

# Nickel resources in India and their exploitation

R. N. MISRA and P. P. BHATNAGAR

**N**ICKEL is one of the important strategic alloying elements; its consumption has increased considerably after World War II and during the last few years it increased by 60-70%. It is felt that the increase would have been still higher if more nickel was available. The present annual production outside the communist block has well exceeded 400 000 tons and there is every likelihood of further rise in production in the near future as new production centres are being established. The largest single producer of nickel is Canada with the world's richest deposits at Sudbury, Ontario. The annual world production of nickel since 1958 is recorded in Table I.

Till recently production of nickel was limited to few countries; owing to the increasing demand, considerable attention is now being paid for the production of nickel or its compounds from the lower grade ores. India, like many other countries, lacks high grade nickel ore, and the domestic nickel consumption is wholly based on imports. Indian imports of nickel during the past decade are shown in Fig. 1. Import of both wrought and unwrought nickel increased continuously till 1964, but following the restrictions imposed and the industrial recession, nickel imports were drastically cut down till 1966. The present trend, however, indicates again an increase in indigenous nickel consumption; with the development and expansion of the alloy steel industry the annual demand for nickel is estimated at 50 000 tonnes. In terms of foreign exchange nickel consumption during 1964 amounted to 18.5 million rupees and the figure is likely to be exceeded in the coming years. In view of the strategic importance of nickel and the foreign exchange required for its import, its production from indigenous low grade ores would be highly advantageous to our national economy and Geological Survey of India are carrying out extensive survey of nickel deposits in the country with this objective in view.

## Indigenous resources

Recent exploration by the G.S.I. has revealed several nickel bearing low-grade deposits of laterites and serpentines. Serpentinous ores of workable nature are located in Moreh area of Assam, while large reserves of low-

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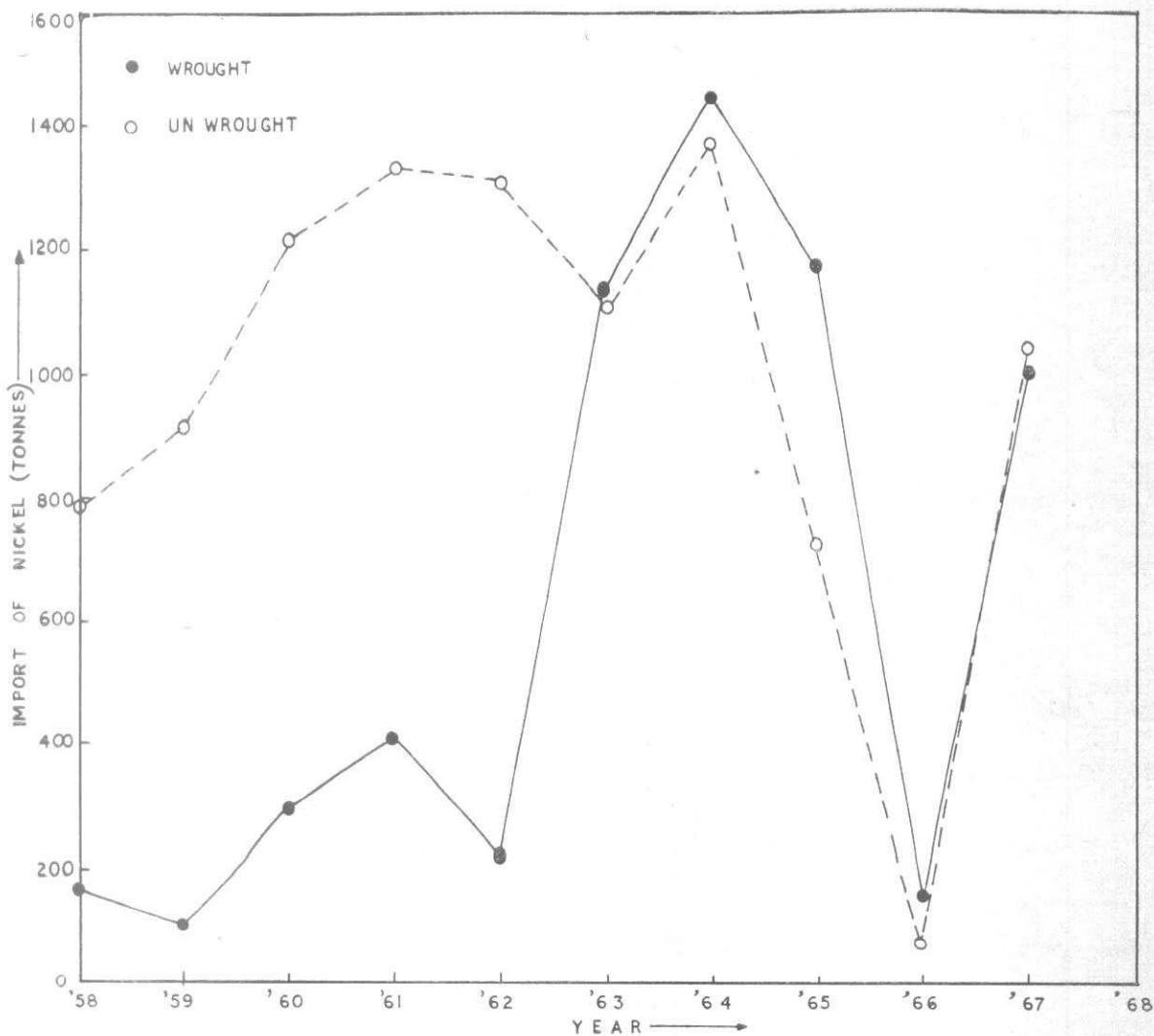
## SYNOPSIS

