JOM World Nonferrous Smelter Survey Part IV: Nickel: Sulfide

A.E.M. Warner, C.M. Díaz, 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 (Nm^3/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 (Nm^3/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 (Nm^3/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 (Nm^3/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

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	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**
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
	Harjavalta Boliden Harjavalta Oy (Smelter) Harjavalta, Finland	Fortaleza de Minas Votorantim Metais Brazil	Copper Cliff CVRD Inco Sudbury, Ontario, Canada
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 (Nm^3/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/m^2)	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 Nm^3/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/m^2)	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]

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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.

JOM World Nonferrous Smelter Survey, Part III: Nickel: Laterite

A.E.M. Warner, C.M. Díaz, A.D. Dalvi, P.J. Mackey, and A.V. Tarasov

In June 2004 JOM *published the first installment in an ambitious TMS program: the World Nonferrous Smelters Survey. The program is intended to develop a database of all known nonferrous smelters. This paper, the third installment in the project, presents a survey for nickel smelters processing lateritic or other types of oxidic nickel ores. Data for nickel sulfide smelting is scheduled to be published by* JOM *in the second half of 2006.*

INTRODUCTION

This nickel smelter survey is one of a series that the Extractive Metallurgy Division of TMS is publishing in *JOM* as an important component of the services that the society delivers to its members. This series was initiated in 2004 with the publication of a copper smelter survey.[1,2] Within TMS, we believe that such surveys constitute a valuable information source for industry, research organizations, engineering companies, and academia, and an excellent means of facilitating benchmarking and the identification of potential areas of technical cooperation.

Several nickel smelting surveys and industry reviews were published between 1987 and 2003;[3–7] the present survey covering 13 smelters presents the latest review of world laterite nickel smelters. The 13 world laterite smelters reported here total some 365,000 t/y of nickel output, representing about 30% of total world primary nickel output. A very high proportion of current operations participated, directly or indirectly, in this new survey. The tables included in this paper present data for nickel smelters processing lateritic or other types of oxidic nickel ores. Part II of the survey, reviewing the data for nickel sulfide smelting, will be published by *JOM* in the second half of 2006.

In this survey, smelter representatives were invited to review/complete technical questionnaires that were pre-filled by the authors using public information. Doniambo and Larymna did not participate. In these two cases, available public data are presented in the accompanying tables. Three operating Ural smelters, Rezh, Ufaleynickel, and Yuzhuralnickel, that are still using blast furnaces to produce matte from agglomerated oxidic nickel ores, were not included in the survey.

> **Within TMS, we believe that such surveys constitute a valuable information source for industry, research organizations, engineering companies, and academia, and an excellent means of facilitating benchmarking and the identification of potential areas of technical cooperation.**

Table I lists the plants in the survey and their respective annual nickel productions. The nickel laterites smelting survey results are presented in Tables II to IV that were composed by grouping the smelters as Latin America (Table II); Japan and New Caledonia (Table III); and Indonesia, Eastern Europe, and Greece (Table IV).

Tonnages in these tables are given in metric tonnes. The acronym NMBF stands for "new metal bearing feed."

NICKELIFEROUS LATERITES: BACKGROUND

Nickeliferous laterites are ores that were generated by the prolonged weathering of "ultramafic" rocks containing ferromagnesian silicate minerals. In this weathering process, nickel leaches from the upper layers and subsequently precipitates in the lower layers, substituting NiO for MgO and FeO in the lattice of respectively silicate and iron oxide minerals. The chemistry and mineralogy of these ores vary within a very wide range, particularly with respect to Fe/Ni and SiO_2/MgO weight ratios, and chemical and physical H_2O contents. Nickel is recovered from high iron-containing laterites (limonite, nontronite/smectite) by hydrometallurgical processing, while pyrometallurgy is generally used to extract nickel from low iron-containing saprolites and garnierites. Dalvi et al. report that laterites contain about 70% of the estimated world land-based nickel reserves;[8] about 40% of these ores would be suitable for smelting.

The first processing treatment for recovering nickel from laterites was developed in 1879 in New Caledonia, based on the iron blast furnace technology of the day. Production of nickel from laterites has grown slowly since that time. However, during the 20th century, sulfide ores were the predominant source of primary nickel, essentially due to the available reserves and the cost of production. With improvements in technology, the proportion of primary nickel produced from laterites increased steadily

Table I. World Laterite Smelters in 2005 TMS Survey, Annual Nickel Output

Plant	Country	Annual Tonnage (t/y)*
Falcondo	Dominican Republic	28,500
Cerro Matoso	Colombia	49,100
Loma de Niquel	Venezuela	17,400
Codemin	Brazil	6,500
Hyuga	Japan	22,000
Hachinohe	Japan	41,000
Nippon Yakin	Japan	15,000
Doniambo	New Caledonia	60,000
PT Inco	Indonesia	72,000
Aneka Tambang	Indonesia	11,000
PFK	Ukraine	16,000
FENI	Macedonia	7,000
Larymna	Greece	19,200
Total		**364,700****

*Annual tonnages are typical for one year in the period 2002–2004.
** Equals 30% of world Ni (1,200,000 t/y).

in the second half of the last century. In 2003, these ores accounted for 42% of the world 1,200 kt primary nickel production; ~70% of the laterite nickel was produced by pyrometallurgical processing.[8] Table I presents this nickel output by plants in the survey.

Dalvi et al. predicted that by 2012 half of the world primary nickel will be produced from laterites, and that the proportion of nickel extracted by hydrometallurgical processing of these ores will also increase. Clearly then, the next decade promises to be an interesting one for nickel laterites.

