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Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

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TECHNOLOGICAL ALTERNATIVES IN THE NICKEL INDUSTRY *

Prepared by

V.V. Ryaskov **
UNIDO consultant

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** Head of Section, All-Union Market Research Institute, Ministry for Foreign Trade, USSR.

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References to dollars ($) are to the United State dollars, unless otherwise stated.

A full stop (·) is used to indicate decimals.

Use of a hyphen between dates (e.g., 1980-1985) indicates the full period involved, including the beginning and end years.

Metric tons have been used throughout.

In tables a dash (-) indicates that the amount is nil or negligible.

Total may not add up precisely because of rounding.

1. PRESENT SITUATION OF TECHNOLOGY IN THE NICKEL INDUSTRY

1.1. Salient features of the industry

Nickel is widely used in different areas. It is estimated that about two thirds of total nickel consumption is used for capital-goods sector and the remainder goes into consumer durable goods. Nickel demand is, therefore, very sensitive to capital expenditures and the business cycle. In the United States, ultimate end uses were: transportation (23%), chemical industry (15%), electrical equipment (12%), construction (10%), fabricated metal products (9%), petroleum (8%), household appliances (8%), machinery (8%), and other (7%).1/

Nickel is primarily used in various ferrous and non-ferrous metal alloys, mainly for its ability to impart corrosion resistance, strength, toughness and other physical properties. Approximately 50% of primary nickel consumption is accounted for by the production of stainless steel, a further 10% is consumed in the production of alloy steels and irons, 25% in non-ferrous alloys, 10% in plating and 5% in chemical and other uses.2/

There is now a range of nickel products, designed to meet the specific needs of the industry. These different forms are classified according to grade.

1/ Mineral Commodity Summaries 1986. United States Bureau of Mines, Washington, D.C., 1986, p. 108.

2/ Metal Bulletin Monthly, No. 166, October 1984, p. 9.

Nickel products fall into two classes. Class I products are essentially 100 per cent nickel. Among them pure unwought nickel cathodes, pellets, powder and briquets. Products with lower nickel content (mainly ferronickel and nickel oxide) form the Class II group. Table 1 summarizes the major products and their compositions.

Table 1. Commercial forms of primary nickel

	Composition (per cent)			
	Nickel	Copper	Iron	Oxigen
Class I				
Pure unwrought nickel:				
Cathode	99.9	0.005	0.002	...
Pellets	99.97	0.0001	0.0015	...
Powder	99.74	...	0.01	0.15
Briquets	99.9	0.001	0.002	...
Class II				
Ferronickel[a]	20-50	...	Balance	...
Nickel oxide	76.0	0.75	0.3	Balance

Source: Minerals Facts and Problems. United States Bureau of Mines, 1985 Edition, Washington, D.C., p. 537.

[a] Cobalt (1% to 2%) included with nickel.

In 1985, the share of Class I products in world (excluding the centrally planned economy countries) nickel production was about 53%.[5]

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[5] World Metal Statistics, May 1987, p. 88.

World nickel resources, as estimated by the United States Bureau of Mines, are shown in Appendix 1. Total economically recoverable land-based resources of nickel amount to 53 million tons of contained metal. Identified world resources in deposits averaging more than 1% nickel have been estimated at the rate of 130 million tons (metal content).[3] World resources of lower grade nickel deposits are very large. In addition, there are extensive resources of nickel in deep seabed nodules containing manganese, nickel, copper and cobalt. Estimates of total world nodule resources have ranged up to nearly 73 billion tons (gross weight). These estimates can only be considered highly speculative until the data base for the emerging resource is improved.[4] Nevertheless it is clear that in the case of nickel exhaustion is not a threat.

Land-based nickel deposits occur as two main types of ore: sulphide and oxide (lateritic) ores. They require a separate technology for extraction from the naturally formed minerals. Sulphide deposits are mostly mined undeground, while lateritic ores, since they occur near the surface, can be mined by open-pit methods.

