Feature — Overview

JOM World Nonferrous Smelter Survey Part IV: Nickel: Sulfide

A.E.M. Warner, C.M. Diaz, A.D. Dalvi, P.J. Mackey, A.V. Tarasov, and R.T. Jones

This paper presents data on nickel sulfide smelting collected by the authors as part of a worldwide TMS nickel smelter survey. Nickel laterite smelting was the subject of another paper published in the April 2006 issue of JOM.[1] *The reader is referred to the latter paper for general information on the survey.*

INTRODUCTION

This article presents data on nickel sulfide smelting, gathered from a survey of the 19 world nickel sulfide smelters. The feed to these smelters normally consists of a nickel-copper concentrate, also containing minor amounts of cobalt and platinum group metals (PGMs). In most African smelters, South Africa in particular, nickel is in fact a by-product of PGM mining operations. The product of nickel sulfide smelting is generally a low-iron containing matte that requires further processing to yield market products. Two different smelting technologies are used for processing nickel sulfide concentrates, namely flash smelting and electric furnace smelting. The latter technology is used by all of the PGM-Ni producers. The combined annual nickel output of the world nickel sulfide smelters is some 740,000 tonnes, representing about 59% of world 2004 primary nickel production. This is in reasonable agreement with the 2003 production numbers that showed that the primary nickel output from laterite smelters corresponded to about 30%, while the output from laterite hydro plants accounted for about 12%.[1]

In this survey, smelter representatives were invited to review/complete technical questionnaires that were pre-filled by the authors using public information. Table I lists the plants in the survey and their respective annual nickel productions from "new metal bearing feed" (NMBF). The nickel sulfide smelting survey results are presented in Tables II to VI that were composed by grouping the smelters as follows:

- Conventional Outokumpu Flash Smelters (Table II)
- Outokumpu DON Smelters and Inco Flash Smelter (Table III)
- Conventional Electric Furnace Smelters (Table IV)
- PGM-Ni Electric Furnace Smelters, Group 1 (Table V)
- PGM-Ni Electric Furnace Smelters, Group 2 (Table VI)

GENERAL

Nickel sulfide minerals in high enough concentration for commercial exploitation are normally found in intrusive igneous rocks high in magnesium and iron (mafic and ultramafic rocks). Pentlandite [$(Ni,Fe)_9S_8$] is the most common of the nickel sulfide minerals. It is invariably associated with pyrrhotite, an iron sulfide with a composition varying between FeS and Fe_7S_8. Quite frequently, small amounts of nickel substitute for iron in the crystal lattice of pyrrhotite. Copper as chalcopyrite ($CuFeS_2$), and cobalt, gold, silver, and PGMs are other common associates of pentlandite. The most important world nickel sulfide ore deposits are found in the Canadian Sudbury district and the Russian Norilsk and Kola-Pechenga districts, while the PGM-Ni sulfide deposits are mainly found in South Africa's Bushveld Complex.[2] At present, South Africa is the world's largest producer of PGMs and has over 80% of the world's platinum reserves.

Table I. Annual Primary Ni Output (Low-Fe Matte) of World Nickel Sulfide Smelters

Technology	Country	Plant	Annual Ni Production from NMBF*
Flash Smelting	Canada	Copper Cliff	133,400
	Brazil	Fortaleza	7,000
	Finland	Harjavalta	38,000
	Russia	Norilsk Nadezda	140,000
	China	Jinchuan	65,000
	Australia	Kalgoorlie	100,000
	Bostwana	BCL	27,400
Subtotal			**510,800**
Electric Furnace Smelting	Canada	Falconbridge	63,000
		Thompson	50,000
	USA	Stillwater	112
	Russia	Norilsk Ni Plant	40,000
		Pechenganickel	35,000
	South Africa	Anglo Platinum Smelters	22,000
		Impala	12,700
		Lonmin	3,700
		Northam	1,500
	Zimbabwe	Zimplats	1,600
Subtotal			**229,612**
Total			**740,412****

* In general, tonnages correspond to 2004 production.
** Equals 59% of world 2004 primary nickel production (1,260,000 t/y).

Table II. Conventional Flash Smelters

	Producer			
	BCL Smelter BCL Limited Selebi Phikwe, Botswana	Kalgoorlie BHP Billiton Nickel West Kalgoorlie, Australia	Jinchuan Jinchuan Group Ltd. Gansu Province, China	Nadezda Metallurgical Plant Norilsky Nickel Norilsk, Russia
Annual Ni Production from New Metal-Bearing Feed (NMBF) (t/y)	27,400 (2003, Ni+Cu 51,000)	~100,000 Mt/y Ni in matte	65,000 (2004)	140,000
Form	Low Fe matte	Low Fe matte	Low Fe matte	Low Fe matte
Ni Recovery (%)	90	95.8	95	94
Feed Composition				
NiCuCo (%)	8.68	15–16	13.2	Ni 10.3–12.3, Cu 4.2–6.2, Co 0.3–0.4
Ni/Cu (Wt. Ratio)	1.12	50	2.04	2.2
Ni/Co (Wt. Ratio)	23.32	40	43.6	32
Fe (%)	43.03	34	38.3	36–48
S (%)	30.57	32	27.1	31.5–34.5
SiO_2 (%)	8.97	7	6.7	1.8–2.0
Technology				
Drying	2 Niro spray dryers & 1 steam dryer	Concentrate received dry	1 rotary dryer	2 Niro spray dryers
Smelting	1 Outokumpu flash furnace	1 Outokumpu flash furnace with electric furnace appendix	1 Outokumpu flash furnace with electric furnace appendix	2 Outokumpu flash furnaces
Converting	3 Peirce Smith (PS) converters	3 PS converters	3 PS converters	6 PS converters
Slag Cleaning	2 electric furnaces + 1 tilting cylindrical, horizontal furnace. equipped with tuyeres	Flash furnace electric furnace appendix	Flash furnace electric furnace appendix + 2 separate electric furnace s	4 circular Krupp furnaces
Drying		Concentrate received dry		
Type of Dryer and Number of Units	2 Niro spray dryers + 1 steam dryer	—	Rotary dryer	2 Niro spray dryers
Outside Dimensions (dia. × l or dia. × h or l × w × h) (m)	Niro 10 m × 10 m high (ID) Steam 3.1 (w) × 8.15 (l) × 4 (h)	—		14 m × 18 m high
Nominal Capacity—Dry t Feed/h	Niro: 55 t/h/unit; steam: 50 t/h	—	60–80	61
Feed Moisture (%)	28	—	11	50 (slurry)
Product Moisture (%)	Bone dry	—	<0.3	0.2
Fossil Fuel–Type	Pulverized coal	—	Pulverized coal	Natural gas
Average Fuel Consumption—L or kg or Nm^3 /t Dry Feed	43.64	—	16	100 Nm^3/Dry t feed
Smelting				
Type and Number of Furnaces	1 Outokumpu flash furnace	1 Outokumpu flash furnace with electric furnace appendix	1 Outokumpu flash furnace with electric furnace appendix	2 Outokumpu flash furnaces
Furnace Outside Dimensions (Settler) (l × w × h) (m)	22 × 8.2 × 4.0	37 m long × 8 m wide	32.5 × 7.2 × 3.4 (includes settling pool and slag cleaning appendix)	31.2 × 10 × 4.5–6.4
Reaction Shaft Internal Dimensions (dia. × h) (m)	8.5 × 10.73	6.9 × 6	6.4 × 6	8.0 × 8.91
Number of Concentrate Burners	4	4	4	1 (18 fossil fuel burners in settler)
Nominal Capacity (Dry t Solid Feed/h)	115	130–140	50 (dry t con/h)	110–150
Reaction Air + Oxygen (Nm^3/h)	150,000	85,000	32,600	34,000
O_2 Vol. %	31	35	42	70
Fossil Fuel Type	Pulverized coal	NG for preheating air to 500°C and NG or oil in the reaction shaft (oil is RF80)	Heavy oil + coal powder	Natural gas
Fuel Consumption (L or kg or Nm^3/t of Dry Solid Feed)	52.6	11 L	25L + 16 kg	40 Nm^3
Furnace Area Availability – Operating Days/Year	356	—	330	330
Furnace Campaign Life (Years)	Previous was 9	~10	8	5
Flux SiO_2 (%)	82.8	75.6	92.7	78
Average Size (wt.% Below X mm)	100% below 4 mm	45% passing 75 μm	90% < 0.25 mm	99% < 2 mm
Matte (t/d)	400–700	630	360	1,300
NiCuCo (%)	32.4	~49	44.8	Ni 32; Cu 15; Co 0.8
Ni/Cu (Wt. Ratio)	1.14	30.2	1.9	2.1
Ni/Co (Wt. Ratio)	41.9	58	52	40

