine the mechanism of dust formation. The following observations and conclusions are based on the results of the waste oxide recycling trials, and the direct ironmaking trials.[1]

The amount of cyclone dust increased significantly with increasing volatile matter content of the coal. The increase was primarily due to additional carbon losses. The carbon losses could not be explained by the entrainment of fines alone. It is known that, during coal devolatilization, fragmentation of a coal particle can occur.[4] This will result in the production of additional fines that may be carried out of the smelter. In addition, carbon from any unburned volatiles may be carried out as soot. During operation with coke breeze, about 50% of the cyclone dust was in the 6-500 mesh range (3mm-25μm) while the remaining 50% was -500 mesh. With medium volatile coal as the fuel source, 90% of the dust was in the 6-500 mesh range while the remainder was finer than 500 mesh. The increased coarser fraction in the cyclone dust with medium volatile coal was a result of higher amounts of carbon dust which resulted in the dust carbon content being greater than 75%. Since most of the additional carbon in the dust was in the coarse size range, it can be concluded that carbon dust is primarily generated by the entrainment of fines and fragmentation of coal.

There was a substantial amount of metallic iron present in both the cyclone dust and smelter sludge. In the cyclone dust, free metallic iron spheres and iron contained in within coarser carbon particles were observed. Microscopic analyses of the cyclone dust and sludge have also shown the presence of micron-sized metallic iron particles, some of which had an outer iron oxide layer. Size consist analysis of the sludge showed that it was almost 100% finer than 500 mesh (25 μm). Finally, the iron-to-carbon ratio in the sludge was almost always more than 100 when operating with coke breeze and hematite. The above information suggests that the iron dust from the smelter primarily comes from vaporization or fuming of iron, and ejected metallic iron droplets or particles.

Zinc Recovery

Three North American zinc producers (Noranda, Cominco and Big River Zinc) provided technical support, in regard to zinc recovery from the smelter sludge, during the AISI Waste Oxide Recycling Program. The zinc producers reviewed the specifications for the suitability of smelter sludge as a feedstock for zinc production. From a chemical standpoint, the elements of concern were iron, alkalis and halogens. The minimum zinc-to-iron ratio required was five. From a size consist standpoint, all the sludge was to be finer than 100μm. Samples of smelter sludge were sent to the Noranda Technology Center which conducted chemical analysis, and optical and scanning electron microscopy studies. Discussed below is the zinc path in the smelting process and the suitability of smelter sludge for zinc recovery.

Zinc Path: During the. waste oxide recycling trials, the zinc oxide input to the smelter was varied up to 1.5 mtph. As stated earlier, zinc oxide charged to the smelter is reduced and zinc volatilizes and exits with the offgas. Figure 6 illustrates mass balances for four trials. As can be seen from the plots, there is good agreement between the zinc input and total amount of zinc present in the cyclone dust and smelter sludge. This implies that very little of the input zinc reports to the hot metal, slag, and contact water. Further, most of the zinc charged to the smelter reports to the sludge. The cyclone efficiency for zinc, which is defined as the ratio of the amount of zinc captured by the cyclone to that present in the cyclone dust and smelter sludge, was less than 10% and this is evident from Figure 6.

In order to minimize zinc deposition in the cyclone, it is important to maintain a critical gas temperature in the cyclone. Thermodynamic calculations had shown that zinc oxide formation is thermodynamically favored at about 850 °C. Consequently, the gas temperature in the cyclone was maintained above 900 °C. In situations, where the temperature was lower than 750 °C, increased levels of zinc in the cyclone catch were observed.

Samples of the contact water showed that there was no build-up in the zinc content. The same water was used over the duration of the waste oxide recycling program without the presence of a bleed stream or addition of make-up water. Based on the chemical analysis of the contact water entering and exiting the scrubber, it was concluded that the transfer of zinc from the gases and solids to the contact water was prevented by using appropriate pH control and chemical addition techniques.

As discussed earlier, zinc retained in the hot metal and slag was less than 1% of the zinc input. Based on these results, it can be concluded that more than 90% of the zinc charged to the smelter reports to the sludge, with most of the remainder being present in the cyclone dust. As stated earlier, in order to make the smelter sludge suitable for zinc recovery, the minimum zinc-to-iron ratio in the sludge is five. Thus, it is desirable to minimize the amount of iron dust exiting the smelter. Discussed below are the parameters affecting iron dust generation and the operating conditions to minimize this.