It is estimated that 80% of identified nickel resources is in latorite and 20% in sulphide deposits. This suggests that future land-based supplies will depend on lateritic ores.

3/ Mineral Commodity Summaries 1986, p. 109.

4/ Mineral Facts and Problems, 1985 Edition, p. 538.

Known sulphide ores are concentrated in only a few countries, mostly in Canada, Australia and southern Africa. These ores are usually associated with copper. Laterite deposits occur mainly in tropical and subtropical regions, mostly in the developing countries (New Caledonia, Indonesia, the Philippines, Cuba, Colombia, and the Dominican Republic). These ores may be associated with cobalt. There are two main types of laterites: limonitic ores and silicate ores. Limonitic deposits are higher in iron content and occur nearer the surface. Limonitic ores usually contain about 1% nickel and 50% iron. Water content of 25% is typical. Silicate ore grades are over 1.5% nickel and less than 30% iron.

Average laterite deposits contain between 1.5 and 2.5% nickel, while sulphide ores often have a lower grade. However, some of sulphide ores being mined in Canada and Australia are comparable in grade.

The regional distribution of world mine and smelter-refinery production is shown in Appendix 2. In 1985, of 21 producing nations, major shares of world total were mined by the U.S.S.R. (23%), Canada (22%), Australia (11%), New Caledonia (6%) and the Philippines (4%). Together, these countries accounted for about 74% of world mine production.

The distribution of primary metal production (ferronickel, oxide sinter, cathodes, powder, etc.) is less concentrated by country. About 67% of 1985 supply was provided by the six largest producers, including the U.S.S.R. (about 25% of world metal production), Canada (14%), Japan (13%), Australia (5%), Norway (5%) and New Caledonia (5%).

Although the bulk of land-based nickel resources is located in the developing countries,[1/] about one third of current mine production and less than 19% of primary metal production is accounted for by this group of countries (see Table 2 below).

Table 2. Nickel industry - Summary of production, 1985

(Thousand tons, metal content)

	Mine production		Smelter-refinery production	
	Tonnage	Share (percentage)	Tonnage	Share (percentage)
Developing countries[a/]	255.5	32.9	142.7	18.7
Developed market economies	315.5	40.6	397.0	52.1
Centrally planned economies[b/]	206.2	26.5	223.0	29.2
WORLD	777.2	100	762.7	100

Source: Derived from Appendix 2.

a/ Including Cuba.

b/ Excluding Cuba.

[1/] The developing countries as a group account for 54% of the total land-based reserves and 63% of the reserve base. Among them, Cuba is by far the best endowed, with roughly 35% of total economically recoverable resources.

The developing countries as a group are the largest exporters of mine and intermediate (matte) production mainly to developed market economy countries, of which Japan, Norway and the United Kingdom are the most important producers with no domestic mine capacities but significant treatment facilities.

A bulk of the nickel mine production not processed in the country where it is mined is treated within a single, vertically integrated company. The three traditional producers (The International Nickel Company (INCO), the Societe Metallurgique le Nickel (SLN) and Falconbridge Limited) have integrated operations from mining to refining. INCO operates a large number of mines and smelters in Canada and Indonesia. It has refineries in Canada and the United Kingdom. Falconbridge has mines and smelter operations in Canada, the Dominician Republic and a refinery in Norway. SLN operates mines and smelters in New Caledonia and a refinery in France. Most producers have control over their raw materials requirements. Notable exceptions are the Japanese companies, which import significant amounts of ores and concentrates from New Caledonia, Indonesia, the Philippines, and other countries.

The most important problem faced by the nickel industry in the 1980s is an economic one. The decline in the growth of nickel demand led to a chronic oversupply and put downward pressure on prices. Although the price of nickel continued its upward trend in nominal terms, it started declining in real terms. These economic conditions forced the closure, at least temporarily, of nickel mine and processing facilities that occured worldwide.