Table II. Conventional Flash Smelters (cont.)				
	Producer			
	BCL Smelter BCL Limited Selebi Phikwe, Botswana	Kalgoorlie BHP Billiton Nickel West Kalgoorlie, Australia	Jinchuan Jinchuan Group Ltd. Gansu Province, China	Nadezda Metallurgical Plant Norilsky Nickel Norilsk, Russia
Smelting (cont.)				
Fe (%)	33.0	19.8	29	23
S (%)	24.68	26.7	23	27
Matte Tapping Temperature (°C)	1,164	~1,170	1,200–1,240	1,150
Slag (t/d)	2,608	1,650	1,100	3,100
SiO_2 (%)	28.05	33	35.6	34
Fe (%)	40	40	40.8	40
Fe_3O_4 (%)	8.16	6.3	<2	7
MgO (%)	1.92	7.1	—	—
Slag Skimming Temperature (°C)	1,244	1,290–1,350	1,380	1,250
Value Metal Partitions (Matte/Slag) (%)				
Ni	11.5	70	116	52
Cu	11.20	33	65	43
Co	2.55	4.5	7.6	4.7
Furnace Off-Gas				
Temperature (°C)	1,400	1,350–1,400	1,380 (uptake)	1,150
Volume (Nm³/h)	87,152	—	60,000 (ESP)	56,000
SO_2 Dry Basis (vol.%)	7.2	—	8 (acid plant)	30–35
Off-Gas Cooling and Cleaning System	WHB (67 bar 125 t/h steaming rate), 2 parallel Lurgi ESPs	WHB and ESP	WHB and ESP	WHB and ESP
Dust (Sludge) Disposition	Recycled to flash furnace	Dry dust back to flash furnace	Recycled to flash furnace	Recycled to flash furnace
Off-Gas Disposition	Atmosphere	Acid plant	Acid plant	Atmosphere
Converting				
Type and Number of Converters	2 PSCs (2 hot, 1 repair)	3 PS converters	3 PS converters	6 PS converters
Outside Dimensions (dia. × l) (m)	3.96 × 9.14	3.6 × 7.3	3.6 × 8.2	4 × 9
No. and Dia. of Tuyeres (mm)	44 @ 38	28 @ 63.5	34 @ 48	52 @ 50
Average Blowing Rate (Nm³/h)	32,000	19,000	18,000–22,000	36,000
Blast Oxygen Content (vol.%)	21	21	21	21
Reverts Addition of Primary Matte (wt.%)	25	10	25–30	—
Converting Flux (SO_2 %)	82.8	98.7	95.4	76
Average Size (wt.% Below X mm)	100% below 4	100% passing 25	90% 30–50	100% <50
Matte Composition				
NiCuCo (%)	80.82	69	73	Ni 40–52; Cu 18–30; Co 0.2–0.3
Ni/Cu (Wt. Ratio)	1.12	37	1.93	1.9
Ni/Co (Wt. Ratio)	95.34	74	56	180
Fe (%)	1.49	4.2	4.2	3.4
S (%)	16.66	24	22.4	22–23
Matte Pouring Temperature (°C)	1,250	1,280	1,250	1,200
Matte Processing Technology	—	Matte granulated and shipped to Kwinana refinery and other overseas refineries	Controlled cooling, milling, separation of Cu_2S, Ni_3S_2, metallics	Controlled cooling, milling, flotation
Slag Composition				
SiO_2	25.92	21	24–28	20
Fe	44.14	55	48	52
Fe_3O_4	17.63	32	14–18	25
Slag Skimming Temperature (°C)	1,250	1,280	1,250–1,300	1,250
Slag Disposition	Slag cleaning vessel and slag cleaning electric furnaces	100% recycled to flash furnace	Slag cleaning furnaces	Slag cleaning furnaces
Converter Off-Gas				
Hood Dilution Factor	2.5	1:1 to acid plant; 2:1 to stack	2.5 to 3	3 to 4
Diluted Volume (Nm³/h)	80,000 one converter; 160,000 two converters in stack	41,000 to acid plant; ~60,000 to stack	50,000–60,000	140,000
SO_2 Dry Basis (vol.%)	5.2	~4% to acid plant, ~2.7% to stack	2.5–3.5	2.5
Off-Gas Cooling and Cleaning System	Collection in balloon flue dust system	Spray cooler (air and water)	WHB and ESP	WHB and ESP
Dust (Sludge) Disposition	Captured and mixed with flash furnace flux	Recycled to flash furnace	Recycled to flash furnace	—

Table II. Conventional Flash Smelters (cont.)

	Producer			
	BCL Smelter BCL Limited Selebi Phikwe, Botswana	Kalgoorlie BHP Billiton Nickel West Kalgoorlie, Australia	Jinchuan Jinchuan Group Ltd. Gansu Province, China	Nadezda Metallurgical Plant Norilsky Nickel Norilsk, Russia
Converting (cont.)				
Off-Gas Disposition	To stack	To acid plant or stack	Acid plant	Atmosphere
Slag Cleaning				
Electric Furnace (No. of Furnaces)	2 circular electric furnaces	Appendix to flash furnace	2 Rectangular furnaces	4 Circular Krupp furnaces
Outside Dimensions (m) (dia. × h or l × w × h)	8 × 6	—	Furnace #2 – 13.2 × 7.6 × 5.2 Furnace #1 – 11.2 × 4.85 × 4.15	14 × 5.6
Type and No. of Electrodes	3 Söderberg electrodes	2 × 3 electrodes	3 on-line self-baking electrodes	3 self-baking electrodes
Electrode Dia. (cm)	89.2	—	Furnace #2 – 90; furnace #1 – 82	127
Maximum Power Setting (MVA)	2.5	—	Furnace #2, 5; furnace #1 – 4	18
Average Operating Voltage (V)	75	—	60–90	300
Average Electrode Current (A)	13,400	—	15,000–22,000	20,000
Other Furnace (Type and No.)	Converter slag cleaning vessel	N/A	N/A	N/A
Outside Dimensions (m) (dia. × l or l × w)	6.46 × 9.172	—	—	—
Number of Tuyeres and Dia. (mm)	4 @ 6.5 mm	—	—	—
Average Blowing Rate (Nm³/h)	3 tuyeres at 1,160/tuyere	—	—	—
Blast Oxygen Content (vol.%)	0	—	—	—
Operating Data				
Furnace Slag Treated (t/d)	2,600	—	490	3,100
Converter Slag Treated (t/d)	250–400	100% recycled to flash furnace	450	580
Type of Value Metals Collector Added (e.g., Concentrate)	Flash furnace matte	—	—	Rich sulfide ore
Slag (wt.%)	2.1	—	18–24	12
Slag Residence Time (h)	2.5	—	3	4
Type of Reductant Added	Graded coal (lump coal with fixed carbon at 52%	—	Lump coal	Coke (25–45 mm)
Electrical Energy Consumption (KWh/t of Slag)	41.0	—	140–160	160
Electrode Consumption (kg/t of Slag)	0	—	1.9	1.1
Value Metal Product Composition				
NiCuCo (%)	80.8	See flash furnace matte	23	Ni 11–20; Cu 15–27; Co 0.6–1.4
Ni/Cu wt. Ratio	1.12	—	2.8	0.7
Ni/Co wt. Ratio	95.34	—	11.3	15
Fe	1.49	—	50.3	40
S	16.7	—	24	22–24
Disposition	To custom refinery in Kristiansand in Norway and Eiffel flats in Zimbabwe	—	To converters	To converters
Discard Slag Composition (%)				
SiO_2	30.3	See flash furnace slag	35	35
Fe	41.5	—	48	40
Fe_3O_4	5.0	—	—	1–1.5
Ni	0.36	—	0.08	0.07
Cu	0.40	—	0.19	0.22
Co	0.15	—	0.09	0.1
Slag Disposition	Haulage by trucks to slag dump	—	Mine filling	Water granulation; to dump
Furnace Off-Gas Disposition	Atmosphere	See flash furnace off-gas disposition	Atmosphere	Atmosphere after dust recovery
Value Metals Recovery				
(% of Ni, Cu, Co in NMBF Reporting to Smelter Product Matte)				
Ni	90.0	95.8	95	94
Cu	86.2	80	93	90
Co	25.8	—	54	69
Annual Sulfuric Acid Production (Mt)	—	500,000	350,000	—
Smelter Oxygen Consumption (t/t of Ni Recovered from NMBR)	—	~2	3	—