Parameters affecting Iron Dust Generation: As stated earlier, it was concluded that vaporization or fuming of iron, and ejection of pure metallic iron droplets or particles were the main cause of

Figure 6: Mass balance for zinc and distribution between cyclone dust and smelter sludge

Figure 6a : Data for operation with coke breeze and agglomerate D2

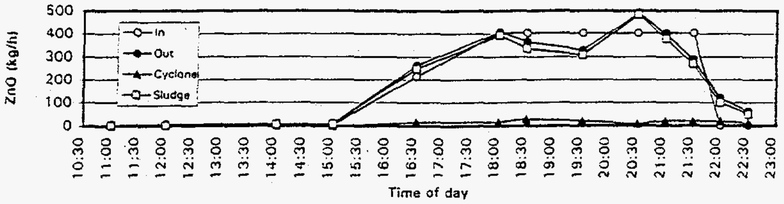


Figure 6b : Data for operation with medium vol coal and agglomerate D2

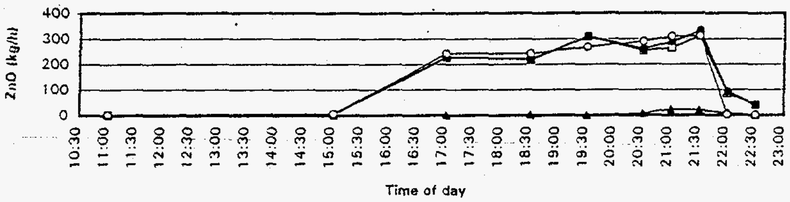


Figure 6c : Data for operation with coke breeze and agglomerate E1

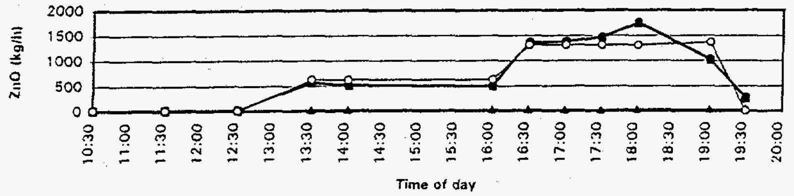
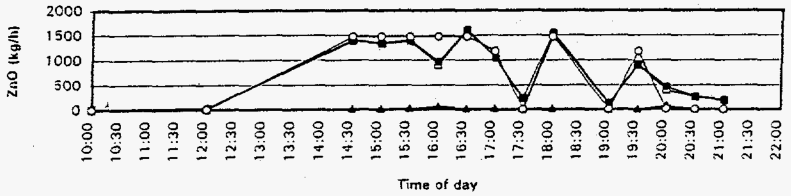


Figure 6d: Data for operation with coke breeze and agglomerate E2



iron dust generation. The amount of iron sludge was found to be dependent on the lance position or lance gap, hot metal temperature, and slag weight. Results reported elsewhere have shown that the amount of iron sludge is dependent on the bottom stirring gas flow rate.[5]

Figure 7a shows the effect of the lance gap on the amount of iron sludge. The lance gap is defined as the distance between the lance tip and the slag height. A positive lance gap implies that the lance tip is positioned above the slag height. The slag height was measured using a conductivity probe attached to the sub-lance. As can be seen from Figure 7a, the amount of iron sludge is inversely related to the lance gap.

Figure 7b shows the effect of hot metal temperature on the amount of iron sludge. The amount of iron sludge is directly related to the hot metal temperature. This is expected to be the case if iron dust is primarily caused by vaporization or fuming of iron. The scatter in the data is a result of varying char weight, lance gap, and slag weight. Figure 7c shows the direct relationship between the lance gap and the measured postcombustion degree. This translates to an inverse relationship between the amount of iron sludge and the PCD as shown in Figure 7d. The relationship shown in Figure 7d is a practical one, and can be used during operation to maintain the sludge below a certain level.