The regional distribution of resources and existing processing gap in developing countries clearly shows that this group of countries has some prospects for further development of nickel production. But a continuing over-abundance of nickel production capacity keeps nickel prices considerably below those required to prompt development of new deposits and expansion of processing facilities.

1.2. Major nickel production processes

The varying characteristics of nickel ores require different production technologies. Historically, pyrometallurgical methods afforded the only commercially feasible technique for the primary nickel extraction. Although these methods are still widely used by the nickel industry, attention is switching to others.

Sulphide ores are readily amenable to concentration by established mineral dressing methods. Typical sulphide concentrates contain between 10% and 15% nickel as well as copper and cobalt, among other metals, where these are present in the ore. Laterits, however, cannot at present be concentrated at the early stages of processing and have to be treated as they are mined.

Various technologies exist for the treatment of nickel sulphide concentrates; the major processes and the resulting products are shown in Appendix 3.

High-grade nickel sulphide concentrate is roasted to form nickel oxide that is smelted in a reverberatory furnace, with petroleum coke as a reductant. The resulting metal is cust into anodes for electrolitic refining into nickel cathodes.

Lower grade sulphide concentrates are smelted first to obtain an impure nickel-copper-iron matte. There are three commercially proven processes of treating sulphide concentrates:

- partial roasting/reverberatory furnace smelting;
- partial roasting/electric furnace smelting;
- flash smelting.

It is generally accepted that flash smelting emits the minimum amount of sulphur dioxide. Flash smelting is also known as the most energy efficient process, estimated to require 5.27 kWh/kg nickel compared to 8.71 kWh/kg nickel for fluid-bed roasting/electric smelting.6/

The nickel-copper-iron matte is transferred to converter, the purpose of which is to remove iron to a slag and part of the sulphur as sulphur dioxide; a sulphur-defficient copper-

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6/ Mining Annual Review 1984, London, 1984, p. 256.

nickel matte is produced. The converter matte when cooled is ground in rod and ball mills to liberate copper sulphides, nickel sulphides and metallics. The metallics are recovered by magnetic separation, dried and sent for carbonyl refining to pellets and powder. The remaining material is treated by froth flotation to separate copper sulphides from the nickel sulphides. The copper sulphide is transferred to copper smelter. The nickel concentrate processing stages produce nickel oxide sinter and pure unwrought metal.

At present, hydrometallurgical technology plays an important part in processing low-iron nickel sulphide mattes rather than concentrates. The only exception is the ammonia pressure leach process (Sherritt-Gordon). Two stage leaching is carried out in pressure autoclaves into which air and ammonia are introduced. Purified nickel solution is passed to reduction autoclaves where hydrogen is injected under pressure. Nickel particles formed at the base of the autoclaves reach the requisite sizes to be sintered as briquettes or for sale as powder. The process produces ammonium sulphate and urea (fertilizer raw materials) from solvent reagents used in refining nickel. The main drawbacks of the ammonia leach technology are the lack of separate precious metals recovery and high energy consumption. The use of the process is, therefore, limited to certain feed composition for economic reasons.

Both pyrometallurgical and hydrometallurgical processes are widely used for treatment of nickel oxide ores (see Appendix 4).

The oxide ores are processed by two pyrometallurgical methods:

(1) smelted with gypsum to produce nickel-iron matte;

(2) smelted directly to produce ferronickel using carbon and/or sulphur as a reductant.

In recent years, hydrometallurgical processes have been increasingly employed as means of treating low-grade lateritic ores. There are two established processes in commercial operation namely:

- the direct sulphuric acid pressure leach process as practised at Moa Bay in Cuba;
- the reduced ore ammoniacal ammonium carbonate leach (Nicaro).

Sulphuric acid leaching of suitable low acid consuming ore converts about 95% of the nickel and cobalt to soluble sulphates, while converting most of the iron in the leach residue to hematite. In this way over 99% of the iron in the ore feed is rejected.