PYROMETALLURGICAL PROCESSING OF LATERITES

The standard laterite pyrometallurgical flowsheet consists of the following stages, each with a specific objective:

- Drying: elimination of most or a substantial portion of the free moisture content of the ore
- Calcining-Reduction: elimination of the remainder of the free ore moisture and of its crystalline water, preheating of the ore, and reduction of a substantial portion of the nickel and a controlled portion of the iron
- Electric furnace smelting: completion of reduction of the nickel and separation of the product ferronickel from the gangue that reports to a ferromagnesian silicate slag
- Refining: elimination of undesirable minor elements from the ferronickel to meet market specifications.

The production of sulfur-deficient matte in smelting by adding sulfur to the feed calcine, followed by converting of this material to a low-iron nickel matte product (Inco's Sorowako operation, see Table IV) is an important variation of the standard flowsheet. A second variation, which developed from a technique for iron production, consists of conducting the calcining-reduction stage at a sufficiently high temperature to cause the partial melting of the calcine, thus permitting the growth of ferronickel granules.

The pasty calcine is subsequently water-quenched and comminuted, and the metal granules (referred to as "luppen" from the original German developments in this approach to iron production) are magnetically separated from the gangue (Nippon Yakin's Oheyama operation, see Table III). The reader is referred to an earlier survey[6] for a thorough discussion of the chemistry of the pyrometallurgical processing of laterites. Good descriptions and flowsheets of a number of laterite smelters are found in References 7, 9, and 10.

Feed

Due to their chemical and mineralogical composition, laterites are not amenable to concentration by physical means. However, screening is normally used to separate low-nickel-containing boulders from run-of-mine ore. Typically, the feed to a laterite smelter contains 1.5–2.5% nickel, 25–35% free moisture, and 10–12% crystalline water. In addition, the normal products of smelting, ferronickel and ferromagnesian silicate slag, have high liquidus temperatures. Not surprisingly, laterite smelting is a highly energy-intensive operation, with an average smelting electrical consumption of 502 kWh/t of calcine, based on the data reported in Tables II to IV.

This survey shows that 77% of the laterite smelters are part of integrated mine-smelter operations; the others are custom operations. In the dedicated plants, blending of ores from various mining sites is practiced to generate a relatively constant composition feed to the smelter. Custom operations, such as the Japanese smelters, process various blends of ores imported from New Caledonia, Indonesia, and the Philippines. The Eastern European smelters, including Larymna (Greece), process oxidic nickel ores that have lower moisture contents and substantially higher Fe/Ni and SiO_2/MgO weight ratios than typical laterites.

Drying

Most plants in the survey use direct-fired rotary dryers for elimination of a portion of the free moisture of the ore. Ideally, the dryer should yield an easy-to-handle, non-dusting product. This limits physical water evaporation in dryers, with the product still containing from about 15% to slightly above 20% moisture. Some smelters do dry to lower moisture contents (e.g., Cerro Matoso [Table II]). Drying is a low-temperature operation, with the moisture-laden off-gas exiting the dryer at about 100°C.

Calcining-Reduction

The partially dry ore is calcined and reduced in slightly sloped rotary kilns (RKs). The exception is the Falcondo Smelter, where these process steps take place in rectangular section shaft furnaces[11] that are fed with partly dried ore as briquettes.

In RKs, fuel is burned substoichiometrically at the solids discharge end in order to generate the reducing atmosphere required to control iron reduction to the desired level. The addition of a solid carbonaceous reductant such as bituminous coal or anthracite to the ore is common practice. Combustion gases travel countercurrent to the slowly moving ore that is successively dried, preheated, calcined, and finally partially reduced. Temperatures above 700°C are required to fully eliminate crystalline water. The accompanying dissociation of the lattice structure of the hydrated silicates generates highly reactive amorphous oxides that in turn lead to fast reduction rates. Much higher temperatures would result in undesirable silicate recrystallization and calcine stickiness. While traveling to the feed end of the kiln, the gas combustibles are gradually burned with air fed through kiln-mounted pipes, thus optimizing fuel utilization. Calcine is normally discharged at 700–900°C, while the low combustibles off-gas leaves at the feed end at 250–400°C. Dusting rates are typically 10–20%. The dust is normally agglomerated prior to being recycled to the RK.

Current RK technology efforts focus on adopting/improving computerized process monitoring/control and dependable kiln on-board instrumentation, and achieving higher energy efficiency and ore throughputs. Replacing refractory bricks by monolithic castable lining has resulted in longer kiln campaigns. At some plants, efforts are underway to control dust generation and improve the treatment of this dust. Recently, a computational fluid dynamics model was used for the basic design of Sorowako's RK #5.[12]

Electric Furnace Smelting

In laterite smelting, the high liquidus temperatures of ferronickel and ferromagnesian slag require slag bath temperatures of about 1,600°C. Increased furnace power density, leading to a higher specific processing rate and lower specific energy consumption, has been achieved by adopting a high-voltage (shielded-arc) operation.[13,14] In this mode of operation, a substantial proportion of the power input is transferred directly to the calcine surrounding the arc, and it is almost exclusively used for smelting, while the power released in the bath suffice to maintain slag and metal at temperatures adequate for tapping.