Table III. Outokumpu DON Smelters and Inco Flash Smelter

	Producers		
	DON Flash Smelters		Inco Oxygen Flash Smelter
	Harjavalta Boliden Harjavalta Oy (Smelter) Harjavalta, Finland	Fortaleza de Minas Votorantim Metais Brazil	Copper Cliff CVRD Inco Sudbury, Ontario, Canada
Annual Ni Production from NMBF (t/y)	38,000	7,000	133,400
Form	Low Fe matte	Low Fe matte	Low Fe (Bessemer) matte
Ni Recovery (%)			
Feed Composition			
NiCuCo (%)	15.5	8.1	21.5 (18–26)
Ni/Cu wt. Ratio	19	7	0.84
Ni/Co wt. Ratio	39	70	~30
Fe (%)	30	30	39.0
S (%)	29	21	33.5
Technology			
Drying	Rotary dryer	Multicoil dryer	2 Fluid bed dryers
Smelting	Outokumpu flash furnace	Outokumpu flash furnace	2 Inco oxygen flash furnaces
Converting	N/A	N/A	PS converters
Slag Cleaning	Electric furnace	Electric furnace	N/A
Drying			
Type of Dryer and Number of Units	1 Rotary dryer	Multicoil 2/7–42	2 Fluid bed dryers
Outside Dimensions (dia. × l or dia. × h or l × w × h) (m)	2.54 × 24	7.8 × 2.2	5.27 × 10.1
Nominal Capacity (t/h Dry Feed)	60	24	100–124
Feed Moisture (%)	7	14.6	11.3
Product Moisture (%)	0.2	0.36	0.2
Fossil Fuel Type	Heavy oil	—	Natural gas (back up light oil)
Average Fuel Consumption (L or kg or Nm^3/t Dry Feed)	11.5 kg	—	14–17 Nm^3/t
Smelting			
Type and Number of Furnaces	1 Outokumpu flash furnace	1 Outokumpu flash furnace	2 Inco flash furnaces
Furnace Outside Dimensions (Settler) (l × w × h) (m)	19.5 × 7.02 × 2.655	15 × 4.6 × 1.9	30.51 × 8.23 × 6.9
Reaction Shaft Internal Dimensions (dia. × h) (m)	4.6 × 7.6	2.8 × 5	N/A
Number of Concentrate Burners	1	1 (5 oil burners)	4
Nominal Capacity (Dry Solid Feed t/h)	45	20	100–125
Reaction Air + Oxygen (Nm^3/h)	7,380	300 Nm^3/t	12,200–15,200
O_2 (vol.%)	60–90	90	96
Fossil Fuel (Type)	Heavy oil	Fuel oil	Natural gas on supplemental heat burners; coke with feed
Fuel Consumption (L or kg or Nm^3/t Dry Solid Feed)	23.5	28.82	2 natural gas, 3 Nm^3, and coke ~12 kg/t of dry solid charge
Furnace Area Availability (Operating Days/Year)	330	93.8% (mechanical, electrical, and instrumentation availability)	~84% based on 365 d/y
Furnace Campaign Life (Years)	10	1.5	2–3
Flux SiO_2 (%)	90	93.9	95
Average Size (wt.% Below X mm)	90% <1 mm	80% <0.45 mm	99%–2.38 mm, 97%–600 µm, 100% + 53 µm
Matte (t/d)	116	42	1,535
NiCuCo (%)	70	63	47.5
Ni/Cu wt. Ratio	13	5.50	0.91
Ni/Co wt. Ratio	93	70	34.6
Fe (%)	4.8	7	24.4
S (%)	22	23	25.9
Matte Tapping Temperature (°C)	1,360	1,150–1,200	1,210
	Matte is granulated and treated hydrometallurgically	Matte is granulated and shipped for treatment abroad	—
Slag (t/d)	530	258	2,910
SiO_2 (%)	29	32	36.4
Fe (%)	38	30	43
Fe_3O_4 (%)	16	21	12
MgO (%)	7	9	1

Table III. Outokumpu DON Smelters and Inco Flash Smelter

	Producers		
	DON Flash Smelters		Inco Oxygen Flash Smelter Copper Cliff CVRD Inco Sudbury, Ontario, Canada
	Harjavalta Boliden Harjavalta Oy (Smelter) Harjavalta, Finland	Fortaleza de Minas Votorantim Metais Brazil	
Smelting (cont.)			
Slag Skimming Temperature (°C)	1,400	1,400	1,280
Slag Disposition	Laundered to electric furnace	—	—
Value Metal Partitions			
(Ni%)Matte/(Ni%)Slag	14.9	19.3	50
(Cu%)Matte/(Cu%)Slag	16.9	23	53
(Co%)Matte/(Co%)Slag	1.3	1.4	3.2
Furnace Off-Gas Temperature (°C)	1,400	1,300	1,300–1,400
Volume (Nm^3/h)	16,000	13,100	24,000–28,000
SO_2 (vol.%) (Dry Basis)	30	26	~55 dry basis
Off-Gas Cooling and Cleaning System	WHB + ESP	—	Quencher, Dynawave scrubbing, Wet ESPs
Dust (Sludge) Disposition	Recycled to FFce	Recycled to FFce	Neutralized sludge sent back to front end of furnace
Off-Gas Disposition	Acid plant	Acid plant	To liquid SO_2 plant and to acid plant
Converting	N/A	N/A	—
Type and Number of Converters	—	—	5 PS converters
Outside Dimensions (dia. × l) (m)	—	—	Three 3.96 × 13.7; two 3.96 × 10.7
Number of Tuyeres (dia.) (mm)	—	—	(13.7)–51; (10.7)–42
Average Blowing Rate (Nm^3/h)	—	—	~35,000
Blast Oxygen Content (vol.%)	—	—	24–27
Reverts Addition (wt.% Primary Matte)	—	—	—
Converting Flux (SiO_2) (%)	—	—	~96
Average Size (wt.% Below X mm)	—	—	−1 1/2 + 3/8 inch
Matte Composition			
NiCuCo (%)	—	—	77.3
Ni/Cu (Wt. Ratio)	—	—	0.82
Ni/Co (Wt. Ratio)	—	—	78.9
Fe (%)	—	—	0.52
S (%)	—	—	21–22
Matte Pouring Temperature (°C)	—	—	1,020
Matte Processing Technology	—	—	Separation of controlled cooled and comminuted matte to yield; NiCuCo metalics, Ni sulfides, and Cu sulfides
Slag Composition			
SiO_2 (%)	—	—	26
Fe (%)	—	—	51
Fe_3O_4 (%)	—	—	23
Slag Skimming Temperature (°C)	—	—	1,225
Slag Disposition	—	—	To flash furnace
Converter Off-Gas			
Hood Dilution Factor	—	—	~3–4
Diluted Volume (Nm^3/h)	—	—	~140,000
SO_2 (vol. %) (Dry Basis)	—	—	3–5% SO_2 during regular blows
Off-Gas Cooling and Cleaning System	—	—	ESPs
Dust (Sludge) Disposition	—	—	Dry dust back to flash furnaces
Off-Gas Disposition	—	—	To stack
Slag Cleaning			
Electric Furnace (Number)	1	—	—
Outside Dimensions (dia × h or l × w × h) (m)	9.256 × 5.420	8.7 × 5.2	—
Type and Number of Electrodes	3 Söderberg electrodes	3	—
Electrode Diameter (cm)	1,260	91	—
Maximum Power Setting (MVA)	8	4	—
Average Operating Voltage (V)	210	—	—
Average Electrode Current (A)	5,000	—	—