The Nicaro process is operated by Queensland nickel, (Australia), Nonoc Nickel (the Philippines), Companhia Niquel Tocantins Brazil, and Nicaro in Cuba. The flowsheet of the process is: selective reduction - ammonia/ammonium carbonate leaching - purification of leach liquor - recovery of cobalt and ammonia - production of basic nickel carbonate. Run of mine ore is dried from 20-50% moisture down to 3-5% in rotary kilns.

The dried ore is ground and fed to a selective reduction roast step in multihearth roasters. The reduced ore is quenched in ammoniacal ammonium carbonate leach liquor. The slurry is aerated to leach the nickel, cobalt, and copper components and to oxidize the metallic iron during roasting converting it to hydrated iron oxide. The reduction roast/ammonia leach process suffers from high energy consumption and generally low metal recoveries. Drying the wet ore in multihearth furnaces is the largest energy consumer. The absolute heat balance has little room for improvement, but costs can be reduced by the use of less expensive or indigenous fuels and reductants.

The selection of the process of treating nickel oxide ores to be used is determined by various geological and metallurgical criteria. However, each method has its advantages and drawbacks. Pyrometallurgical processes are characterised by high energy consumption and the lack of separate cobalt recovery. Hydrometallurgical processes are limited to certain feed composition for economic reasons.

Laterite-sourced production of nickel is, relatively speaking, energy intensive, whereas nickel production from sulphides is, again relatively speaking, labor intensive. In very round numbers, the labor: energy cost ratios are 1:5 for laterites and 5:1 for sulphides.[7] It is estimated that energy

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[7] *Metal Bulletin*, No. 7105, July 25, 1986, p. 9.

requirements for nickel production from oxide ores are two to three times higher than those for sulphide-based output.

To sum it up, the advantages of treating sulphide compared to oxide ores are:

- sulphide ores can be concentrated whereas nickel from laterites has to be produced at the ore content level.
- most sulphide ores contain other revenue generating metals (copper, cobalt, precious metals and platinum group elements) whereas laterites usually only contain small amounts of cobalt;
- energy requirements for processing of oxide ores exceeds sulphide processing specifically because oxides are wet and cannot contribute exothermic heats of reaction in the smelting process;
- nickel recovery is high from sulphide ores;
- capital costs are lower for sulphide operations whereas oxides often have very high and unpredictable cost levels.

These characteristics make the cost of nickel production from oxide ores considerably higher than from sulphide ores.

As it follows from the above consideration, the main features of the nickel production technology are the complexity of most ores, the variety of production processes and generally high energy requirements.

Along with efficiency of recovery and environmental pressures, these factors define the main routes of technological development of the nickel industry which are discussed in the next chapter.

2. TECHNOLOGICAL DEVELOPMENT OF THE NICKEL INDUSTRY

In 1980-1986, the main research and development programmes in the field of technology have been primarily aimed at improving the most critical characteristics of nickel production processes. Much of the impetus in developing new technology was the quest to develop techniques that are less energy intensive than are current ones.

In the 1980s, a number of new nickel production processes have been developed in different countries. But the complexity of most oxide ores means that special pilot test are required before extraction can start on a commercial scale. Problems with a number of projects indicate that even extensive testing cannot completely eliminate the risk of technology problems.[8/] On the other hand, because of the poor market conditions, few companies have invested in expansion of their processing facilities. Thus, there are new nickel production technologies newly emerging and not yet fully tried in commercial operation. These technologies are defined as newly emerging processes.

2.1. New and emerging processes - Sulphide ores

Smelting.

In the U.S.S.R., a new autogenous fluidized bed smelting process of treating copper-nickel sulphide ores of high sulphur

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8/ Resources Policy, vol. 13, No. 1, March 1987, p. 39.