High-voltage operation was first developed by Falcondo and Hatch Associates in the 1970s, and adopted at Cerro Matoso and Sorowako in the mid-1980s. Today, furnaces in these smelters operate at power inputs of 60 MW to 75 MW, with power densities of 230 kW/m^2 to 360 kW/m^2 of the furnace hearth. New furnace control and power electronics technology have been developed to respond to the decreased furnace stability and power swings associated with high-voltage operation.[15,16]

Figure 1 presents the average electrical consumption in the electric furnaces of the laterite plants reviewed in this survey. The data show that the electrical consumption varies from 379 kWh/t to 600 kWh/t of calcine, with the average being 502 kWh/t of calcine.

Furnace sidewall integrity is an important issue in intensive smelting operations, in particular in those cases where the smelting requirements call for highly superheated slag. A variety of copper water-cooling devices, each of which respond to specific refractory protection needs, are being used to protect furnace integrity.[13,14] Currently, nickel laterite smelting furnace campaigns of 10–20 years between major rebuilds are quite common.

With the exception of P.T. Inco's Sorowako and Nippon Yakin's Oheyama, either high- or low-carbon ferronickel is the usual product of laterite smelters. Ores with a relatively low Fe/Ni weight ratio, not higher than 6, are amenable to producing lower liquidus temperature high-carbon metal at an acceptable nickel grade. This is the case of the Japanese smelters and of Pomalaa. Low-carbon ferronickel is produced from ores with higher Fe/Ni weight ratio. Converting is practiced at the Pobuzhie, FENI MAK, and Larymna smelters to increase the nickel content of the low-grade electric furnace product. The feed to the last two smelters has an unusually high Fe/Ni weight ratio.

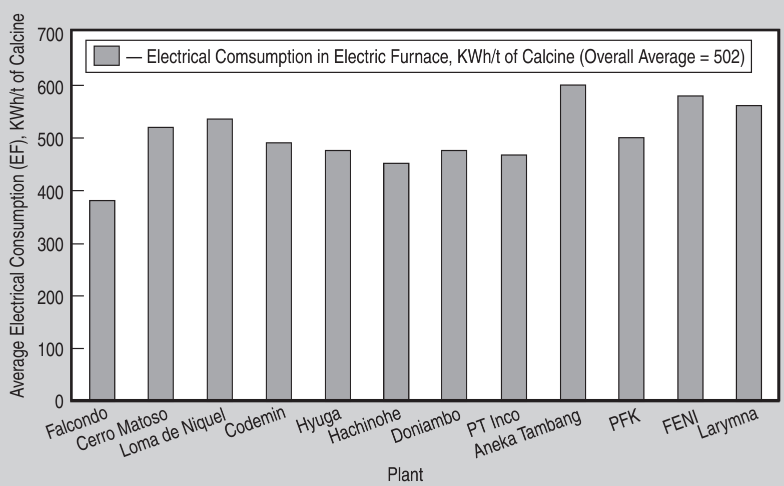

Figure 1. World laterite smelters–electric furnace electrical consumption.

Converting and Refining

Tables II to IV give detailed information on the process stages and type of equipment and reagents used for refining crude ferronickel and converting matte to meet market product requirements in different smelters. The tables also contain data on product form and composition.

Nickel Recovery from New-Metal-Bearing Feed

Except for lower-capacity operations, nickel recovery from new-metal-bearing feed in laterite smelting is higher than 90%. In most cases, the survey data show that the smelting nickel partition ratio (i.e., the ratio of the %Ni content of the ferronickel to the %Ni content of the slag) is close to or above 200, based on reported data for the plants in the survey (see Tables II–IV). However, due to the low nickel content of the ore, in laterite smelting the weight ratio of slag to metal product is also high. The highest recoveries are observed in smelters with relatively high-grade and low Fe/Ni weight ratio feed.

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Table II. Smelters in Latin America