Table III. Outokumpu DON Smelters and Inco Flash Smelter (cont.)

	Producers		
	DON Flash Smelters		Inco Oxygen Flash Smelter Copper Cliff CVRD Inco Sudbury, Ontario, Canada
	Harjavalta Boliden Harjavalta Oy (Smelter) Harjavalta, Finland	Fortaleza de Minas Votorantim Metais Brazil	
Operating Data			
Furnace Slag Treated (t/d)	530	258	—
Converter Slag Treated (t/d)	N/A	N/A	—
Type of Value Metals Collector Added (e.g., Concentrate)	Concentrate	—	—
Slag (wt.%)	2.0	—	—
Slag Residence Time (h)	2	2–3	—
Type of Reductant Added	Coke	Coke	—
Reductant Consumption (kg/t of Slag)	30	35	—
Electrical Energy Consumption (KWh/t of Slag)	172	230	—
Electrode Consumption (kg/t of Slag)	0.8	3.65	—
Value Metal Product Composition			
NiCuCo (%)	57.5	55	—
Ni/Cu (Wt. Ratio)	16	6.8	—
Ni/Co (Wt. Ratio)	12	70	—
Fe (%)	34.2	36	—
S (%)	6.9	24	—
Disposition	Matte is granulated and treated hydrometallurgically	Matte is granulated and shipped for treatment abroad	—
Discard Slag Composition			
SiO_2 (%)	35	33	—
Fe (%)	39	30	—
Fe_3O_4 (%)	2	5	—
Ni (%)	0.11	0.15	—
Cu (%)	0.06	0.2	—
Co (%)	0.18	0.04	—
Slag Disposition	Granulated and discarded	Discarded	—
Furnace Off-Gas Disposition	Baghouse and stack	—	—
Value Metals Recovery (% of Ni, Cu, Co in NMBF Reporting to Smelter Produce Matte)			
Ni	—	—	97
Cu	—	—	97
Co	—	—	46–48
Annual Sulfuric Acid Production (Mt)	150,000 (plus 12,000 t of liquid SO_2)	60,000	600,000–650,000 (plus 45,000–55,000 t of liquid SO_2)
Smelter Oxygen Consumption (t/t of Ni Recovered from NMBF)	—	5.9	3.8

Table IV. Electric Furnace Smelters—Conventional Nickel Producers

	Producer					
	Sudbury Smelter Xstrata Nickel Sudbury, ON, Canada	Thompson CVRD Inco Manitoba, Canada	Nickel Plant Norilsky Nickel Norilsk, Russia		Pechenganickel Norilsky Nickel Pechenga, Russia	
Annual Ni Production from NMBF (Mt/y)	63,000	50,000	40,000		35,000	
Form	Low-Fe NiCu matte	Low-Fe NiCu matte	Low-Fe NiCu matte		Low-Fe NiCu matte	
Ni Recovery (%)	—	—	—		—	
Feed Composition			Roasted agglomerate	Ore	Roasted granules (10 parts)	Ore (1 part)
NiCuCo (%)	17	14.4	5.0; 2.5; 0.2	0.3; 0.38; 0.14	9.3; 4.1; 0.31	2.1; 1.05; 0.05
Ni/Cu (Wt. Ratio)	2.94	53	2	0.08	2.26 (Combined)	
Ni/Co (Wt. Ratio)	23.5	44	25	2.1	30.2 (Combined)	
Fe (%)	31	36.5	40	45	31.7	21.6

Table IV. Electric Furnace Smelters—Conventional Nickel Producers (cont.)

	Producer			
	Sudbury Smelter Xstrata Nickel Sudbury, ON, Canada	Thompson CVRD Inco Manitoba, Canada	Nickel Plant Norilsky Nickel Norilsk, Russia	Pechenganickel Norilsky Nickel Pechenga, Russia
S (%)	28	29.2	12 1.2	16.3 9.6
MgO (%)	4	2.9	3 8.5	10.4 13.6
Technology				
Roasting	2 fluid bed roasters	2 fluid bed roasters	7 traveling grates (AKM5-75)	2 traveling grates
Smelting	1 rectangular furnace	2 rectangular furnaces	3 rectangular furnaces	2 rectangular furnaces
Converting	3 PS converters	5 PS converters	4 PS converters	5 PS converters
Slag Cleaning	1 horizontal, cylindrical, tilting furnace	N/A	1 rectangular electric furnace	N/A
Roasting				
Type of Roaster and No. of Units	2 fluid bed roasters	2 fluid bed roasters	7 traveling grates (AKM5-75)	2 traveling grates
Inside Dimensions (Each Type) (dia. × h or l × w × h) (m)	5.6 m dia. bed, 8 m dia. freeboard	5.5 m dia. bed, 6.4 m dia. freeboard, 6.5 m high abode grate	45 × 2.8 × 0.3	36 × 2 × 0.35,
Nominal Capacity (Dry Solid Feed) (Mt/h)	—	55	220–250 (total)	30 (concentrate + dust + pellets)
Feed Moisture (%) or Slurry Feed Solids (%)	70% solids slurry	10	—	9 to 12
Bed Temperature (°C)	760	600	700–900	1,100–1,250
Concentrate Sulfur Elimination (%)	~70	40	40	40–45
Calcine Discharge Temperature (°C)	760	580	100	150–200
Off-Gas Volume (Nm³/h)	40,000	48,000 at 530°C	280,000 (total)	46,000
SO_2 (Dry Basis) (Vol.%)	11 to 13	25	1 to 2	2.2
Off-Gas Handling System	Cyclones–gas cooling–ESPs	Cyclones to balloon flue to ESP to stack	—	—
Off-Gas Disposition	Acid plant	Stack	Stack	Stack
Smelting				
Number of Furnaces	1 rectangular six-in-line	2 rectangular six-in-line	3 rectangular six-in-line	2 rectangular six-in-line
Furnace Outside Dimensions (dia. × h or l × w × h) (m)	30 × 9 × 2.7 (inside)	31.7 × 10.7 × 6.4	27.2 × 9.5 × 4.8	27.5 × 11.2 × 6.6
Furnace Wall Cooling System	Water-cooled copper plates and fingers	#2 coolers around skimming and tapping; #1 same + sidewall coolers	Water-cooled copper elements	
Maximum Power Setting (MVA)	60	30	45	45
Average Operating Power (MW)	40	16	—	—
Average Power Density (kW/m²)	130	62	—	—
Average Operating Voltage (V)	1,050	320	500	400–550
Secondary Current (kA)	38	17	50	36
Nominal Capacity (Dry Solid Feed) (t/h/Furnace)	80	65	70–75	50
Type of Reductant Added	Coke	—	—	—
Reductant Consumption (kg/t Dry Solid Feed)	4% on concentrate	—	—	—
Average Electrical Energy Consumption (kWh/t of Dry Solid Feed)	440	470	515	770
Electrode Consumption (kg/t of Dry Solid Feed)	—	3.5	2 to 3	1.1
Matte Temperature (°C)	1,250–1,275	1,190	1,200	1,250
Matte Composition				
NiCuCo (%)	48	32.2	12–14; 7–8; 0.6–0.8	25.9
Ni/Cu (wt. Ratio)	3.1	26	1.75	2
NiCo (wt. Ratio)	32.2	32	18.5	25
Fe (%)	33	37	52–54	40.3
S (%)	17	27	22–24	23.3
Slag Temperature (°C)	1,300–1,320	1,310	1,300	1,350
Slag Composition				
SiO_2 (%)	35	35	35.2–38.9	37.2
Fe (%)	35	37	31.8–34.3	25.3
Fe_3O_4 (%)	—	10	1–3	—
MgO (%)	4–6	2.7	2–3	12.5
Partition Coefficient (Ni)	—	100	185	105
Partition Coefficient (Co)	—	5	11.7	11
Furnace Off-Gas SO_2 (Dry Basis) (Vol.%)	1	3.3	0.07	<0.3
Furnace Off-Gas Disposition	Stack	Stack	Stack	Stack
Converting				
Type and Number of Converters	3 PS converters	5 PS converters	4 PS converters	5 PS converters
Outside Dimensions	1 slag-making converter: 4 m dia. 15 m long; 2 finishing converters: 4 m dia., 9 m long	4 m dia,, 10.7 m long	4 m dia., 9 m long	4 m dia., 12 m long
Number of Tuyeres and Dia. (mm)	Slag-making converter: 6, 32 mm OD shrouded injectors; finishing converter: 42, 50 mm	30–42; 51 mm	52; 50 mm	52; 50 mm