The slag weight plays an important role in iron dust generation. Adequate slag cover is necessary to shield the metal bath from the oxygen jets and reduce iron fuming. High levels of iron dust generation were observed during the slagmaking period, and after a heavy slag cast.

The amount of iron reporting to the sludge may be reduced if a high efficiency cyclone with respect to iron is present before the scrubbers. As stated earlier, almost all the sludge was finer

Figure 7: Parameters affecting iron generation

Figure 7a: Relationship between Lance gap and Iron Sludge

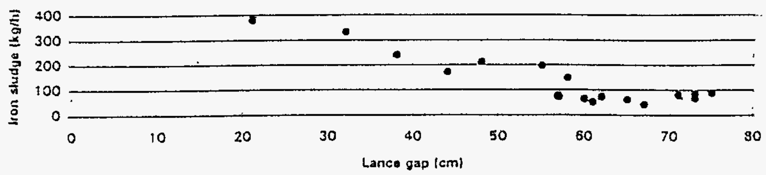


Figure 7b: Relationship between Metal Temperature and Iron Sludge

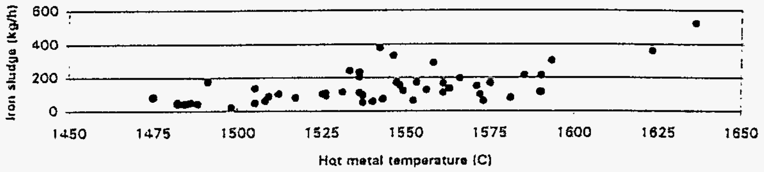


Figure 7c: Relationship between Lance gap and Offgas PCD

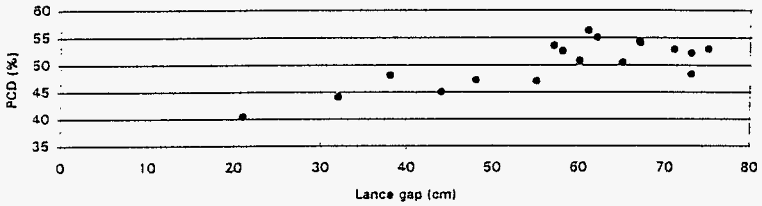
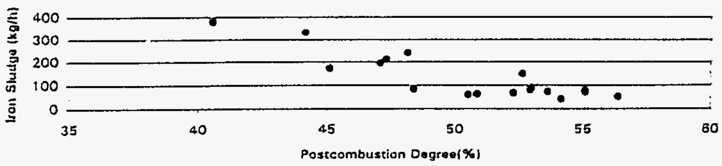