	Producer			
	Falcondo Falconbridge Dominicana Dominican Republic	**Cerro Matoso BHP Billiton Montelibano, Colombia**	**Loma de Niquel Anglo American PLC Venezuela, SA**	**Codemin Codemin S.A. (Anglo American), Brazil**
Annual Ni Production from NMBF (t/y)	28,500	49,100 (2003)	17,400 (2004)	6,500 (2004)
Form	FeNi	FeNi	FeNi	FeNi
Recovery (%)	91.2	93.8	—	87.5
Feed Composition				
Ni (%)	1.38	2.2	1.48	1.44
Co (%)	0.04	0.085	0.08	0.04
Fe (%)	14.5	15.2–15.4	17	16.9
Fe/Ni	10.5	7	11.5	11.7
S/M	1.6	2.76–2.8	1.3	1.6
Technology				
Drying	2 rotary dryers	2 rotary dryers	1 rotary dryer	1 rotary dryer
Reduction	12 shaft furnaces	2 rotary kilns	2 rotary kilns	2 rotary kilns
Smelting	2 rectangular furnaces	2 round furnaces	2 round furnaces	2 round furnaces
Converting	Not applicable	Not applicable	Not applicable	Not applicable
Refining	2 ASEA-SKF ladles	COBS and ASEA ladles	ASEA ladles	6.5 MVA refining Electric furnace
Blending				
Blending System	—	Blending piles	Blending piles (stacker/reclaimer)	Tripper system/ loader reclaimer
Materials Blended	<64 mm ore + fines recovered from >64 mm fraction	<63 mm ore from screening and crushing	<60 mm ore	Chevron piles <80 mm ore
Drying				
Type of Dryer and Number of Units	2 rotary dryers	2 rotary dryers	1 rotary dryer	1 rotary dryer
Outside Dimensions (Diam., Length–m)	4.27 × 24.4	5.1 × 45	4.8 × 34	3.4 × 22
Nominal Capacity (Dry t Ore/h)	285	260	234	104
Ore Moisture In (%)	23–28	22–30 (seasonal)	25–30	25–27
Ore Moisture Out (%)	18	10–12 (seasonal)	Minimum of 15	23–24
Evaporation Rate (kg H_2O/m^3 Dryer)	93	64	60	27
Fossil Fuel–Type	Naptha	Natural gas	Natural gas	Fuel oil
Average Fuel Consumption (L or kg or Nm^3/Dry t Ore)	—	12–18 Nm^3/t (seasonal)	10–11 Nm^3/t	9.0 kg/t
Dust Handling Rate (%)	—	4	—	0.5
Disposition	Recycled back to dryer	Kiln feed mixer-struder	Pelletized and fed to RK	Transported to the dust bin
Calcination/Reduction				
Equipment: Number of Units and Type	12 shaft furnaces	2 rotary kilns	2 rotary kilns	2 rotary kilns
Size (diam. × length or length × width × height) (m)	5.5 long × 1.37 wide × 8.4 high	RK1 6.1 × 185 RK2 6.0 × 135	5.4 × 120	3.6 × 70
Feed Rate (Dry t Ore/h)	30 (briquettes)	165 each RK	65	75
Calcine Discharge Temperature (°C)	800–1,000	800–850	850	900
Fossil Fuel Type	See reductant	Natural gas	Natural gas	Heavy oil
Average Fossil Fuel Consumption (L or kg or Nm^3/t of Dry Ore)	—	50–55 Nm^3/t	80–85 Nm^3/t	52 kg/t
Reductant Type	Partially combusted naphtha (reformed gas)	Anthracite	Coal	Woodchip
Average Reductant Consumption (kg/t of Dry Ore)	—	50–60	55	180
Dusting Rate (%)	3	RK1 12, RK2 22	15	20
Dust Disposition	Blended with fresh ore	Rotary kiln mixer–Struder	Pelletized and rec. to RK	Recycled to rotary kiln
Smelting				
Electric Furnace	2 rectangular furnaces (Six-electrode in-line)	2 round furnaces	2 round furnaces	2 round furnaces
Outside Dimensions (m)	24.3 × 8.8 × 7.3	22.15 × 7.6	16.8 × 6.8	15 × 6
Furnace Wall Cooling System	Copper cooling fingers	Finger and plate copper coolers	Spray cooling water–shell	Spray cooling water–shell
Maximum Power (MW)	80	75	45	22
Average Power (MW)	56	65–70	40	15.5
Power Density (kW/m^2 Hearth–Average)	329	211	—	117

Table II. Smelters in Latin America (cont.)

	Producer			
	Falcondo Falconbridge Dominicana Dominican Republic	Cerro Matoso BHP Billiton Montelibano, Colombia	Loma de Niquel Anglo American PLC Venezuela, SA	Codemin Codemin S.A. (Anglo American), Brazil
Smelting (cont.)				
Average Voltage (V)	1,500	1,080	500	500
Secondary Current (kA)	—	24	25	15
Nominal Capacity (t of Calcine/h/fce)	140	178	75	29
Average Electrical Energy Consumption (kWh/t of Calcine)	379	520	535	490
Electrode Consumption (kg/t of Calcine)	1.08	1.3	3.9	3.3
Matte/Metal Temperature (°C)	1,455	1,450–1,470	1,550	1,480–1,500
Matte/Metal Composition				
Ni (%)	37–40	35	20–25	28
Co (%)	0.92	0.77	0.45	0.56
Fe (%)	60.3	Balance	78	Balance
Slag Temperature (°C)	1,550	1,560	1,650	1,600
Slag Composition				
SiO_2 (%)	43.4	56	45.3	44.5
MgO (%)	29.3	20	36.6	28.7
Fe (%)	13.9	14.7	11.8	14.9
SiO_2/MgO	1.7	2.8	1.24	1.55
Partition Coefficient (Ni)	257	175	205	215
Partition Coefficient (Co)	92	26	>22.5	—
Converting	See refining	See refining	See refining	See refining
Number & Type	—	—	—	—
Outside Dimensions (m)	—	—	—	—
No of Tuyeres	—	—	—	—
Tuyeres Diam. (mm)	—	—	—	—
Average Blowing Rate (Nm^3/h)	—	—	—	—
Blast O_2 (Vol.%)	—	—	—	—
Feed	—	—	—	—
Product Matte Composition				
Ni (%)	—	—	—	—
Co (%)	—	—	—	—
Fe (%)	—	—	—	—
S (%)	—	—	—	—
Slag Composition				
SiO_2 (%)	—	—	—	—
Fe (%)	—	—	—	—
Slag Disposition	—	—	—	—
Refining				
First Step	Dephosphorization	De-P and De-C	De-P and De-C	Dephosphorization
Equipment	2 4 MW ASEA-SKF ladles	COBS and ASEA ladles	ASEA ladles	FeNi tapping ladle
Reagent (s)	Basic oxidizing slag	CaO/SiO_2 slag and O_2	CaO and O_2	CaO and O_2
Process Temperature (°C)	1,500–1,550	1,440	1,650–1,700	1,500
Second Step	Deoxidation	Deoxidation	Desulphurization	Desulphurization
Equipment	Same as above	Same as above	Same as above	6.5 MVA refining electric furnace
Reagent(s)	Ferrosilicon	FeSi and Al	CaO, CaSi, FeSi, Al_2O_3	CaO and O_2
Process Temperature (°C)	1,500–1,550	1,550	>1,600	1,630
Third Step	Desulphurization if required	Desulphurization	—	—
Equipment	Same as above	Same as above	—	—
Reagent(s)	Basic reducing slag	Basic reducing slag	—	—
Process Temperature (°C)	1,500–1,550	1,620	—	—
Form of Product FeNi	100% 0.1 kg "ferrocones"	100% 3–50 mm shots	100% 3–30 mm shot	100% shot
Comp of Product FeNi				
Ni (%)	38.9	34–36	20– 25	30
Co (%)	0.93	<1.0	0.49	0.56
C (%)	0.06	<0.04	≤0.04	0.005
S (%)	0.04	<0.06	≤0.06	0.067
Si (%)	0.35	<0.7	≤0.2	—
P (%)	0.01	<0.04	≤0.03	0.016
Cr (%)	0.02	<0.03	—	—