Table IV. Electric Furnace Smelters—Conventional Nickel Producers (cont.)

	Producer			
	Sudbury Smelter Xstrata Nickel Sudbury, ON, Canada	Thompson CVRD Inco Manitoba, Canada	Nickel Plant Norilsky Nickel Norilsk, Russia	Pechenganickel Norilsky Nickel Pechenga, Russia
Converting (cont.)				
Average Blowing Rate (Nm^3/h)	6,450 and 30,000 respectively	About 600	36,000	36,000
Blast O_2 (Vol.%)	33–43 and 21 respectively	21	21	21
Product Matte Composition	Finishing converter	—	—	—
NiCuCo (%)	75.5	80	67.8	72.6
Ni/Cu (Wt. Ratio)	3.1	26	1.1	1.6
Ni/Co (Wt. Ratio)	30	109	46	55
Fe (%)	2–2.5	0.6	3.2	3
S (%)	21	18.7	22.9	24.3
Matte Processing Technology	Granulated and shipped to Xstrata's Norway Refinery	Cast as anodes; electrorefining	Cast, slow cooling, milling, Cu/Ni separation by flotation	Slow cooling; ingots to customer
Slag Composition	Slag making converter	—	—	—
SiO_2 (%)	21	26	18	20
Fe (%)	48	50	55	45
Slag Disposition	To slag cleaning vessel	Recycled to electric furnace	To slag cleaning electric furnace	Recycled to electric furnace
Converter Off-Gas Diluted Volume (Nm^3/h)	—	75,000	140,000	180,000
Converter Diluted Off-Gas SO_2 (Dry Basis) (vol.%)	—	3.6	1–2.5	2.5
Off-Gas Disposition	Off-gases from slag-cleaning vessel, slag-making converter, and finish converter to stack	Stack	Stack	To acid plant
Slag Cleaning		Not applicable		Not applicable
Electric Furnace (# of units)	—	—	1 rectangular furnace with 3 self-baking electrodes	—
Outside Dimensions (l × w × h) (m)	—	—	19.1 × 9.7 × 5.7	—
Maximum Power Setting (MVA)	—	—	25	—
Average Operating Voltage (V)	—	—	380	—
Secondary Current (kA)	—	—	30	—
Other Furnace (Type and Number of Units)	Rotary, horizontal, tilting furnace	—	Not applicable	—
Operating Data				
Converter Slag Treated (Mt/d)	—	—	800	—
Solid Reverts Addition (wt.% of Slag)	—	—	—	—
Type of Value Metals Collector Added (e.g., Concentrate)	—	—	Ore	—
Slag (wt.%)	—	—	8	—
Slag Residence Time (h)	—	—	2	—
Type of Reductant Added	Ferrosilicon	—	Coal	—
Reductant Consumption (kg/t of Slag)	—	—	50	—
Electrical Energy Consumption (kWh/t of slag)	—	—	295	—
Value Metal Product Composition				
NiCuCo (%)	—	—	18	—
Ni/Cu (Wt. Ratio)	—	—	1.27	—
Ni/Co (Wt. Ratio)	—	—	7.8	—
Fe (%)	—	—	55	—
S (%)	—	—	23.4	—
Disposition	Slag making converter	—	To converters	—
Discard Slag Composition				
SiO_2 (%)	—	—	34	—
Fe (%)	—	—	41	—
Fe_3O_4 (%)	—	—	1.5–2	—
Ni (%)	—	—	0.06	—
Cu (%)	—	—	0.2	—
Co (%)	—	—	0.08	—
Slag Disposition	Discarded	—	To dump	—
Furnace Off-Gas Disposition	Stack	—	Stack	—
Value Metals Recovery				
(Ni, Cu, Co in NMBF Reporting to Smelter Product Matte) (%)	—	—	—	—
Ni	—	98	97.9	97
Cu	—	97	96.8	96.4
Co	—	51	65.7	74.8
Annual Sulfuric Acid Production (Mt)	320,000	Not applicable	Not applicable	64,000