(about 35%) and iron (about 45%) content was developed.[9] The first semi-commercial plant was completed in 1985. The resulting matte contains 40-55% copper and nickel. The main advantage of the new process is considerable energy savings. It is expected that about 35% of the U.S.S.R. nickel production in 1990 will be produced using this new technology.[10]

Soviet metallurgists devised a new pressure leach process of producing nickel directly from concentrates.[11] the main feed to the process was low-grade pyrrhotite concentrates. The flowsheet consists of the following steps: - pressure acid leaching; - precipitation of metallic sulphides (copper, nickel, and cobalt); - flotation and pressure separation of sulphur as well as ferric sulphide and oxide.[12] The sulphuric-acid leaching is carried out in pressure autoclaves at a temperature of about 150°C using oxigen-air mixture as an oxidant. The two-stage precipitation using hydrogen yields copper concentrate containing about 50% copper and nickel-cobalt concentrate of about 60% nickel content. In addition, sulphureous concentrate containing about 70% free sulphur is produced as a coproduct. As nickel is extracted electrolitically from concentrate in solution, the new process offers considerable energy savings compared to smolting alternatives.

9/ Tsvetnye metally (Non-Ferrous Metals), Moscow, 1987, No. 1, p. 10.

10/ Op. cit., 1986, No. 10, p. 4.

11/ Tsvetnye metally (Non-Ferrous Metals), Moscow, 1984, No. 8, pp. 21-24.

12/ Op. cit., 1983, No. 12, p. 1.

Matte processing.

The new chlorine leach electrowinning process is in commercial operation at Falconbridge Nikkelwerk A/S Norway.[13] The changeover to the new process was completed in 1981. The main feed to the process is nickel-copper matte with typical analysis: 35-40% nickel, 30-35% copper, 22-24% sulphur, 2-3% iron, 0,9-1,0% cobalt. In the new process, nickel is dissolved selectively by controlling redox potential of the slurry in a train of leach/cementation tanks. Essentially all the copper and sulphur contained in the matte is present in the leach redidue. The resulting strong nickel chloride solution is purified by the following steps: - precipitation of iron and arsenic - solvent extraction of cobalt and other minor elements - precipitation of lead and the final impurities. The nickel solution is passed to electrowinning circuit. Cobalt is stripped from the reagent and electrowon. The copper sulphide leach residue is roast - leach-electrowon and the precious metals recovered from the leach residue. The main benefits of the Falconbridge chlorine leach process compared to the old technology (Hybinette electrorefining process) are:

- less labor intensive (1600 employees reduced to 900) and lower consumption of chemicals and steam giving lower operating costs;
- improved purity of nickel and cobalt products;

13/ Mining Annual Review 1986, London, 1986, p. 260.

- reduction of sulphur dioxide emission and losses of metal in liquid effluent.

AMAX developed a process for treating copper-nickel matte to produce copper cathodes and a pure nickel sulphate solution.[14/] The matte is preleached in copper sulphate electrolyte bleed solution so as to dissolve nickel from the matte and cement copper from solution. The AMAX process avoids the conventional energy intensive step of electrowinning copper from copper rich solutions by electrorefining a bimetallic copper-nickel soluble anode. It is claimed that the process produces high purity metal steams while consuming less energy and smaller amount of reagents as compared with other matte processes.

The new and emerging production processes of treating sulphide ores are given in Table 3.

[14/] Tsvetnye metally (Non-Ferrous Metals), Moscow, 1983, No. 11.

Table 3. New and emerging production processes-
Sulphide ores

Process	Resulting products	Main advantages
SMELTING		
Autogenous fluid-bed smelting (the U.S.S.R.)	Ni-Cu-Fe-matte	Energy savings; environmental improvements
Pressure leach process	Ni-Co-sulphide concentrate; Cu-concentrate; sulphureous concentrate	Energy savings
MATTE PROCESSING		
Falconbridge chlorine leach process	Ni-metal Cu-metal Co-metal	Labor savings; improved purity of products; environmental improvements
AMAX leach process	Ni-sulphate solution	Energy savings

2.2. New and emerging production processes - Oxide ores

Alternatives to the energy intensive direct smelting and ammonia leaching processes that are used for many laterites were actively sought in a number of countries.