Table III. Smelters in Japan and New Caledonia

	Producer			
	Hyuga Hyuga Smelting Co Ltd Miyazaki, Japan	**Hachinohe Pacific Metals Co. Ltd. Hachinohe, Japan**	**Oheyama Nippon Yakin Kogyo, Ltd. Oheyama, Japan**	**Doniambo SLN (Eramet Nickel) Noumea, New Caledonia**
Annual Ni Production from NMBF (t/y)	22,000	41,000 (Avg. 2002–2004)	15,000 (2003)	60,000 (80% as FeNi, 20% as matte)
Form	FeNi (1% ingots, 99% shots)	FeNi (30% ingots, 70% shots)	FeNi Luppen (0.5–20 mm)	FeNi (ingots and granules)
Recovery (%)	97–98	97	93	—
Feed Composition				
Ni (%)	2.1–2.5	2.3	2.3	2.7
Co (%)	<0.1	0.08	—	0.06
Fe (%)	11–23	14	13.6	13
Fe/Ni	4.8–10	6.1	5.9	4.8
S/M	1.49–1.67	1.6	1.9	1.75
Technology				
Drying	1 rotary dryer	1 rotary dryer 2 impact dryers	5 preheating grates (each attached to one RK)	2 rotary dryers
Reduction	2 rotary kilns	3 rotary kilns	5 rotary kilns	5 rotary kilns
Smelting	2 round furnaces	3 round furnaces	Not applicable	3 rectangular furnaces
Converting	Not applicable	Not applicable	Not applicable	PS converters (20% of crude FeNi + sulfur)
Refining	Induction furnace and LD converter	Ladles with stirrers	Not applicable	Shaking ladle
Blending				
Blending System	Ore stockyard	—	1/3 ore ground wet, 2/3 ore ground dry; two fractions blended in rod mill	Blending piles
Materials Blended	±100 mm ore from New Caledonia and Indonesia (target Fe/Ni 0.14–0.18, SiO_2/MgO 1.49–1.67)	Ores from New Caledonia, Indonesia, and Philippines	Blend of ground (<3mm) New Caledonia and Indonesia ores, limestone and anthracite is briquetted	Various saprolite ores
Drying				
Type of Dryer and Number of Units	1 rotary dryer	1 rotary dryer 2 impact dryers	5 preheating grates (each attached to one RK)	2 rotary dryers
Outside Dimensions (Diam., Length–m)	5 × 40	Rotary: 4.75 × 35 Impact: 9 m × 4 m × 3 m	17 m × 4 m	4 × 32
Nominal Capacity (Dry t Ore/h)	160	Rotary: 105; impact: 210	27 (each lower cap. line)	220
Ore Moisture In (%)	23–30	30	17 (feed briquettes)	26
Ore Moisture Out (%)	22–23	24	0	18
Evaporation Rate (kg H_2O/m^3 Dryer)	30	19 (rotary dryer)	NA	72
Fossil Fuel Type	Pulverized coal + bunker C oil for ignition + electric furnace off-gas	Waste electric furnace gas	Rotary kiln hot gas	Heavy fuel oil
Average Fuel Consumption (L or kg or Nm^3/ Dry t Ore)	12–13 L (includes oil equivalent of coal)	None	—	—
Dust Handling Rate (%)	2–5	1	14 (RK plus preheater)	—
Disposition	Recycled to dryer	Blended with ore	Recycled to ore blending	To dryer discharge
Calcination/Reduction				
Equipment: Number of Units and Type	2 rotary kilns	3 rotary kilns	5 rotary kilns	5 rotary kilns
Size (diam. × length or length × width × height–m)	4.8 × 105	5.25 × 100, 5.5 × 115, 4.6 × 131	4 RKs 3.6 × 72 1 RK 4.2 × 72	4 × 95
Feed Rate (Dry t Ore/h)	60-65 (each kiln)	90, 110, 90, respectively	27 (Each low cap. line)	—
Calcine Discharge Temperature (°C)	800–900	1,050	1,200–1,250. Pasty discharge is water-cooled, ground. Jigging/magnetic separation yields 23% Ni, 0.5–20mm FeNi luppen	900
Fossil Fuel Type	55–65% pulverized coal, balance Bunker C oil	Pulverized coal	Coal	Pulverized coal
Average Fossil Fuel Consumption (L or kg or Nm^3/t of Dry Ore)	60–62 L/t (includes oil equivalent of coal)	30–50 kg/t	80 kg/t	—
Reductant Type	Coal	Coal	Anthracite (briquettes)	Anthracite
Average Reductant Consumption (kg/t of Dry Ore)	70–80	110	130	50
Dusting Rate (%)	15–20	25	14 (RK plus preheater)	10
Dust Disposition	Pelletized and recycled to rotary kiln	Pelletized and recycled to RKs	Recycled to ore blending	Recycled to RKs

Table III. Smelters in Japan and New Caledonia (cont.)