Table V. Electric Furnace Smelters—PGM Producers A

	Producer			
	Union-Mortimer Anglo Platinum Limited South Africa	**Waterval Anglo Platinum Limited South Africa**	**Polokwane South Africa**	**Impala Impala Platinum South Africa**
Annual Ni Production from NMBF (t/y)	2,500	22,000 (includes Union and Polokwane)	6,000	12,700
Form	Electric furnace matte converted at Waterval	Low-Fe Ni matte	Electric furnace matte converted at Waterval	Low-Fe Ni matte
Ni Recovery (%)	—	—	—	—
Feed Composition				
NiCuCo (%)	3.34	5.78	2.5–4	2.87
NiCu (Wt. Ratio)	2	1.7	1.6–1.9	1.59
Ni/Co (Wt. Ratio)	55	45	40–60	35.3
Fe (%)	11.7	15.6	10–13.5	12.3
S (%)	5	9	3–6	4.5
MgO (%)	20	15	16–20	18.12
Technology				
Drying	1 Flash dryer	2 Flash dryers	2 Flash dryers	4 Niro spray dryers
Smelting	1 rectangular furnace	2 rectangular furnaces	1 rectangular furnace	2 rectangular furnaces
Converting	Not applicable	2 Ausmelt converters	Not applicable	6 PS converters
Slag Cleaning	—	1 round electric furnace	—	Converter slag milling and flotation
Drying				
Type of Dryer and Number of Units	1 Flash dryer	3 Flash dryers	2 Flash dryers	4 Niro spray dryers
Nominal Capacity (Dry t Feed/h/Dryer)	—	2×35 @ 18% moisture; 1×57.8 @ 22% moisture	78.5@ 10% moisture	25, 25, 45, 60, respectively
Feed Moisture (%)	12 to 22	12 to 22	10 to 16	42.7
Product Moisture (%)	<0.5	<0.5	<0.5	<1
Fossil Fuel (Type)	Coal	Coal	Coal	Coal
Average Fuel Consumption (L or kg or Nm^3/h/Dry t Feed)	—	—	—	128.31
Smelting				
Number of Furnaces	1 rectangular six-in-line	2 rectangular six-in-line	1 rectangular six-in-line	2 rectangular six-in-line
Furnace Outside Dimensions (dia. × h or l × w × h) (m)	25.3 m long, 7 m wide	25.8 m long, 8 m wide	28.7 m long, 9.6 m wide	25.9 m long, 8.2 m wide
Furnace Wall Cooling System	Water-cooled copper plates	Water-cooled copper plates	Copper waffle coolers and plates	Water-cooled copper plates
Maximum Power Setting (MVA)	19.5	39	—	—
Average Operating Power (MW)	19	32–34	68 (max. 80)	#3 38, #5 35
Average Power Density (kW/m^2)	110	160	250	180
Average Operating Voltage (V)	—	300–340	300–800	500
Secondary Current (kA)	—	25–29	40–75	26.8
Nominal Capacity (Dry Solid Feed) (t/h/furnace)	23 t/h, max. 35 t/h	40 t/h, max. 50 t/h	82.5 t/h, max 106 t/h	54 t/h
Type of Reductant Added	Nil	Nil	Nil	N/A
Average Electrical Energy Consumption–(kWh/t of Feed)	820–850	750–850	750–850	680
Electrode Consumption–(kg/t of Feed)	—	2	3	1.5–2.0
Matte Temperature (°C)	1,550	1,350–1,450	1,400–1,500	1,260
Matte Composition				
NiCuCo (%)	19.3	26.5	22.3	23.4
Ni/Cu (Wt. Ratio)	1.71	1.89	1.75	1.6
Ni/Co (Wt. Ratio)	40	34	47	44.4
Fe (%)	37	41	40	44.5
S (%)	25	27	30	29.8
Slag Temperature (°C)	1,650	1,500–1,550	1,600–1,750	1,460
Slag Composition				
SiO_2 (%)	41	46	45–50	46.8
Fe (%)	15.6	24.1	8	11.4 (FeO)
Fe_3O_4 (%)	—	—	—	—
MgO (%)	13	15	20	21.1
Partition Coefficient (Ni)	75	89.5	100	98
Partition Coefficient (Co)	—	10	15	60
Furnace Off-Gas SO_2 (Dry Basis) (Vol.%)	0.5–1.0	0.5–1.3 (combined 2 furnaces)	0.5–1.0	0.9

Table V. Electric Furnace Smelters—PGM Producers A (cont.)

	Producer			
	Union-Mortimer Anglo Platinum Limited South Africa	Waterval Anglo Platinum Limited South Africa	Polokwane South Africa	Impala Impala Platinum South Africa
Smelting				
Furnace Off-Gas Disposition	Stack	To nitrification-type "tower plant." Weak acid produced blended with strong acid from converter gas	Stack	ESP followed by Sulphacid™ technology
Converting				
Number and Type	—	2 Ausmelt converters	—	6 PS converters
Outside Dimensions (m)	—	4.5 m inner dia., 4 m high	—	2 @ 3.6 m × 7.3 m; 4 @ 3 m × 4.5 m
Number of Tuyeres and Dia. (mm)	—	—	—	26 (small); 32 (large); 51 mm
Lance Outer Tube Dia. (cm)	—	45	—	—
Average Blowing Rate (Nm^3/h)	—	25,000 max (including all air)	—	11,000 and 22,000
Blast O_2 (Vol.%)	—	Up to 40% enrichment	—	Air, no addition
Product Matte Composition				
NiCuCo (%)	—	73.5	—	78.0
Ni/Cu (Wt. Ratio)	—	1.81	—	1.6
Ni/Co (Wt. Ratio)	—	94	—	160
Fe (%)	—	2.9	—	0.6
S (%)	—	21.7	—	20.3
Slag Composition				
SiO_2 (%)	—	24–28	—	27
Fe (%)	—	42–48	—	64.45 (FeO)
Slag Disposition	—	Granulated to slag cleaning furnace	—	Granulated to milling/flotation
Converter Diluted Off-Gas SO_2 (Dry Basis) (vol.%)	—	12 to 16	—	3–8% (no dilution)
Off-Gas Disposition	—	To acid plant	—	Single contact acid plant
Slag Cleaning	—	—	—	Milling/flotation of converted slag
Electric Furnace (Number of Units)	—	1 round furnace (3 Söderberg electrodes)	—	—
Outside Dimensions (dia.) (m)	—	12	—	—
Maximum Power Setting (MVA)	—	30	—	—
Average Operating Voltage (V)	—	200–800	—	—
Secondary Current (kA)	—	45–60	—	—
Operating Data				
Converter Slag Treated (Mt/d)	—	About 450	—	—
Solid Reverts Addition–Slag (wt.%)	—	—	—	—
Type of Value Metals Collector Added (e.g., Concentrate)	—	Concentrate	—	—
Slag (wt.%)	—	About 40%	—	—
Slag Residence Time (h)	—	—	—	—
Type of Reductant Added	—	—	—	—
Reductant Consumption—(kg/t of slag)	—	—	—	—
Electrical Energy Consumption—(kWh/t of slag)	—	About 600	—	—
Slag Disposition	—	—	—	—
Furnace Off-gas Disposition	—	—	—	—
Value Metals Recovery (in NMBF Reporting to Smelter Product Matte) (%)				
Ni	90	93	94	92
Cu	89	89	91	90
Co	30	35	35	30
Annual Sulfuric Acid Production (Mt)	—	Max. 920 t/d Current average 400 t/d	—	50,000

Table VI. Electric Furnace Smelters—PGM Producers B				
	Producer			
	Lonmin Lonmin Platinum Marikana	**Northam Northam Platinum Northam, South Africa**	**Zimplats Zimplats Selous, Zimbabwe**	**Stillwater Stillwater Mining Company Montana, USA**
Annual Ni Production from NMBF (t/y)	3,700	1,500	1,600	112
Feed Composition				
NiCuCo (%)	4.1	3.85	3.55	8–9
Ni/Cu (Wt. Ratio)	1.7	1.92	1.39	1.5–1.8
Ni/Co (Wt. Ratio)	20	50	30	—
Fe (%)	17.1	13.2	13.2	14–16
S (%)	5.5	5.4	5.9	11–14
MgO (%)	16.7	18	24	10–14
Technology				
Drying	1 Flash dryer	1 Flash dryer	1 Flash dryer	1 fluid bed dryer
Smelting	4 round electric furnaces	1 rectangular electric furnace	1 round electric furnace	1 rectangular electric furnace
Converting	3 PS converters	2 PS converters	2 PS converters	2 top-blown rotary converters (TBRCs)
Slag Cleaning	Flotation (converter slag)	—	—	—
Drying				
Type of Dryer and Number of Units	1 Flash dryer	1 Flash dryer	1 Flash dryer	1 fluid bed dryer
Outside Dimensions (Each Type) (dia. × l or dia. × h or l × w × h) (m)	—	Approx. 2 × 2 (inner dia.)	—	4.3 m dia., 9.0 m high
Nominal Capacity (Dry t Feed/h/Dryer)	30	18	25	6.5
Feed Moisture (%)	12–15	20	17.5	10
Product Moisture (%)	<0.5	Bone dry	<0.5	<0.1
Fossil Fuel Type	Coal	Pea coal	Coal	Natural gas
Average Fuel Consumption (L or kg or Nm³/t of Dry Feed)	—	50	78 kg	—
Smelting				
Number of Furnaces	4 Round three-electrode furnaces	1 Rectangular six-in-line furnace	1 Round three-electrode furnace	1 Rectangular three-in-line with circular endwalls
Furnace Outside Dimensions (dia. × h or l × w × h) (m)	1 @ 11.8 m dia; 3 @ 6.2 m dia.	25.9 × 8.7 × 5.6 5	12 m dia.	7.5 × 2.6 × 2.1
Furnace Wall Cooling System	Copper waffle coolers; water-cooled shell	No coolers	Copper plate coolers	Water-cooled copper plates
Maximum Power Setting (MVA)	28 and 5, respectively	—	13.5	5 MW
Average Operating Power (MW)	20 and 4.2, respectively	15	12.5	1.4 (1.2–1.6)
Average Power Density (kW/m²)	225 and 198, respectively	90	131	140
Average Operating Voltage (V)	300 and 150, respectively	200	125	160–200
Secondary Current (kA)	62 and 19, respectively	18	—	4–5
Nominal Capacity–Dry Solid Feed (t/h/Furnace)	26 and 5, respectively	10–12	13.8	1.1–1.5
Type of Reductant Added	Nil	—	Nil	Coke
Reductant Consumption–(kg/t of Dry Solid Feed)	—	—	—	3.5
Average Electrical Energy Consumption–(kWh/t of Dry Solid Feed)	700 and 900, respectively	1,044 kWh/t of conc.	850–950	900
Electrode Consumption– (kg/t of Dry Solid Feed)	2.6 (large furnace)	2.6	3.1	3.5
Matte Temperature (°C)	1,500–1,580	1,385	1,330–1,450	1,200–1,300; matte is granulated for feeding TBRC
Matte Composition				
NiCuCo (%)	25	24.3	25.3	26–30
Ni/Cu (Wt. Ratio)	1.67	2.03	1.59	1.5–1.8
Ni/Co (Wt. Ratio)	32	40	20.7	—
Fe (%)	43	41	40–46	40–45
S (%)	28	27	25–30	26–28
Slag Temperature (°C)	1,600–1,650	—	1,580	1,400–1,550
Slag Composition				
SiO_2 (%)	45	44	53.8	42–48