Ferronickel production processes

In the U.S.S.R., a new smelting process to produce ferronickel from oxide ores is used in commercial operation.[15] The process utilizes the immersion-fired shaft furnace and includes the following steps: melting-down of ore or pellets by the immerced flame jet - reduction of valuable metals by a solid reductant - magnetic separation of the reduced melt. The resulting concentrate is smelted to produce ferronickel. The end product of 25-40% nickel content and 90-93% extraction can be produced from the oxide ore containing 0.8-1.0% nickel. The process provides great flexibility to use different types of fuel and solid reductants and relatively low consumption of energy.

Production of a metallic nickel preconcentrate from nickel oxide ores using nickel segregation reactions has been pursued for many years.

Nippon Steel Corp., the Minerals Processing Research Institute (MINPRO), and Pacific Metals Corp. (PAMCO), all of Japan, in cooperation with Rio Tuba Mining of the Philippines, have developed a nickel segregation process.[16] The process utilizes a ball mill in which nickel ore, carbon, and calcium chloride are ground at a temperature of about 1000°C to reduce

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[15] Tsvetnye metally (Non-Ferrous Metals), Moscow, 1983, No. 11.

[16] Minerals Yearbook 1983, Vol. 1. United States Bureau of Mines, Washington, D.C., 1984, p. 645.

and partially separate nickel, cobalt, and iron, principally from silica. Nickel, cobalt, and iron then undergo a two-stage wet-magnetic separation. The end product contains 30% to 40% nickel in a finely ground form, with a recovery rate for nickel about 90%. The advantages claimed for the process are energy savings and recovery of cobalt. By the currently used rotary kiln-electric furnace process, a temperature of 1250°C is required to produce ferronickel at Pacific Metals. Use of this newer technology, originally patented in 1963-64, could result in more efficient processing of acidic ores, such as those of Rio Tuba Mining in the Philippines.

As a result of research at MINPRO in Sweden, the development of a segregation process has reached to a conclusion with the operation of a pilot plant unit.[17/] Oxide nickel ore grading about 2% nickel and 13% iron was calcined and segregated using calcium chloride and coke additions. A metallic concentrate containing over 60% nickel was produced by magnetic separation with total nickel recovery of over 90%. The MINPRO-PAMCO process utilizes a rotary kiln and mechanical kiln where mechanical energy is converted to heat. As the process worked well below 950°C compared to over 1600°C for smelting alternative, a total of 25-30% energy savings are anticipated for a full scale plant. The process also provides great flexibility to treat different ore compositions particularly with regard to basicity, often a problem with direct smelting.

17/ Mining Annual Review 1985, London, 1985, p. 289.

Changes in the prereduction/electric smelting flowsheet for ferronickel production have been made by SMM of Japan.[18/] The aim was to develop a process to give a high rate of recovery of ferronickel from lateritic ores with a low nickel: iron ratio. The annular vertical kiln is used in the SMM process instead of the conventional rotary kiln, and a mixed pellet process is developed. Semi commercial tests demonstrated that crude ferronickel of 30-40% nickel content and a greater than 98% extraction could be produced from ore containing 2.4% nickel and 20% iron.

Acid leach processes

In the United States, Ni-Cal Developments Ltd. and Raymond Kaiser Engineers have developed an acid leaching process to treat lateritic nickel-cobalt ores.[19/] The Ni-Cal process is designed to extract nickel, cobalt, chromite, and, if required, magnesium oxide and nickel and cobalt chemical compounds. The Ni-Cal process is based on the commercial sulfuric acid leach process. The new technology features an acid leach to provide intermediate nickel-cobalt hydroxide followed by an extraction step using ammonia that eventually enables a plant to recover metallic nickel and cobalt. In addition to much lower energy input as compared with other

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18/ Mining Annual Review 1987, London, 1987, p. 259.