*The paper outlines the different indigenous resources for nickel and stresses the need for extraction of the metal from these resources. The common methods for treating low grade nickel ores have been reviewed and the processes most suited for the lean-indigenous nickel ores have been discussed in the light of the work carried out at the National Metallurgical Laboratory. A flow sheet for pilot plant treatment of oxidic nickel ores has been presented and the limitation of the process to treat ores containing less than 0.43% Ni has been indicated. A proposal is made for economic use of nickel and its conservation from various sources.*

TABLE I Annual world production of nickel <sup>1,2</sup>

Year	Nickel production (short tons)	Price (\$/lb)
1955-59 (Av.)	2 86 000	0.74
1960	3 53 000	0.74
1961	3 98 000	0.74-0.81
1962	3 94 000	0.81-0.79
1963	3 89 000	0.79
1964	4 23 000	0.79
1965	4 72 000	0.79-0.78

grade nickel bearing serpentines are found in Rajasthan. Lateritic ores containing up to 1.8% nickel oxide have been located in the iron and chrome ore belts of Orissa. It has been estimated that 7.9 million tons of nickeliferous laterites are located in Sukinda area alone, whilst the extent of these reserves in other localities are not yet definitely known. No definite mineral of nickel has been identified in silicate ores, although it is known that such ores contain garnierite, noumeite, revdinskite, nepouite minerals. The exact nature of occurrence of nickel in silicate ores has remained con-



1 Indian import of nickel

troversial,<sup>3</sup> but for all metallurgical purposes it can be regarded as  $NiSiO_3 \cdot m MgSiO_3 \cdot n H_2O$ ; where  $m$  and  $n$  can be found by mineralogical and chemical examination of the ore. The nickeliferous laterites can, on the other hand, be represented as  $(Fe, Ni) O (OH) \cdot n H_2O$  where nickel as well as moisture content are widely variable, nickel content being usually low.

Besides the nickel bearing ores of Assam, Orissa and Rajasthan, the copper ore belt of Singhbhum, Bihar, also contains nickel in the ore body and may serve as a source of exploitation. Nickel has also been found in the uranium bearing belt in the region and it is estimated that with the treatment of 1 000 tonnes per day of ore at the Uranium Corporation, Jadugoda, it may be possible to recover about 1000 tonnes of nickel annually.

The copper tailings, as well as the anode sludge of the copper plant of Messrs Indian Copper Corporation at Ghatsila may also be other potential sources of nickel. The tailings, however, contain less than 0.1% as pentlandite and violarite associated with pyrrhotite and a method has to be developed before such low

grade materials can be treated. The anode sludge contains the precious metals, selenium and tellurium besides nickel and copper. National Metallurgical Laboratory is already engaged on studies for the recovery of these elements and encouraging results have been obtained.

The different indigenous sources of nickel and the typical chemical analyses are indicated in Table II. Exact data on the reserves is not available and a detailed survey may be necessary.

#### Method for treatment of low grade ores

Owing to the increasing demand for nickel, considerable attention is being paid for its recovery from the low-grade lateritic or silicate ores and a world-wide search continues for such deposits. Commercial exploitation of low grade oxidised nickel ores is well established; the ores are either smelted to nickel matte or ferro-nickel by pyro-metallurgical methods or they are treated by hydro-metallurgical methods to produce nickel oxide.