Figure 7d: Relationship between Iron Sludge and Offgas PCD

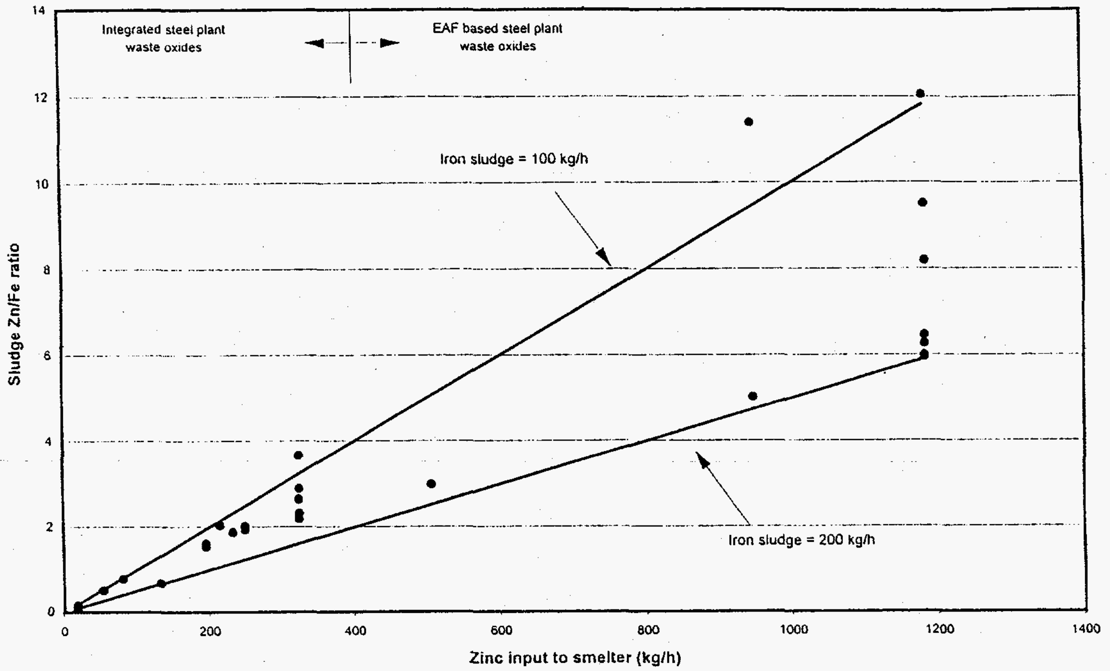


than 500 mesh (25μm) and the cyclone efficiency for capture of iron was about 50% when the iron dust generation rate was less than 200 kg/h. This resulted in half the iron dust from the smelter reporting to the sludge.

In order to minimize iron dust generation, it is necessary to maintain adequate slag cover, and lance gap as well as avoid high temperature excursions. At the pilot plant, the minimum slag weight, for this purpose, was determined to be 4 mt and the total slag height required was in the 1.5-2 m range. A lance gap of about 60 cm was necessary to control the iron sludge to below 100 kg/h. This lance gap was consistent with the aim PCD of 50-55% when operating with coke breeze and 35-40% when operating with medium volatile coal. Under these operating conditions, it was possible to control the amount of iron in the sludge to below 100 kg/h.

Sludge Suitability for Zinc Recovery: In order to obtain the minimum zinc-to-iron ratio of five, it was necessary to control the amount of iron in the sludge as well as charge the adequate amount of zinc to the smelter. Figure 8 shows the zinc-to-iron ratios in the sludge as a function of zinc input to the smelter. As can be seen, zinc-to-iron ratios in excess of five were achieved when operating with a high zinc input as in the case of the synthetic EAF dust agglomerates. For operations with agglomerated waste oxides from integrated steel plants, the zinc-to-iron ratio in the sludge was less than four. In order to obtain zinc-to-iron ratios in excess of five with integrated steel plant waste oxides, two options are available. The integrated steel plant waste oxides can be blended with EAF dust to obtain the desired zinc-to-iron ratio in the sludge. Alternatively, the smelter sludge generated during operation with the integrated steel plant waste oxides can be recycled to increase the zinc load to the smelter to obtain the desired zinc-to-iron ratio.

Figure 8 : Zinc-to-iron ratio in sludge as a function of zinc input to smelter



The alkalis and halogens contained in the waste oxides mostly report to the contact water system with the remainder reporting to the sludge. It was estimated that about 70-90% of the sodium and potassium, and more than 95% of the chlorine and fluorine report to the contact water system. The presence of alkalis and halogens, in high concentrations in the sludge, are detrimental to zinc recovery from the sludge. Chemical analyses of the sludge samples showed that the concentration of these elements was not a concern.

Table 6 shows the chemical analyses of four samples of smelter sludge as analyzed by the Noranda Technology Center. Although a total of 32 elements were analyzed for, the concentrations of the key elements is listed. As can be seen, the zinc-to-iron ratios in the sludge were well in excess of five. From a size consist standpoint, the sludge is suitable for zinc recovery since it is finer than 25 µm, which is well below the requirement of 100 m. Based on this analysis and their experience, Noranda concluded that smelter sludge will be suitable for zinc recovery, and could be sold commercially. The purchase price for the sludge was quoted to be 45% of the LME zinc price.

Environmental Testing

The study was conducted by an environmental systems company. Samples of the hot metal and slag were analyzed for RCRA (Resource Conservation and Recovery Act) metals and TCLP (Toxicity Characteristic Leaching Procedure) test was also conducted. It was concluded that the hot metal and slag produced during the waste oxide recycling trials did not pose any environmental concern.