	Producer			
	Hyuga Hyuga Smelting Co Ltd Miyazaki, Japan	**Hachinohe Pacific Metals Co. Ltd. Hachinohe, Japan**	**Oheyama Nippon Yakin Kogyo, Ltd. Oheyama, Japan**	**Doniambo SLN (Eramet Nickel) Noumea, New Caledonia**
Smelting				
Electric Furnace	2 round furnaces	3 round furnaces	Not applicable	3 rectangular furnaces
Outside Dimensions (m)	#3 18.5 × 5.5; #5 17.5 ×5.4	18 × 5.6, 19 × 6.15, 20 × 6.6	—	33 × 13 × 5.5
Furnace Wall Cooling System	Spray cooling water-shell	Spray cooling water-shell	—	—
Maximum Power (MW)	#3 60; #5 40	43, 54, 54, respectively	—	50
Average Power (MW)	Max. power 60MW day time, 80 MW night time	45	—	36
Power Density (kW/m² Hearth–Average)	#3 170, #5 140	—	—	94
Average Voltage (V)	400–900	664, 760, 760, respectively	—	300
Secondary Current (kA)	28–32	35, 42, 42, respectively		20
Nominal Capacity (t of Calcine/h/fce)	60–65	80, 100, 100, respectively	—	76 (at 36 MW)
Average Electrical Energy Consumption (kWh/t of Calcine)	470–480	450	—	475
Electrode Consumption (kg/t of Calcine)	~1	1.5	—	—
Matte/Metal Temperature (°C)	1,400−1450	1,450	—	1,500
Matte/Metal Composition				
Ni (%)	17–25	18.5	—	22–28
Co (%)	<0.8	0.5	—	—
Fe (%)	70–75	—	—	—
Slag Temperature (°C)	1,550−1,600	1,550	—	1,600
Slag Composition				
SiO_2 (%)	50–55	54	—	55.8
MgO (%)	32−36	35	—	31.9
Fe (%)	7–10	5	—	5.7
SiO_2/MgO	1.49–1.67	1.5	—	1.75
Partition Coefficient (Ni)	210	264	—	185
Partition Coefficient (Co)	—	25	—	—
Converting	See Refining	See Refining	Not Applicable	
Number & Type	—	—	—	PS converters
Outside Dimensions (m)	—	—	—	—
No. of Tuyeres	–	–	–	—
Tuyeres Diam. (mm)	—	—	—	—
Average Blowing Rate (Nm³/h)	—	—	—	—
Blast O_2 (Vol.%)	—	—	—	—
Feed	—	—	—	20 wt.% crude FeNi + S
Product Matte Composition				
Ni(%)	—	—	—	75–78
Co (%)	—	—	—	—
Fe (%)	—	—	—	—
S (%)	—	—	—	—
Slag Composition				
SiO_2 (%)	—	—	—	—
Fe (%)	—	—	—	—
Slag Disposition	—	—	—	—
Refining				
First Step	Desulphurization	Desulphurization	—	Desulphurization
Equipment	Low-frequency induction furnace	Ladles with stirrers	—	Shaking ladle
Reagent(s)	CaC_2	CaC_2	—	CaC_2
Process Temperature (°C)	1,400–1,450	1,500	—	—
Second Step	De-C & De-Si	—	—	Decarburizing
Equipment	LD converter	—	—	Shaking ladle
Reagent (s)	Oxygen	—	—	Oxygen
Process Temperature (°C)	1,600–1,650	—	—	—
Third Step	—	—	—	—
Equipment	—	—	—	—
Reagent (s)	—	—	—	—
Process Temperature (°C)	—	—	—	—
Form of Product FeNi	1% ingots (I), 99% shots (S)	30% ingots, 70% granules	Luppen (crude FeNi)	15–40 kg ingots & granules
Comp. of Product FeNi				
Ni (%)	Hi-C I & S>16 LoC I & S 17–28	17–23	—	FN1 24–30, FN4 22–28
Co (%)	Hi-C & Lo-C I & S <Ni × 0.05	Ni/Co wt. ratio <20	—	—
C (%)	Hi-C I & S<3 Lo-C I & S<0.02	2	—	FN1 0.03, FN4 1.2–1.9

Table III. Smelters in Japan and New Caledonia (cont.)

	Producer			
	Hyuga Hyuga Smelting Co Ltd Miyazaki, Japan	**Hachinohe Pacific Metals Co. Ltd. Hachinohe, Japan**	**Oheyama Nippon Yakin Kogyo, Ltd. Oheyama, Japan**	**Doniambo SLN (Eramet Nickel) Noumea, New Caledonia**
Refining (Cont.)				
S (%)	<0.03	<0.030	—	FN1 0.03, FN4 0.23
Si (%)	Hi-C I & S <5 Lo-C I & S<0.3	2	—	FN10.03, FN4 1.0–3.0
P (%)	Hi-C I & S<0.05 Lo-C I & S<0.02	<0.050	—	—
Cr (%)	Hi-C I & S<2.5	1.3	—	—