TABLE II Indigenous nickel resources and their typical analysis

Nickel resources	Source	Typical chemical analysis (%)						
		Ni	Fe	Cu	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	Others
1. Nickeliferous serpentine	Moreh Assam	0.51	7.86	—	38.34	—	33.14	—
2. do	Ranakpur Rajasthan	0.26	5.75	—	38.45	1.83	37.18	16.19
3. Nickeliferous laterite	Badam Pahar Orissa	0.34	29.4	trace	15.5	22.4	—	L.O.I. 3.4% Cr <sub>2</sub> O <sub>3</sub> 0.27% V <sub>2</sub> O <sub>5</sub>
4. do (dense)	Sukinda Orissa	0.62	39.5	0.02	16.5	14.0	1.2	1.85 Mn
5. do (light)	Sukinda Orissa	1.41	47.04	trace	6.8	12.36	1.1	2.9 MnO
6. Copper tailings	I.C.C. Ghatsila	0.073	9.33	0.17	59.7	13.94	—	1.45 S 1.27 P <sub>2</sub> O <sub>5</sub>
7. Anode sludge	do	31.5	0.5	19.4	6.5	—	—	10.5 Se 12.2% Te 3.87 S 0.77 Ag 0.093 Au
8. Cu-Ni-MO concentrate	U.C.I. Jadugoda	Beneficiation tests under progress						

*(a) Matte smelting*

Smelting of silicate nickel ores to nickel matte is practised at the Le Nickel Plant at Doniambo, New Caledonia,<sup>4</sup> at the Sumitomo Metal Mining Company on Shisake Island, Japan,<sup>5</sup> and also at Orsk, Rezk and Ufaley in U.S.S.R.<sup>6</sup> Matte melting is carried out in blast furnaces using selectively mined ores.

The New Caledonian ores containing about 3% Ni, and 3 to 5½% Fe are smelted in the low shaft blast furnaces with gypsum, coke and limestone, to produce a 25% Ni grade matte with Ni/S ratio of 2.7:1, which is further refined in a converter to 78% Ni and 22% S grade matte. The matte from Doniambo is sold to Japan and Canada for refining and also shipped to Le Havre, France, for conversion of nickel oxide by roasting and finally to nickel rondelles of 99.25% purity by reduction of the oxide.

Matte smelting by the Sumitomo process involves smelting of a mixture of New Caledonian silicate ores and Canadian sulphide concentrate in a 70:30 proportion with coke and flux to produce a 27% Ni-grade matte which is converted to 74% Ni-grade matte by oxidation and slagging of iron. The granulated high grade matte is roasted to oxide and then reduced with coke breeze in an electric furnace to metallic nickel which is finally refined electrolytically.

The Russian practice is similar in principle to the New Caledonian practice where gypsum as well as

pyrite are used for sulphidising purposes, and the primary mattes containing 10-17% Ni are refined to 77%-Ni grade matte for roasting and reduction to a metal containing 98% Ni, some of which is further electro-refined.

*(b) Smelting to ferro-nickel*

Silicate nickel ores are smelted to ferro-nickel in New Caledonia,<sup>8</sup> Japan,<sup>5,6</sup> Greece,<sup>9</sup> Brazil<sup>10</sup> as well as by the Hanna Nickel Co. of Oregon,<sup>11</sup> U.S.A. Smelting is carried out in electric arc furnaces although vertical shaft furnaces are also used to a limited extent.

Le Nickel's smelter at Doniambo is presently producing half of its nickel in the form of ferro-nickel. The silicate ore is calcined and preheated in a rotary kiln, the hot ore is smelted with restricted amount of coke breeze in an electric arc furnace provided with 3 one-row electrodes, chromite lining and a closed arch. The ore is fed through a hole in the arch along the wall, as in the copper smelting reverberatory practice. To avoid excessive reduction of iron and silicon, a current of 10 amps/cm<sup>2</sup> electrode cross section is recommended. Electrodes are of small cross section and operate with an open arc and almost without immersion in the slag. Exact batching of the ore charge is the next important factor. Coke addition is restricted to 2-3% of the charge to reduce all the nickel and a part of iron. Restricted coke addition leaves sufficient

iron, silica and magnesia for slag formation. In case of high magnesia ores, addition of small proportion of lime is helpful in bringing down the slag melting point. The slag leaving the furnace contains up to 0.4% Ni and the produce is a ferro-nickel containing 24% Ni, 0.3-0.4% S, 2% C, 0.03% P, 1.6% Cr, 3% Si and the rest iron. The metal is first desulphurised under reducing conditions in ladles and subsequently blown in a converter to remove chromium, silicon, carbon and phosphorus. The refined ferro-nickel contains 29% Ni, 0.02% (max.) of S P C, and Si and the balance iron.

Ferro-nickel production in Japan is based on New Caledonian silicate ores. Three of the smelters use electric furnaces while a fourth uses a blast furnace for production of ferro-nickel containing 20-30% nickel. Refining of ferro-nickel is carried out by desulphurisation in ladles followed by a converter practice either in the Bessemer or in L.D. Another Japanese concern, Messrs Nippon Yakin Kogyo Company uses the New Caledonian ores but utilises a rotary kiln practice very similar to the Krupp-Renn process for iron ores. The ore mixed with coke and a flux is fired in a rotary kiln while the reduced iron and nickel coalesce to form nodules called 'luppen' which are separated from the slag by grinding and gravity separation as well as magnetic separation. The 'luppen' are further refined in an electric furnace.