Chemical analysis of the offgas showed that the equivalent H_2S or SO_2 was less than 50 parts per million by volume (ppm_v). This is less than 5% of the equivalent H_2S contained in desulfurized coke oven gas. The level of nitrogen oxides were found to be one-tenth of the concentrations in blast furnace stove gas. The measured total hydrocarbons (THC) in the smelter offgas was 2.25 ppm_v, which was estimated to be less than half that present in exhaust gases from a blast furnace stove stack.

Samples of the contact water showed that there was pick-up of dissolved solids. These solids were identified to be alkali (sodium and potassium) chlorides and fluorides. The pick-up of organic compounds was found to be very small. It was concluded that the contact water could, after clarification, be recycled to the quencher.

Table 6: Chemical Composition of Smelter Sludge with Synthetic EAF Dust Agglomerates (Samples Analyzed by Noranda)

	Sample #1	Sample #2	Sample #3	Sample #4
Aluminum (ppm)	2185	2935	3446	2880
Cadmium (ppm)	1593	1827	2545	2166
Calcium (ppm)	553	1018	1165	739
Iron (%)	5.56	7.72	5.43	7.43
Potassium (ppm)	2000	2105	2100	2777
Magnesium (ppm)	3129	2729	2586	4377
Manganese (ppm)	1069	862	729	1368
Sodium (ppm)	1959	2731	2646	2861
Lead (ppm)	7934	8989	12240	10654
Sulfur (%)	1.52	1.33	1.47	1.54
Silicon (ppm)	1370	3055	1172	4234
Zinc (%)	56.8	70.8	85.1	82.8
Chlorine (ppm)	1937	1383	1874	1951
Fluorine (ppm)	808	1036	974	789

Samples of the smelter sludge, taken during operation with zinc bearing waste oxides, were analyzed for RCRA metals. A TCLP test showed that the lead and cadmium levels exceeded regulatory limits. This result was not unexpected considering that in the recycling process the volatile metals present in BF/BOF/EAF waste oxides are concentrated in the sludge. Since the smelter sludge will be processed for recovery of zinc, lead and cadmium, the concentration of the volatile metals are not a concern.

Based on their tests and results, the environmental systems company concluded that the hot metal, slag, contact water, and properly combusted offgas do not present environmental concerns.

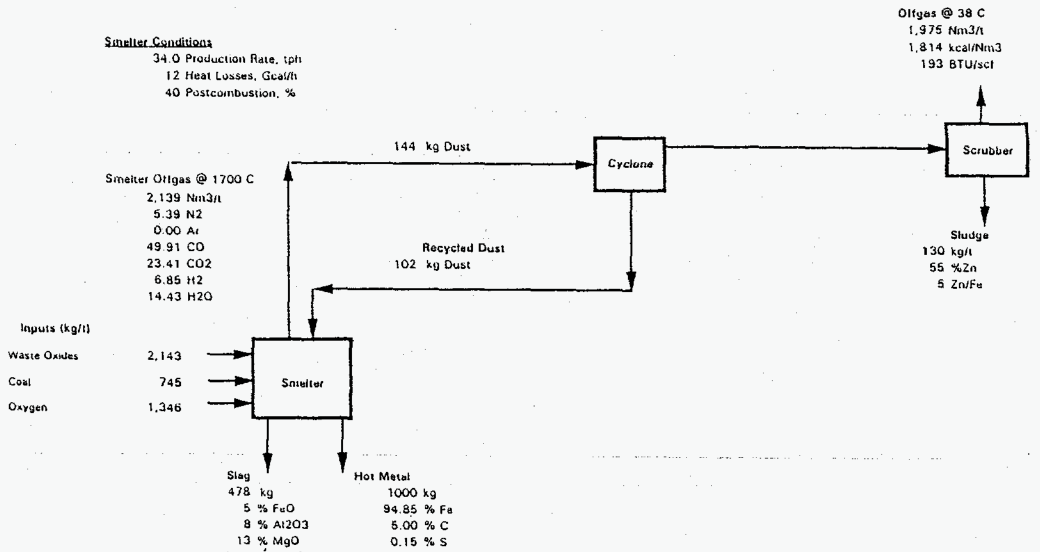
Demonstration Plant Feasibility Study

The technical, engineering, economic, and environmental aspects were extensively investigated during the feasibility study for a demonstration plant processing about 533,000 mtpy of steel plant waste oxides to produce about 256,000 mtpy of hot metal. The fundamentals of the smelting process, pilot plant results, scale-up criteria, waste oxide preprocessing and raw material charging, management of the hot metal, slag, offgas, and contact water were some of the critical technical and engineering issues that were comprehensively reviewed during the development of the process flowsheet.