Table IV. Smelters in Indonesia and Eastern Europe

	Producer				
	Sorowako P.T. Inco Sulawesi, Indonesia	**Pomalaa P.T. Aneka Tambang Sulawesi, Indonesia**	**Pobuzhsky Ferronickel Combine PFK Pobuzhie, Ukraine**	**FENI FENI MAK Macedonia**	**Larymna Larco GMM SA Larymna, Greece**
Annual Ni Production from NMBF (t/y)	72,000 (2004)	11,000	16,000	7,000	19,200 (2002)
Form	Bessemer matte granules	FeNi ingots and shots	FeNi–90% ingots and 10% pigs	FeNi ingots	Converter alloy shot
Recovery (%)	90	96	87	88.5	88–89
Feed Composition					
Ni (%)	1.8–1.9	2.2	2.4	1.25	1.1
Co (%)	0.06	0.05	0.04	0.06	0.06
Fe (%)	20	13.4	18–20	21	32.0
Fe/Ni	10.5	6.1	7.9	16.8	29
S/M	2	1.64	1.9	2.5	12
Technology					
Drying	3 rotary dryers	2 rotary dryers	Not applicable	Not applicable	Not applicable
Reduction	5 rotary kilns	2 rotary kilns	4 rotary kilns	2 rotary kilns	4 rotary kilns
Smelting	4 round furnaces	2 round furnaces	2 rectangular furnaces	2 rectangular furnaces	4 round furnaces
Converting	3PS converters	Not applicable	Not applicable	Two oxygen vertical converters	2 OBM converters
Refining	Not applicable	Ladle with refractory stirrer and shaking ladle	Electric furnace FeNi tapping ladle and vertical oxygen converter	Induction furnace	Not applicable
Blending					
Blending System	No blending prior to drying	Whell loader	Ore stockpile	Ore is crushed, wet ground, and magnetically separated. Non-magnetic fraction is fed to RK	Yes
Materials Blended	Dry, <2.54 cm EB & WB ores blended to control S/M ratio to ~2.0	Ores from 3 different mining areas	Various nickel oxide ores (not typical laterites)	Various nickel oxide ores (not typical laterites)	Various nickel oxide ores (not typical laterites) crushed to <15 mm
Drying	—	—	Not applicable	Not applicable	Not applicable
Type of Dryer and Number of Units	3 rotary dryers	2 rotary dryers	—	—	—
Outside Dimensions (diam., length–m)	#1–5 × 50, #2–5.5 × 50, #3–6 × 65	3.2 × 30	—	—	—
Nominal Capacity (Dry t Ore/h)	#1–240, #2–305, #3–410	50	—	—	—
Ore Moisture In (%)	29–34	30	—	—	—
Ore Moisture Out (%)	20	22	—	—	—
Evaporation Rate (kg H_2O/m^3 Dryer)	47	30	—	—	—
Fossil Fuel–Type	Oil (HSFO)	Pulverized coal	—	—	—
Average Fuel Consumption (L or kg or Nm^3/Dry t Ore)	26	35	—	—	—
Dust Handling					
Rate (%)	—	3	—	—	—
Disposition	Mixed in Pugmill with dust from RK	Added to dryer product	—	—	—
Calcination/ Reduction					
Equipment: Number of Units & Type	5 rotary kilns	2 rotary kilns	4 rotary kilns	2 rotary kilns	4 rotary kilns

Table IV. Smelters in Indonesia and Eastern Europe (cont.)

	Producer				
	Sorowako P.T. Inco Sulawesi, Indonesia	**Pomalaa P.T. Aneka Tambang Sulawesi, Indonesia**	**Pobuzhsky Ferronickel Combine PFK Pobuzhie, Ukraine**	**FENI FENI MAK Macedonia**	**Larymna Larco GMM SA Larymna, Greece**
Calcination/ Reduction (Cont.)					
Size (Diam. × Length or Length × Width × Height–m)	RK 1, 2, 3–5.5 × 100: RK 4–6 × 115, RK 5–6 × 135	RK1 4 × 90; RK2 4.2 × 90	3.6 × 75	4.6 × 75	Two RKs 4.2 × 90; One RK 5.2 × 90; One RK 6.1 × 125
Feed Rate (Dry t Ore/h)	RK 1, 2, 3–160 RK 4–220, RK 5–235 all wet t/h	RK1 32; RK2 35	80 (each kiln)	140 (sintered pellets)	80 (6.1 × 125 RK)
Calcine Discharge Temperature (°C)	700	800–1,000	750–800	750–800	850
Fossil Fuel Type	HSFO	Pulverized coal	Coal	Coke	Pulverized anthracite/lignite
Average Fossil Fuel Consumption(L or kg or Nm^3/t of Dry Ore)	66 kg oil/t calcine	115 kg/t	40 kg/t	5 kg/t	—
Reductant Type	Bituminous coal	Anthracite and coal	Anthracite	Lignite	Lignite, coal
Average Reductant Consumption (kg/t of Dry Ore)	35–40	67	80	140	—
Dusting Rate (%)	15–17	8	12–16	About 10	6.7 (6.1 × 125 RK)
Dust Disposition	Blended in pug mill and recycled to ore dryer	Pellets of dust + fine ore are recycled to RK	To ore storage	To ore storage	Pelletized and reverted to RK
Smelting					
Electric Furnace	4 round furnaces	2 round furnaces	2 rectangular furnaces	2 rectangular furnaces	4 round EFs
Outside Dimensions (m)	18 × 6	15 × 5.6	24.7 × 9.5 × 6	40 × 11.5 × 6	Diam.–one EF 17.6m; three EFs 12.2m
Furnace Wall Cooling System	Copper cooling fingers	Spray cooling water–shell	Spray cooling water–shell	Spray cooling water–shell	—
Maximum Power (MW)	70–80/furnace	20 and 25, respectively	50	85	1EF 50; 1EF 36; 2EFs 32
Average Power (MW)	55–60	17	38	55	42 (large EF)
Power Density (kW/m^2 Hearth–Average)	236	114	170	120	189 (large EF)
Average Voltage (V)	1,000–1,800	430	500	300	—
Secondary Current (kA)	28–35	23.5	45	175	—
Nominal Capacity (t of Calcine/h/fce)	126	28.3	63	94	—
Average Electrical Energy Consumption (kWh/t of Calcine)	465	600	620	580	560
Electrode Consumption (kg/t of Calcine)	1.4	1.1	3	2	—
Matte/Metal Temperature (°C)	1,350–1,400	1,450	1,350	1,500	1,450
Matte/Metal Composition					
Ni (%)	26	19.15	17	17	15
Co (%)	0.6	0.3	0.5	0.8	0.7
Fe (%)	63	Balance	Balance	Balance	82
Slag Temperature (°C)	1,500–1,550	1,550	1,550	1,550	1,550
Slag Composition					
SiO_2 (%)	47.6	57.2	48	About 40	36.8
MgO (%)	22.7	31	20	About 18	3.1
Fe (%)	18.4	4.6	20	35	32.7
SiO_2/MgO	2.1	1.85	2.4	2.2	12
Partition Coefficient (Ni)	173	213	>212	170	100
Partition Coefficient (Co)	20	NA	>50	40	35
Converting	**—**	**Not Applicable**	**See Refining**	**See Refining**	**See Refining**
Number & Type	3PS converters	—	—	—	—
Outside Dimensions (m)	CV 2–7.3 × 11.8, CV3 and CV4–7.3 × 12.7	—	—	—	—
No. of Tuyeres	20–28	—	—	—	—
Tuyeres Diam. (mm)	51	—	—	—	—
Average Blowing Rate (Nm^3/h)	18,000	—	—	—	—
Blast O_2 (Vol.%)	Air	—	—	—	—
Feed	EF matte	—	—	—	—
Product Matte/Metal Composition					
Ni (%)	78	—	—	—	—
Co (%)	1	—	—	—	—
Fe (%)	>0.7	—	—	—	—
S (%)	18–22	—	—	—	—