The Societe Miniere et Metallurgique Larco S.A. associated with Le Nickel has started operation of their plant at Larymma, Greece. The process involves pre-reduction and pre-heating of ore in a rotary kiln followed by electric smelting and refining in a L.D. converter to a 90% Ni-grade metal.

The Brazilian silicate ore containing about 2% Ni and 6% Fe is converted to 30% Ni-grade ferro-nickel by the Le Nickel process at Pratapolis in the smelter of Messrs Morro do Niquel. The desulphurisation of ferro-nickel is carried out either by lime-fluorspar treatment in an electric furnace, or by soda ash in the ladle. The metal is finally oxygen-blown in LD-converters to 80% Ni-grade ferro-nickel.

The lateritic ores of Riddle containing 1.4% Ni, 8-15% Fe, 25-35% MgO, 45-55% SiO<sub>2</sub>, 0.02% CO, 2% Al<sub>2</sub>O<sub>3</sub>, 1.5% CaO, and 1.5% Cr<sub>2</sub>O<sub>3</sub> are treated by the Hanna Nickel Smelting Company at Riddle, Oregon. The process is essentially a modified Uginde Process consisting of initial melting of the ore followed by selective complete reduction of nickel and a part of iron by controlled quantity of ferro-silicon. Melting of the ore is carried out in an electric arc furnace while a part of Fe<sub>2</sub>O<sub>3</sub> is reduced to FeO stage also. The molten ore is treated with ferro-silicon in mixing type of ladles and the resulting ferro-nickel is refined in an electric furnace. The ferro-nickel produced contains on average 48.5% Ni, 0.5% Co, 0.1% Cu, 0.005% S, 0.01% P, 0.02% C, 0.02% Cr, 0.9% Si, and balance iron.

### (c) Hydro-metallurgical methods

Two different commercial processes are followed for

hydro-metallurgical extraction of nickel: the Nicaro Process for Cuban lateritic nickel ores,<sup>12</sup> and Free Port Sulphur Process for Moa Bay lateritic nickel ores.<sup>13,14</sup>

The Cuban laterite ores containing 1.43% Ni, 0.1% Co, 39% Fe, 8% MgO and 14% SiO<sub>2</sub> have been exploited successfully at Nicaro. The Cuban process involves low temperature solid state reduction of the lateritic ore, to reduce nickel oxide to metallic state, with producer gas followed by ammoniacal leaching under atmospheric pressure to extract nickel in the form of a soluble nickel ammonium complex. The nickel ammonium carbonate solution is decomposed to insoluble basic nickel carbonate that is collected and ignited to nickel oxide. The nickel oxide so obtained is briquetted with coke and reduced to produce metallic nickel. The plant produced over 16 000 tonnes of nickel oxide annually.

The Free Port Sulphur Company treats by an acid process the Moa Bay lateritic ore containing 1.35% Ni, 0.15% Co, 0.8% Mn, 2.9% Cr<sub>2</sub>O<sub>3</sub>, 3.7% SiO<sub>2</sub>, 1.7% MgO, 8.5% Al<sub>2</sub>O<sub>3</sub> and 47.5% iron. The ore is leached with sulphuric acid under pressure at about 250°C to extract 95% of nickel along with other impurities. The process liquor is purified and the nickel is precipitated either as sulphide for further refining or as metal by hydrogen reduction in an autoclave.

Other processes used for treating lean oxidised ores are still of academic interest. These methods include acid leaching of the ores, sulphation<sup>20</sup> or chlorination<sup>21</sup> followed by aqueous leaching. The nickel industry is now at the verge of a revolution as low-grade ores have attracted considerable attention and it is not unlikely that some of the methods now at the laboratory stage will turn up as full-fledged processes for commercial production of nickel.

The high grade sulphide ores have long been smelted to matte and further refined to nickel in a series of refining stages. The low-grade Cu-Ni-ores have, however, been treated in Canada, at Sherrit Gordon Mines, Fort Saskatchewan, using a hydro-metallurgical technique, where the nickel concentrate is pressure leached with ammonia to yield soluble amines of Ni, Cu and Co. The metals are subsequently recovered from the solution by hydrogen reduction under pressure as metal powders.