19/ Minerals Yearbook 1984, Vol. 1. United States Bureau of Mines. Washington, D.C., 1985, p. 683.

commercially proven laterite extraction processes, improved metal recoveries of more than 90% nickel and cobalt are claimed.

Amax in conjunction with Compagnie Francaise d'Enterpises Minieres, Metallurgiques et d'Investissement (COFREMMI) offered the further extension of the pressure sulfuric acid leaching. The new hydrometallurgical technique for processing laterite nickel ores yields nickel sulfates that would require additional refining. The process also offers lower energy costs and doubled by-product cobalt recovery over current ammonia leaching processes.[20/]

In Japan, Sumitomo Metal Mining Co. Ltd. (SMM) investigated an improved selective reduction/ammonia leach process for laterites.[21/] The testwork covered all aspects of the flowsheet. The most important development of the conventional ammonia leach process is the adoption of an annular vertical kiln for the reduction equipment in which pellets containing lignite are heated by a nonreductive combustion gas. The test results showed that nickel extractions from limonitic and garnieritic ores were more than 90% and 85% respectively.

The new and emerging production processes considered above are shown in Table 4.

[20/] Op. cit., p. 683.

[21/] Mining Annual Review 1987, London, 1987, p. 259.

Table 4. New and emerging production processes - Oxide ores

Process	Resulting products	Main advantages
FERRONICKEL PRODUCTION PROCESSES		
Immersion-fired furnace smelting (the U.S.S.R.)	Ferronickel	Energy savings; Flexibility to use different fuels
Segregation process (Japan)	Ferronickel	Energy savings; cobalt recovery
MINPRO-PAMCO process	Ferronickel	Energy savings; flexibility to ore feed composition
SMM electric smelting		High rate of Ni recovery
ACID LEACH PROCESSES		
Ni-Cal acid leach process	Ni-metal	Energy savings; improved nickel and cobalt recovery
Amax acid leach process	Ni-sulphate	Energy savings; improved cobalt recovery

As to possible technological progress in the nickel industry, iron and steel smelting methods in all probability will be applied in smelting nickel ores and concentrates. Modified blast furnaces and large electrical smelting furnaces similar to those used in the iron and direct-iron industries may be applied. A top-blow rotary converter has been developed and is in use with good results.

Hydrometallurgical and vapor metallurgical processes may be refined and combined to extract nickel from laterites more effectively. These processes, as well as mechanical extraction, probably will be used to obtain iron and chromium coproducts profitably from lateritic ores. An energy efficient an economical method of concentrating oxide ores early in the stages of processing has yet to be developed.

As to developing countries, the nickel industry is extremely capital intensive. Capital required for a new laterite project has been estimated to be in excess of $17 per pound of annual capacity. Such costs make even the highest grade laterite projects look unattractive if construction were to begin today. The new and emerging processes considered in this chapter seem to have no opportunity to make the situation changed in the near future.

Furthermore, employment creation can hardly be an important objective in justifying further nickel processing, since most of the new processes are less labor intensive than present production technologies.

Among the new and emerging nickel production processes, there do not seem to be any processing technologies that are especially labor intensive or that become fully efficient at low production volumes and that are therefore particularly suited for developing countries.

To conclude, it must be underlined that the decision on each processing plant must be preceded by individual assessment, to ascertain that its benefits exceed its costs.