Demonstration Plant Flowsheet: The projected flowsheet for the waste oxide recycling demonstration plant is shown in Figure 9. Smelter operation would be conducted with a medium volatile coal, and micro-agglomerated waste oxides. These micro-agglomerates would be homogeneous, free flowing, granular, dry and dustless. Tests conducted at three different pilot facilities with dusts and sludges to be processed at the demonstration plant showed that micro-agglomerates (0.3-6.3 mm) with adequate crush, impact, and abrasion strength to withstand normal handling and storage could be produced without the use of a binder.

The hot metal production rate was based at 34 tph resulting in an annual production of 256,000 mt. The smelter would be operated at a pressure of 3 bar gage and a PCD of 40% which would result in a total heat generation, within the smelter, of about 117 Gcal/h. The aim slag and hot metal temperature were taken to be 1525 °C while the temperature of the gases at the barrel-cone interface was estimated to be about 1700 °C. The heat losses within the smelter to the refractory and water-cooled sections were estimated to be 12 Gcal/h, and the resultant thermal efficiency of the process was about 84%. The process thermal efficiency projected for the demonstration was higher than that observed at the pilot plant (80%). The thermal efficiency of the smelting process increases during scale-up due to a decrease in the surface area to volume ratio of the containment vessel.

Figure 9 : Waste Oxide Recycling Demonstration Plant Flowsheet



NOTE: Units are per metric ton of HM unless otherwise specified

The hot metal carbon and sulfur content, at tap, were estimated to be 5% and 0.15% respectively while the slag FeO was estimated to be 5%. The hot metal would be desulfurized to 0.04% sulfur, in the casting ladle, using technology developed at the pilot plant. The iron yield for the process would be about 95% which is similar to that observed in a blast furnace.

The coal rate was estimated to be 745 kg/mt of hot metal. It must be noted that the carbon contained in the waste oxides is about 250 kg/mt of hot metal. The oxygen requirement, at 95% purity, was calculated to be 1346 kg/mt. An oxygen plant producing 1100 metric tons per day (mtpd) would be required. The slag production was calculated to be about 478 kg/mt at a slag CaO/SiO_2 ratio of about 1.8. The MgO content of the slag was expected to be 13% while the alumina content was projected to be 8%. Based on tests conducted on the slag, it was concluded that it would be suitable for use in road construction applications.

The offgas flow rate exiting the scrubber was estimated to be 1975 Nm^3/mt. The fuel value in the cleaned gas was calculated to be 1814 kcal/Nm^3 (193 Btu/scf). The offgas can be used in slab reheating furnaces, and partially replace purchased natural gas, or desulfurized coke oven gas. The sludge generated would contain 55% zinc with a zinc-to-iron ratio in excess of five. The sludge production rate was estimated to be about 130 kg/mt.

Process Economics: The projected economics for commercial operation of a waste oxide recycling plant are shown in Table 7. These calculations were based on an annual hot metal production rate of 256,000 mt, and the flowsheet shown in Figure 9. The total operating costs were estimated to be $133.42/mt of hot metal produced. The coal and oxygen cost form a major portion of the operating cost. The cost of coal was taken to be $60/mt, and the delivered coal was assumed to contain 5% moisture. The cost of oxygen was taken to be $31.30/mt. The costs for electrical power, refractories, labor, cooling water, etc. were developed as part of the feasibility study.

The total operating credits were estimated to be $115.12/mt. This included an offgas credit of $2.50/million BTU for the offgas, $450/mt of zinc in the sludge, and $25/mt of dry waste oxides processed. Energy recovery from the offgas was taken at 90% and, in addition, the fuel required for drying the coal and waste oxides was deducted. The credit for the sludge was based on Noranda's quotation of 45% of the LME zinc price which was taken to be $1000/mt.