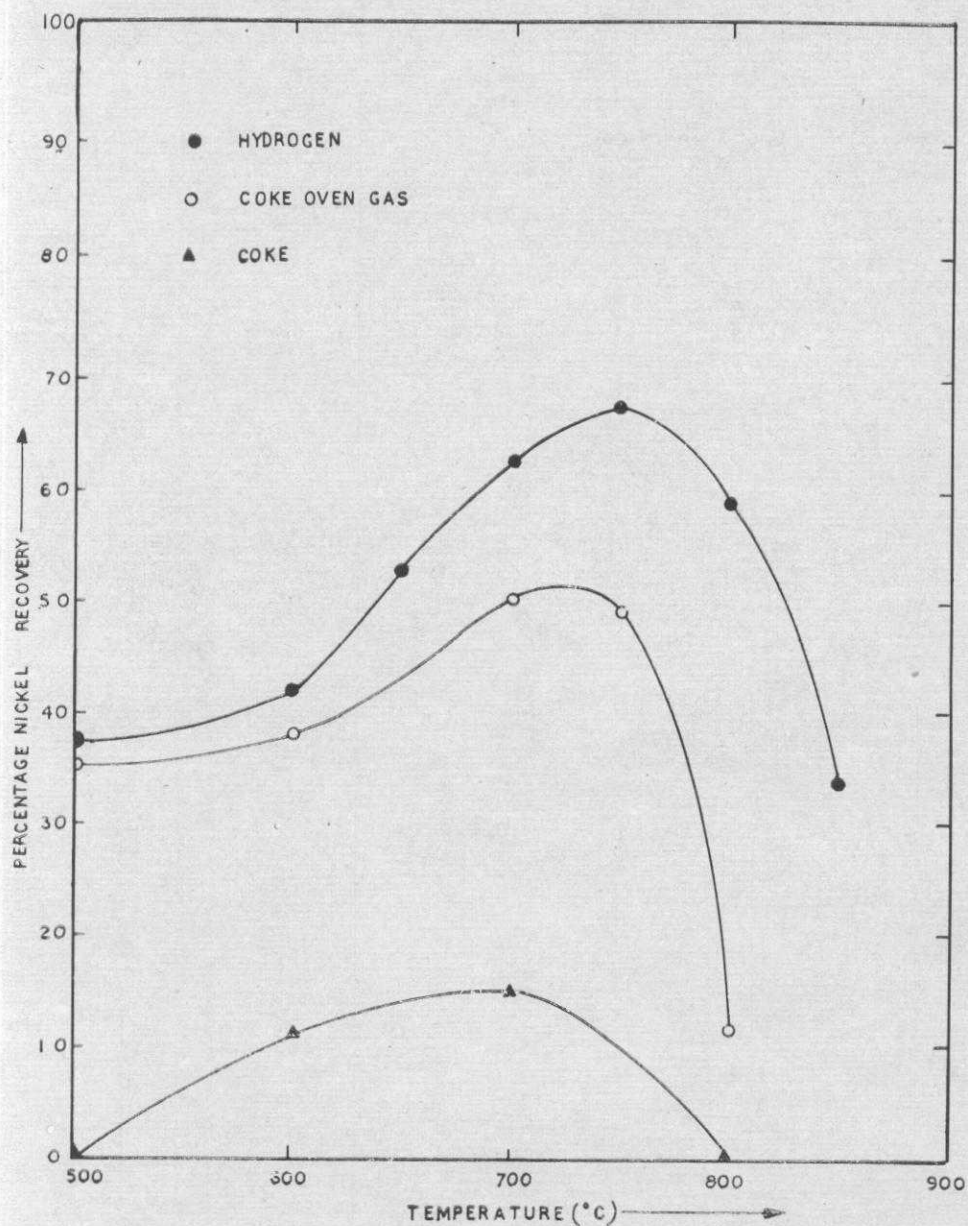
The smelting processes for production of ferro-nickel or nickel matte are not suitable for Indian ores containing 0.2 to 1.4% nickel, partly because of the extremely low nickel content and partly due to a relatively high Fe/Ni ratio.

### Process adopted by NML

Roast reduction followed by ammoniacal leaching appears to be the most suitable process for treating both silicate and lateritic nickel ores available indigenously and investigations were therefore, conducted at National Metallurgical Laboratory on these lines.