Table VI. Electric Furnace Smelters—PGM Producers B (cont.)				
	Producer			
	Lonmin Lonmin Platinum Marikana	Northam Northam Platinum Northam, South Africa	Zimplats Zimplats Selous, Zimbabwe	Stillwater Stillwater Mining Company Montana, USA
Smelting (cont.)				
Fe (%)	21.8	16.3	18.4% FeO	10
Fe_3O_4 (%)	—	—	—	—
MgO (%)	19.5	20	22.1	12–16
Partition Coefficient–Ni	53	80	229	100
Partition Coefficient–Co	12	13.3	16	—
Furnace Off-Gas SO_2 (Dry Basis) (vol.%)	—	—	0.1	4
Furnace Off-Gas Disposition	ESP; dual alkali S fixation	Stack	Stack	Passes through baghouse and SO_2 scrubber; stack
Converting				
Type and Number of Converters	3 PS converters	2 PS converters	2 PS converters	2 TBRCs
Outside Dimensions (m)	3 dia, 4.6 l	3 dia., 6.1 l	3 dia., 4.6 l	0.80 dia., 1.5 m deep (ID)
Number of Tuyeres and Dia. (mm)	20–65 mm	22	18–50 mm	—
Lance Outer Tube Dia. (cm)	—	—	—	—
Average Blowing Rate (Nm^3/h)	11,000	—	8,500	2,600
Blast O_2 (vol.%)	Plain air	Plain air	Plain air	92–94% (tonnage oxygen)
Product Matte Composition				
NiCuCo (%)	77.6	78.5	79.1	75
Ni/Cu (Wt. Ratio)	1.7	1.9	1.4	About 1.3
Ni/Co (Wt. Ratio)	80	102	114	—
Fe (%)	1.4	1.0	0.6	About 2
S (%)	20	19	17.5	20
Matte Processing Technology	Granulation followed by hydrometallurgical treatment	—	Granulated and shipped to Impala for refining	Granulated and shipped to Stillwater Base Metals Refinery
Slag Composition				
SiO_2 (%)	29	27	27.5	5–7 (Lime ferrite slag with 20–25% CaO)
Fe (%)	62 as FeO	49.8	51.3	45–50
Slag Disposition	Granulated; to flotation	Recycled to electric furnace	Recycled molten to electric furnace	Granulated and recycled to electric furnace
Converter Off-Gas Diluted Volume (Nm^3/h)	—	—	—	—
Converter Diluted Off-Gas SO_2 (Dry Basis) (vol.%)	—	—	0.4	65
Off-gas Disposition	ESP; dual alkali S fixation	Stack	Stack	Passes through baghouse and SO_2 scrubber – stack
Slag Cleaning	Flotation of converter slag; concentrate recycled to furnace	—	Not applicable	Not applicable
Value Metals Recovery				
(in NMBF Reporting to Smelter Product Matte) (%)				
Ni	—	99	95.3	—
Cu	—	99	95.8	—
Co	—	—	31.8	—
Annual Sulfuric Acid Production (Mt)	Not applicable (96% of process SO_2 captured)	Not applicable	Not applicable	99.5% captured and disposed as gypsum)

However, Norilsk is the world's largest single producer of palladium, and also an important producer of other PGMs.

Nickel sulfide minerals are amenable to concentration by milling and flotation, with rejection of a high proportion of ore rock and pyrrhotite prior to smelting. In fact, substantial pyrrhotite rejection from the ore is practiced to reduce SO_2 emissions from nickel sulfide smelters. However, increased nickel losses have demonstrated the limitations of this technique. In some operations, flotation circuits are designed to produce separate copper and nickel concentrates. The broad range of compositions of nickel concentrates in this survey (Tables II–VI) is a reflection of the chemical and mineralogical variability of ores and also of differences in milling-flotation practices.

Although the proportion of world primary nickel production from sulfide deposits has always been substantially higher than from laterites, the latter is increasing at a faster rate. It is expected that by 2012 half of the primary nickel will be produced from laterites.[3] At present, it is estimated that lateritic ores account for 72% and sulfide ores for 28% of world's land-based nickel reserves.

TECHNOLOGY

The output of flash smelters accounts for nearly 70% of the primary metal produced from nickel sulfide sources (see Table I). Electric furnace smelters produce the balance. The key merits of flash smelting are very low electrical and fossil fuel energy consumption and generation of a continuous, low-volume, SO_2-rich process gas stream amenable to processing in an acid plant. It should be noted, however, that fluid bed roasting as practiced in some electric furnace smelters also produces a gas well suited for acid production. The ensuing discussion shows that there is hardly a standard flowsheet for either technology. Factors such as feed Ni/Cu and Ni/Co wt. ratio, concentrate PGM content, MgO content of the gangue, and recycling of nickel- and cobalt-rich external reverts influence smelting flowsheet design. Nevertheless, in nickel sulfide smelting the final product always consists of low iron matte, also referred to as Bessemer Matte (BM). The desired iron content of BM, generally in the range 0.5–4.0%, depends on the refining technology later used to process this intermediate material to market products. This in turn has implications for the finishing stage of converting.

Smelter Feed

The data in Tables II–VI show that, with the exception of PGM-Ni concentrates, the combined NiCuCo grade of concentrates are in the range of about 8% to slightly above 20%, with an Ni/Cu weight ratio varying from about 1 to about 50. However, Ni/Cu weight ratios over 3 are rather the exception. The Ni/Co weight ratio of these concentrates is in general within the range of 25 to 40.