Appendix 1

World nickel reserves and reserve base[a/][b/]
(metal content)

Region and country	Reserves		Reserve base	
	1000 tons	%	1000 tons	%
America				
U.S.A.	272	0.5	2 540	2.5
Canada	7 257	13.8	13 426	13.3
Brazil	816	1.5	4 264	4.2
Colombia	590	1.1	635	0.6
Cuba	18 144	34.4	22 680	22.5
Dominican Republic	726	1.4	998	1.0
Other	-	-	1 270	1.3
Total:	27 805	52.7	45 813	45.3
Europe				
Greece	2 359	4.5	2 540	2.5
U.S.S.R.	6 621	12.6	7 347	7.3
Other	2 435	4.6	2 766	2.7
Total:	11 465	21.7	12 653	12.5
Africa				
Botswana	408	0.8	454	0.4
Burundi	-	-	1 179	1.2
South Africa	2 540	4.8	2 631	2.6
Zimbabwe	181	0.3	1 724	1.7
Other	-	-	3 628	3.6
Total:	3 129	5.9	9 616	9.5

(continued)

World nickel reserves and reserve base[a/b/]
(metal content)

(continued)

Region and country	Reserves		Reserve base	
	1000 tons	%	1000 tons	%
Asia				
China	726	1.4	907	0.9
Indonesia	3 901	7.4	5 262	5.2
Philippines	1 814	3.4	4 627	4.6
Other	-	-	544	0.5
Total:	6 441	12.2	11 340	11.2
Oceania				
Australia	2 087	4.0	4 808	4.8
New Caledonia	1 814	3.4	15 422	15.3
Papua New Guinea	-		1 270	1.3
Total:	3 901	7.4	21 500	21.3
World total[c/]	52 700	100	100 900	100

Source: Mineral Facts and Problems. United States Bureau 1985 Edition, Washington, D.C., p. 538.

a/ Nickel content of deep-sea nodules not included.

b/ The reserve base includes demonstrated resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources).

c/ Rounded.

Appendix 2

World nickel production, 1985

Region and country	Mine production[a]		Smelter-refinery production[b]	
	1000 tons	%	1000 tons	%
America				
U.S.A.	5.6	0.7	33.0	4.3
Canada	170.0	21.9	110.1	14.4
Brazil	13.2	1.7	13.2	1.7
Colombia	14.0	1.8	11.4	1.5
Cuba	33.4	4.3	18.0	2.4
Dominican Republic	25.4	3.3	25.4	3.3
Total:	261.6	33.7	211.1	27.7
Europe				
Finland	8.6	1.1	15.7	2.1
France	-	-	7.0	0.9
Greece	15.9	2.0	15.9	2.1
Norway	0.6	0.1	37.5	4.9
United Kingdom	-	-	17.8	2.3
Yugoslavia	1.5	0.2	7.5	1.0
U.S.S.R.	175.0	22.5	193.0	25.3
Other	12.2[c]	1.6	11.0[d]	1.4
Total:	213.8	27.5	305.4	40.0
Africa				
Botswana	19.6	2.5	-	-
South Africa	29.0	3.7	24.0	3.1
Zimbabwe	11.2	1.4	11.5	1.5
Total:	59.8	7.7	35.5	4.7

(continued)

World nickel production, 1985

(continued)

Region and country	Mine production 1000 tons	Mine production %	Smelter-refinery production 1000 tons	Smelter-refinery production %
Asia				
China	19.0	2.4	18.0	2.4
Indonesia	48.2	6.2	4.8	0.6
Japan	-	-	95.2	12.5
Philippines	27.7	3.6	14.8	1.9
Burma	0.1	0.0	-	-
Total:	95.0	12.2	132.8	17.4
Oceania				
Australia	85.8	11.0	40.8	5.3
New Caledonia	61.2	7.9	36.1	4.7
Total:	147.0	18.9	76.9	10.1
World total	777.2	100.0	762.7	100.0

Source: *World Metal Statistics*, May 1987. World Bureau of Metal Statistics, London.

a/ Nickel content.

b/ Production of smelter products such as ferronickel and nickel oxides as well as fully refined nickel.

c/ Including Albania and German D.R.

d/ Including Albania, Czechoslovakia and German D.R.

Appendix 3

Generalized flowsheet for major nickel production processes - Sulphide ores