### Results of laboratory scale studies

Laboratory scale investigations have been completed at



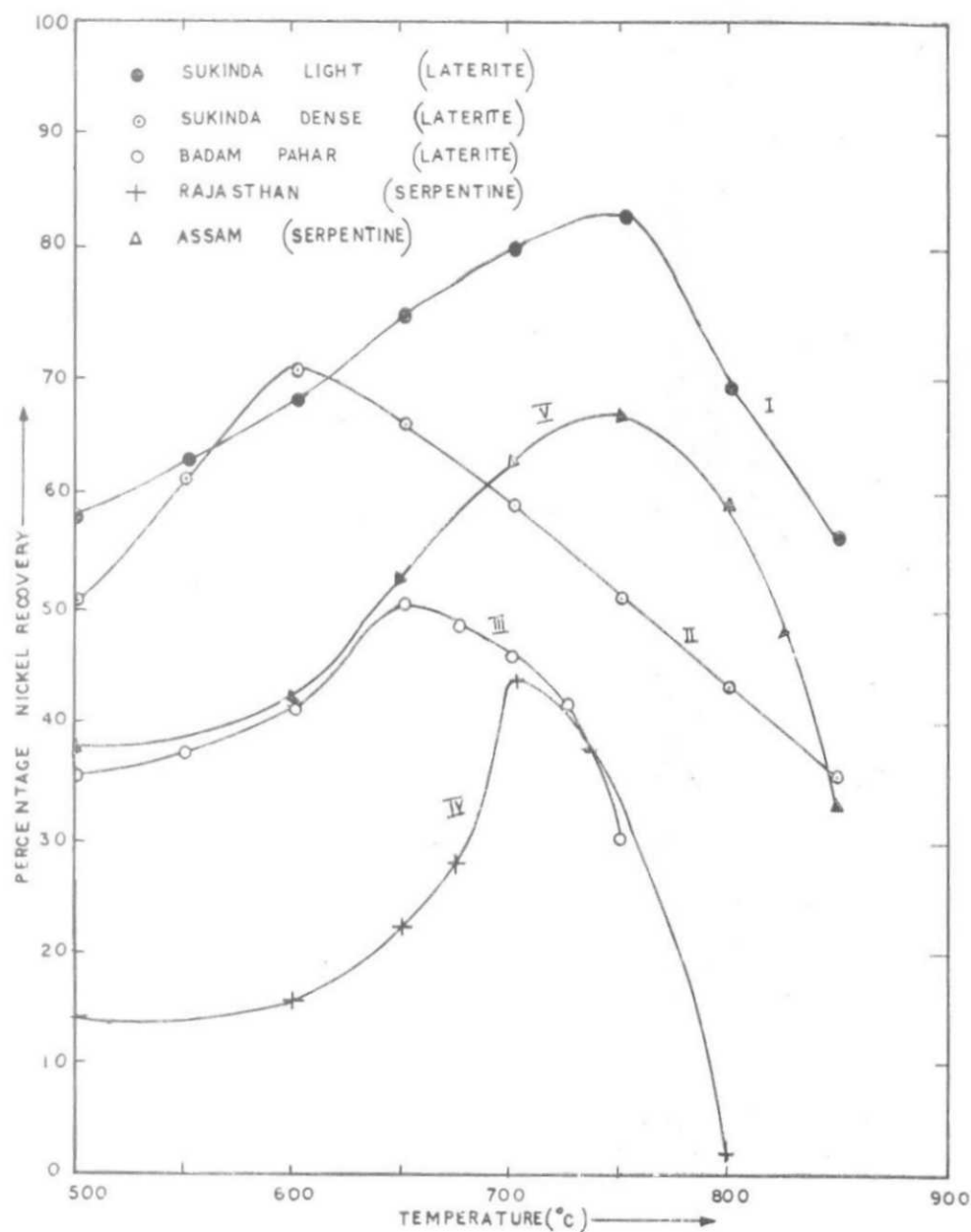
2 Effect of different reducing agents on nickel extraction

the National Metallurgical Laboratory, to treat the serpentinous and lateritic nickeliferous ores from Assam,<sup>2</sup> Orissa<sup>3,4</sup> and Rajasthan.<sup>5</sup> The process studied consists of solid state roast reduction followed by ammoniacal leaching as the ores are not amenable to physical methods of beneficiation.

Reduction of nickel ores was studied with coke, hydrogen and coke oven gas. A comparison of reduction efficiencies of various reducing agents for the serpentinous ore from Assam is shown in Fig. 2. It is observed that coke is the least effective as reducing agent for extraction of nickel and only a maximum of 15% nickel could be recovered. Gases are more efficient reducing agents than a solid reductant such as

coke, owing to their diffusivity, resulting in a faster reduction rate. The maximum nickel recovery was 50.7% with coke oven gas, while up to 67.4% nickel recovery was observed using hydrogen for reduction.