Table IV. Smelters in Indonesia and Eastern Europe (cont.)

	Producer				
	Sorowako P.T. Inco Sulawesi, Indonesia	**Pomalaa P.T. Aneka Tambang Sulawesi, Indonesia**	**Pobuzhsky Ferronickel Combine PFK Pobuzhie, Ukraine**	**FENI FENI MAK Macedonia**	**Larymna Larco GMM SA Larymna, Greece**
Converting (cont.)					
Slag Composition					
SiO_2 (%)	25	—	—	—	—
Fe (%)	53	—	—	—	—
Slag Disposition	Slag >0.6% Ni is reverted cold to electric furnace	—	—	—	—
Refining					
First Step	—	Desulphurization	Desulphurization	Desulphurization	Electric furnace FeNi upgrading
Equipment	—	Ladle with refractory stirrer	Electric furnace tapping ladle	Induction furnace	2 OBM converters
Reagent (s)	—	$CaC_2 + Na_2CO_3$	soda ash	Calcium carbide	Lime-ferrite slag
Process Temperature (°C)	—	1,350	1,350	1,280–1,330	—
Second Step	—	De-Si (low C FeNi)	Converting (1st stage)	—	—
Equipment	—	Shaking ladle	Vertical oxygen converter (acid lining)	Two vertical oxygen converters	—
Reagent(s)	—	O_2, burnt lime, limestone (1.2 slag basicity)	Ni Oxide/iron ore, scrap, cold crude FeNi	Lime-ferrite slag	—
Process Temperature (°C)	—	1,450	1,450–1,500	—	—
Third Step	—	De-C (low C FeNi)	Converting (2nd stage)	—	—
Equipment	—	Shaking ladle	vertical oxygen Converter (basic lining)	—	—
Reagent (s)	—	O_2, burnt lime, limestone (3.0 slag basicity)	Limestone, FeSi	—	—
Process Temperature (°C)	—	1,620	1,590–1,650	—	—
Form of Product	Granulated Bessemer matte	Ingots and granules	Ingots and pigs	Ingots	Shots (<40mm)
Comp of Product FeNi	—	Hi-C / Lo-C	—	—	—
Ni (%)	—	18.0/21.0	25–35	35–50	20–25
Co (%)	—	0.33/0.38	0.1–0.5	<1.5	—
C (%)	—	2.22/0.011	<0.1	<0.1	—
S (%)	—	0.01/0.008	<0.07	<0.07	—
Si (%)	—	2.22/0.06	<0.05	<0.06	—
P (%)	—	0.021/0.002	<0.03	<0.03	—
Cr (%)	—	1.65/0.07	<0.3	<0.3	—

Visit the JOM *web site (*http://www.tms.org/JOMPT*) to access spreadsheets used to compile the tables presented in this article. Also available on-line is a spreadsheet of additional information not published in these tables.*

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A.E.M. Warner is Senior Consultant with WorleyParsons HGE in Toronto, Canada (Formerly with Inco Limited). C.M. Díaz is an independent consultant based in Mississauga, Canada (Formerly with Inco Limited). A.D. Dalvi is with. Inco Technical Services Limited in Mississauga, Canada, P.J. Mackey is with Falconbridge Technology Centre, Sudbury, Canada, A.V. Tarasov is with the State Research Institute of Non-Ferrous Metals "Gintsvetmet" in Moscow, Russia.

For more information, contact A.E.M. Warner, WorleyParsons HGE, Toronto, ON, Canada; (905) 637-8699; e-mail aemwarner@cogeco.ca.