The hot metal cost was estimated to be $18.30/mt. The net operating profit of the waste oxide smelting plant was estimated to be $116.70/mt if the hot metal was credited at $135/mt. This would result in an annual operating profit of $29.88 million.

The investment cost for the waste oxide recycling demonstration plant was developed following a preliminary engineering study. The estimated capital cost for construction of the demonstration plant was estimated to be about $70 million.

Table 7: Economics of Smelting Steel Plant Waste Oxides (Basis: 1 metric ton hot metal)

Operating Costs	
Coal	$46.92
Oxygen	$42.13
Nitrogen	$2.38
Air	$0.04
Electric Power	$1.50
Refractories	$5.03
Cooling Water	$1.42
Labor	$11.69
R & M Materials	$6.00
Spares	$6.00
Sub-lance Tips and Maintenance	$4.96
Hot Metal Desulfurization	$1.98
Slag Removal and Disposal	$1.24
Plant Operating Expense	$2.13
Total Operating Costs	**$133.42**
Operating Credits	
Offgas	$29.36
Sludge	$32.18
Landfill Avoidance	$53.58
Total Operating Credits	**$115.12**
Hot Metal Cost	**$18.30**
Net Operating Profit with Hot Metal at $135/t	**$116.70**
Annual Operating Profit, $MM/year	**$29.88**

Summary and Conclusions

The pilot plant trials demonstrated the viability of recycling millions of tons of steel plant dusts and sludges, that are now typically landfilled, and converting these materials into useful products, i.e., hot metal for steel production, a zinc-rich raw material for the non-ferrous industry, and slag for roadbed or cement production. Recycling of synthetic electric arc furnace dust was also successfully tested. The pilot plant trials and the subsequent feasibility study showed that steel plant waste oxides can be smelted in an environmentally and economically sound manner for an attractive return on investment. Specific results of the pilot plant trials and feasibility study are:

- Recovery of Iron: The iron oxides and metallic iron present in steel plant waste oxides were smelted in a manner similar to the smelting of hematite or wustite pellets. Hot metal production rates, with waste oxides as the feed, ranged up to 5 tons per hour. Dust loading from the smelter was less than 6% of the feed. Most of the carbon dust, and much of the iron dust in the smelter offgas were recovered in the cyclone, and could be recycled to the smelter. The overall iron yield in smelting on a commercial basis will be similar to that for the blast furnace. The hot metal produced was carbon saturated, and lower in silicon and manganese as compared to blast furnace hot metal.
- Recovery of Zinc: The zinc present in the waste oxides reported to the sludge with zinc-to-iron ratios in excess of six. This sludge is a valuable raw material for the zinc industry as verified by Noranda.
- Energy: The carbon present in the waste oxides, mainly in BF dust and sludge, was used as a fuel/reductant resulting in a decrease in the fuel requirement for the smelting process. The process offgas has significant fuel value, and can be used in steel plants for stream generation, or as a partial replacement for natural gas or desulfurized coke oven gas in slab reheating furnaces.
- Refractories: A unique furnace design, subject of a pending patent application, provides for the formation of a protective frozen slag layer on the inner surface of a stable brick lining. This system consists of special water-cooled copper staves and a combination of refractories, carefully selected for their heat transfer properties, supporting the frozen slag layer.
- Environment: Technology was developed to reduce the process offgas sulfur to less than 50 ppm$_v$, when operating with zinc bearing material. This is less than 5% of the sulfur content in desulfurized coke oven gas. Hot metal desulfurization technology was also developed at the pilot plant to achieve hot metal sulfur comparable to blast furnace hot metal.
- Process Control: The pilot plant program confirmed and clarified our understanding of the fundamentals of smelting reduction. Process control schemes were developed, tested, and fully demonstrated during the waste oxide recycling trials.

The feasibility study confirmed the design and operating considerations for a plant to process about 533,000 mtpy of waste oxides into about 256,000 mtpy of hot metal. This involves a fivefold scale-up in size, and a threefold increase in pressure over the pilot plant. The oxygen requirement, at 95% purity, is about 1100 mtpd.

The total project cost for the demonstration project was developed as part of the feasibility study. The capital cost for such a plant would be about $70 million with a profit potential of about $30 million per year, an attractive return on capital once the process has been demonstrated on a commercial basis.

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