The effect of temperature of reduction on nickel recovery using hydrogen for reduction has been recorded in Fig. 3 for the different nickel ores investigated at National Metallurgical Laboratory. It is observed that with the increase of reduction temperature the nickel recoveries increase and reach a maximum and thereafter the recovery falls with further rise in temperature. The optimum temperature of reduction varies between 500°C and 750°C depending on the ore sample investigated. Table III records the optimum reduction



3 Effect of temperature of reduction on nickel recovery

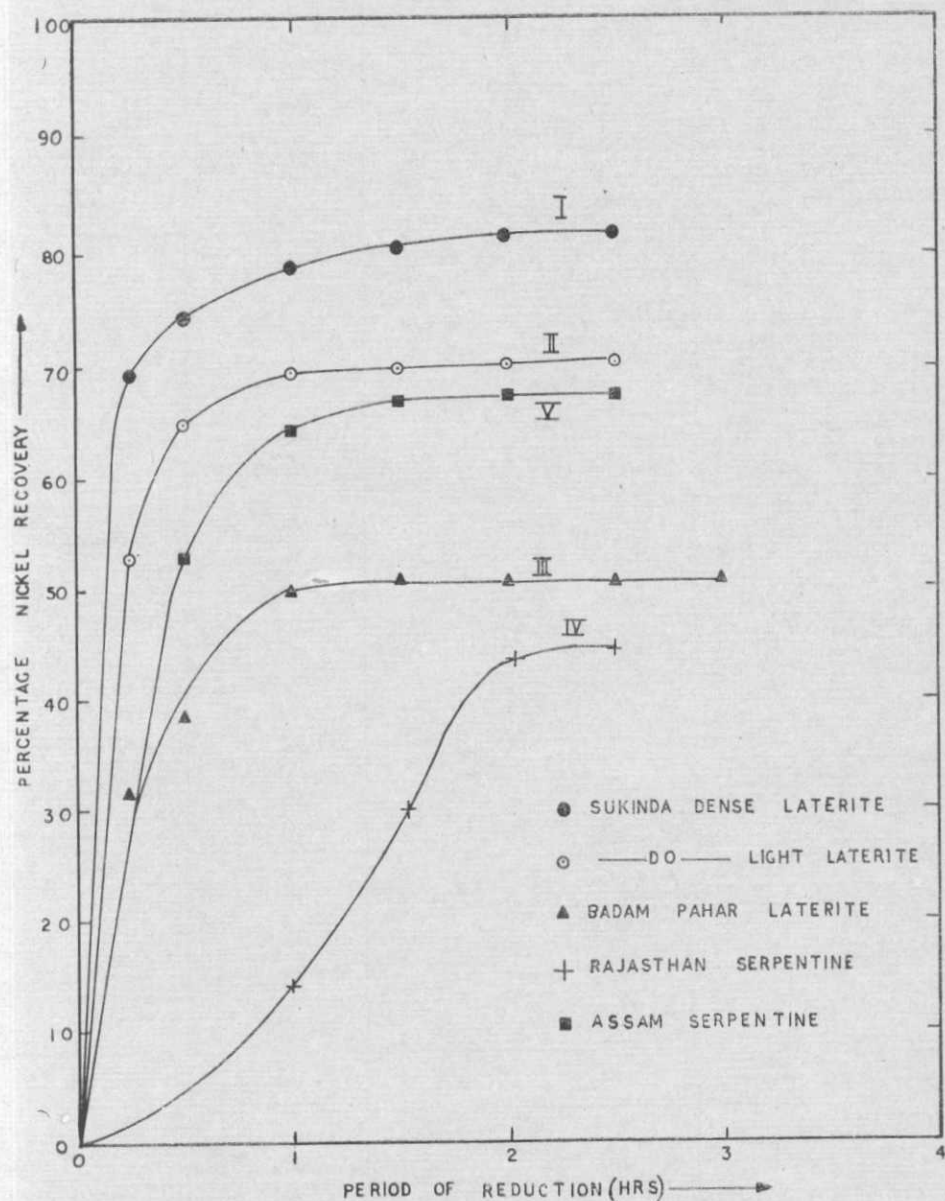
TABLE III Optimum temperatures for reduction of nickel ores with hydrogen

Sl. No.	Ore source	Type of ore	Optimum temperature °C
1.	Sukinda (Orissa)	Laterite (Light)	750
2.	do	do (Dense)	600
3.	Badam Pahar (Orissa)	do	650
4.	Moreh (Assam)	Serpentine	750
5.	Ranakpur (Rajasthan)	do	700

temperatures for reduction of the different ores indicated therein.

The decrease in nickel recovery beyond the optimum temperature of reduction is evidently due to simultaneous iron reduction and consequent alloy formation between iron and nickel since nickel is leached readily with ammoniacal solution, whilst the iron-nickel alloys are not amenable to such leaching.