The African PGM-Ni concentrates have a lower NiCuCo content of about 3–4%, with Ni/Cu and Ni/Co weight ratios of 1.5–2 and 20–50, respectively. The true value of these materials are their high content of PGMs that varies from about 100 g/t to about 400 g/t.[2]

Flash Smelting

All flash smelters use Outokumpu technology with the exception of Inco's Copper Cliff Smelter that practices Inco oxygen flash smelting. The flowsheet of conventional flash smelters (see Table II), including Copper Cliff (Table III), consists of bone drying the concentrate, flash smelting, and converting the primary smelting matte to a low iron matte. Dry solid feed flash furnace throughputs are normally 100–150 t/h. In Outokumpu furnaces, the oxygen content of the reaction gas varies from 30–40 vol.% to 70 vol.%, while the Inco furnace operates with 100% tonnage oxygen. Matte grades (NiCuCo%) are usually in the upper 40s. A nickel partition ($Ni\%_{matte}/Ni\%_{slag}$) of about 50 is observed in Nadezda and Copper Cliff. Higher nickel partitions, 70 and 116, respectively, characterize the Kalgoorlie and Jinchuan operations where the flash furnace has an electric furnace appendix. Primary smelting matte is converted in Peirce Smith converters. The iron content of Bessemer Matte (converter product) varies from about 0.5% to about 4%. This material is further treated by either controlled cooling-milling-physical separation into nickel and copper intermediate products, or hydrometallurgical processing and electrowinning. With the exception of Kalgoorlie and Copper Cliff, where converter slag is recycled to the flash furnace, other smelters recover value metals from flash furnace and converter slag in dedicated slag cleaning units, normally electric furnaces. Smelter nickel recovery from NMBF is 94–97%.

An important variation of the Outokumpu technology is the direct Outokumpu nickel (DON) process, in which the concentrate is directly flash smelted to about 5% iron matte, thus eliminating separate converting and associated molten transfers.[4,5] This process is practiced at the Harjavalta and the Fortaleza smelters (see Table III). A substantial proportion of nickel reports to the flash furnace slag. This is recovered as a highly metallized matte in a dedicated slag cleaning electric furnace. Following granulation, the flash furnace and the electric furnace mattes are treated in separate hydrometallurgical installations.

The majority of the nickel sulfide flash smelters capture most or part of the process SO_2 in acid plants. Only in the BCL and Norilsk smelters do all of the process SO_2 go up the stack.

Electric Furnace Smelting

In this survey, the data for the 12 smelters using electric furnaces have been organized in two groups. The four straight nickel producers are called "conventional smelters." The corresponding data are presented in Table IV. The data of the smelters processing PGM-Ni feed are presented in Tables V and VI.

Conventional Smelters

Two of the conventional smelters, Falconbridge and Thompson, are located in Canada, and the other two, Norilsk Nickel Plant and Pechenganickel, are in Russia. Their combined output accounts for 80% of primary nickel production by electric furnace smelting of sulfide feed. The flowsheet of these plants consists of roasting, smelting, and converting. Separate converter slag cleaning is practiced in Falconbridge and in the Norilsk Nickel Plant. Process SO_2 is partially captured in Falconbridge and Pechenganickel. In Falconbridge, the fluid bed roasters' off-gas is processed in an acid plant. At roaster sulfur elimination of 75%, emissions amount to about 10% of concentrate sulfur.

Electric furnace nominal capacity varies from 50 t to 80 t dry solid feed/h, and energy consumption from 440 kWh/t to 770 kWh/t. Matte grade varies within a wide range, 21–48% NiCuCo. The Falconbridge Smelter produces the highest-grade matte, a material that is also highly metallized due to high sulfur elimination in the roasters. Nickel partitions of 100 and higher are typical of electric furnace smelting. The electric furnace matte is converted in Peirce-Smith converters to a <1.0% to about 3% iron matte. The practice of further processing this material to market products varies from plant to plant. A high nickel recovery of 97–98% is observed in all these operations.

Falconbridge in 1994 changed from a two-furnace operation into a single-furnace operation while maintaining nickel production rates.[6] New furnace transformers and improved water-cooled refractory protection elements were later installed. At present, the Sudbury Smelter is operating at an average calcine smelting rate of 300 kg/h/m^2 of furnace hearth, at a nominal power of 40 MW. A 4 m diameter, 17 m long PS converter, blowing at 40% oxygen enrichment, is used for slag making and for processing nickel- and cobalt-containing scrap, while matte finishing to Bessemer is done in conventional converters.[7] The converter slag value metals are recovered in Falconbridge's slag cleaning vessel. The clean, molten slag is discarded.

PGM-Ni Smelters

The Bessemer matte produced in these plants account for only 6% of primary nickel from sulfide sources (see Table I). As shown in Tables V and VI, the smelter flowsheet generally consists of concentrate drying, smelting, and converting. Due to the high MgO content of most of these concentrates, smelting temperatures are substantially higher than in straight nickel smelting. Slag temperature is usually about 1,600°C. Energy consumption is also higher, and varies between 700 kWh/t and 900 kWh/t of dry furnace feed. Converting of primary smelting matte normally takes place in PS converters, except in Waterval and Stillwater, where Ausmelt converters and top-blown rotary converters are respectively used. As in straight nickel sulfide smelters, the technology later used for processing the converter product determines the desired iron content of this material. The reader is referred to an earlier paper by one of the present authors for a detailed review of the South African PGM-Ni smelters.[2]

ACKNOWLEDGEMENTS

The authors express their appreciation to the smelters that directly or indirectly participated in this survey; without their cooperation this survey could not have been conducted. Thanks are also due to CVRD Inco (formerly Inco Ltd.), Xstrata (formerly Falconbridge Limited), the Russian State Research Institute of Non-Ferrous Metals (Gintsvetmet), Worley-Parsons HGE and Mintek for supporting this work.

References

1. A.E.M. Warner et al., "*JOM* World Nonferrous Smelter Survey Part III: Nickel: Sulfide," *JOM*, 58 (4) (2006), pp. 11–20.
2. R.T. Jones, "Platinum Smelting in South Africa," *South African Journal of Science*, 95 (November/December 1999), pp. 525–534.
3. A.D. Dalvi, W.G. Bacon, and R.C. Osborne, "Past and the Future of Nickel Laterite Projects," *Laterite Nickel 2004*, ed. W.P. Imrie and D.M. Lane (Warrendale, PA: TMS, 2004), p. 23.
4. I.V. Kojo, T. Mäkinen, and P. Hanniala, "Direct Outokumpu Nickel Flash Smelting Process (DON)—High Metal Recoveries with Minimum Emissions," *Nickel-Cobalt 97, Vol. III, Pyrometallurgical Operations, the Environment, and Vessel Integrity in Nonferrous Smelting and Converting*, ed. C. Díaz et al. (Montreal, Canada: MetSoc of CIM, 1997), pp. 25–34.
5. T. Mäkinen and P. Taskinen, "Physical Chemistry of Direct Nickel Matte Smelting," *Sulfide Smelting '98: Current and Future Practices*, ed. J.A. Asteljoki and R.L. Stephens (Warrendale, PA: TMS, 1998), pp. 59–68.
6. D.G. Tisdale and C.G. Ransom, "Adapting to One Furnace at Falconbridge," *Nickel-Cobalt 97, Vol. III, Pyrometallurgical Operations, the Environment, and Vessel Integrity in Nonferrous Smelting and Converting*, ed. C. Díaz et al. (Montreal, Canada: MetSoc of CIM, 1997), pp. 35–43.
7. S.W. Marcuson and C.M. Díaz, "The Changing Canadian Nickel Smelting Landscape—Late 19th Century to Early 21st Century," *Nickel and Cobalt 2005: Challenges in Extraction and Production*, ed. J. Donald and R. Schonewille (Montreal, Canada: MetSoc of CIM, 2005), pp. 179–207.

A.E.M. Warner is Senior Consultant with Worley-Parsons HGE in Toronto, ON, Canada; C.M. Díaz is an independent consultant in Mississauga, ON, Canada; A.D. Dalvi is with Inco Technical Services Limited, a subsidiary of CVRD Inco in Mississauga, ON, Canada; P.J. Mackey is with Xstrata Process Support (formerly Falconbridge Technology Centre) in Falconbridge, ON, Canada; A.V. Tarasov is with the State Research Institute of Non-Ferrous Metals "Gintsvetmet" in Moscow, Russia; and R.T. Jones is with the Pyrometallurgy Division at Mintek in Randburg, South Africa. A.E.M. Warner can be reached at (905) 637-8699; e-mail aemwarner@cogeco.ca.