It has been shown by the authors<sup>15,19</sup> that mineralogical changes occurring on heating serpentine ore help nickel reduction. The density and porosity of the ores determine the proximity of iron and nickel in the reduced ores and the denser ores thus assist the iron-nickel alloy formation. As a consequence, the optimum temperature for reduction is lower for denser grade



4 Effect of period of reduction on nickel recovery

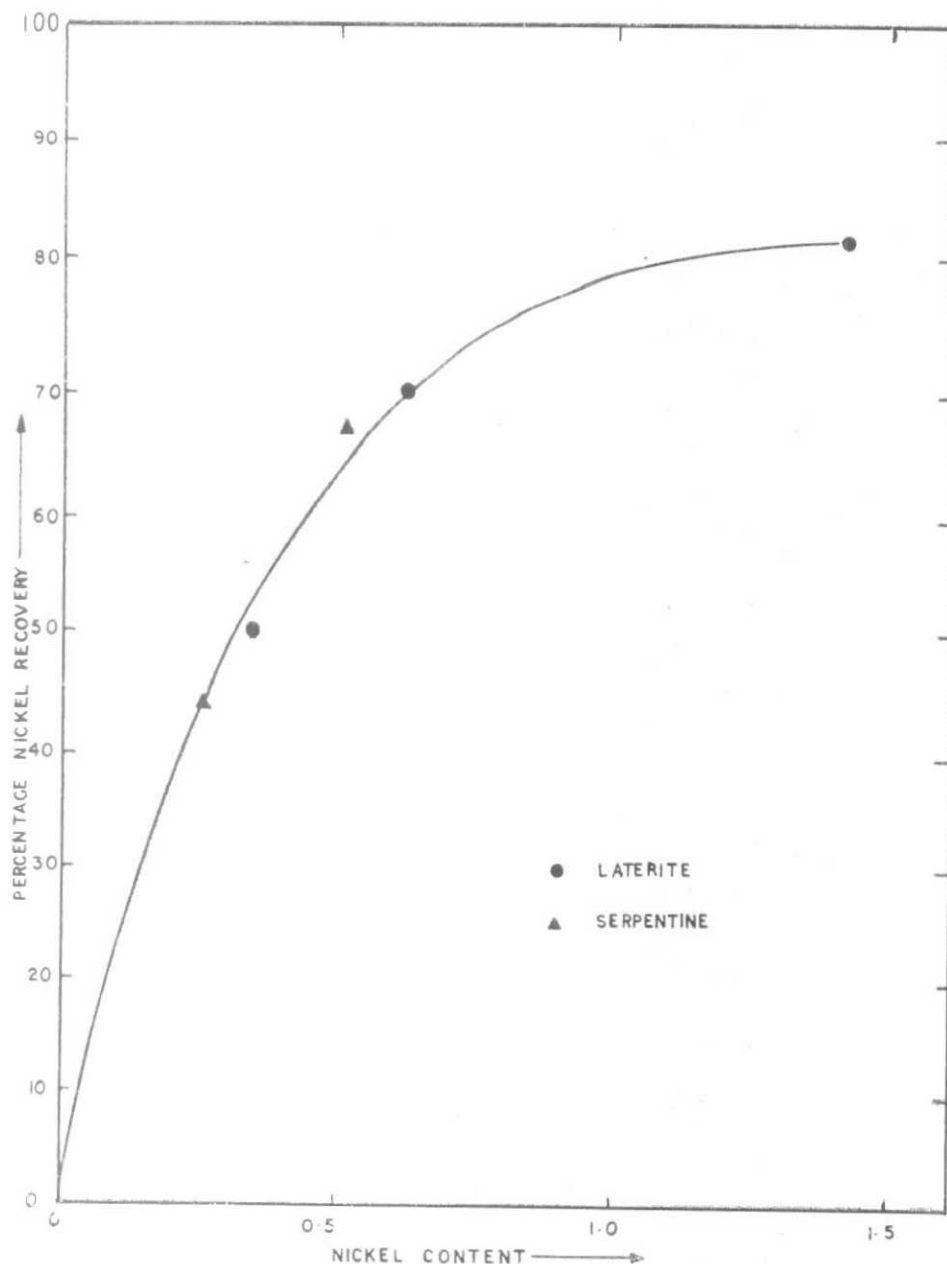
ores than for porous and hydrated ores. The reduction of nickel ores thus depends as much on the physical nature of the ores, as on their chemical composition.

Reduction studies were carried out with different particle sizes of these ores at the optimum temperatures and it was observed that, in general, finer grinding helps in better nickel extraction. The optimum particle size of the ores with the extent of nickel recoveries for different ores studied are recorded in Table IV.

It was seen that the light grade laterite from Sukinda, Orissa, due to its higher porosity, yields as much as 80.81% nickel at a crushing size of -25 mesh (BSS), while the denser lateritic ores were to be crushed to

TABLE IV Optimum particle sizes of oxidised ores for nickel extraction

Sl. No.	Source of ore	Ore type	Optimum particle size (B.S.S.)	% Nickel recovery
1.	Sukinda	Laterite (Light)	- 25	80.81
2.	Sukinda	do (dense)	-100	70.36
3.	Badam Pahar	do	-170	50.63
4.	Moreh	Serpentine	-200	70.00
5.	Ranakpur	do	-200	43.95



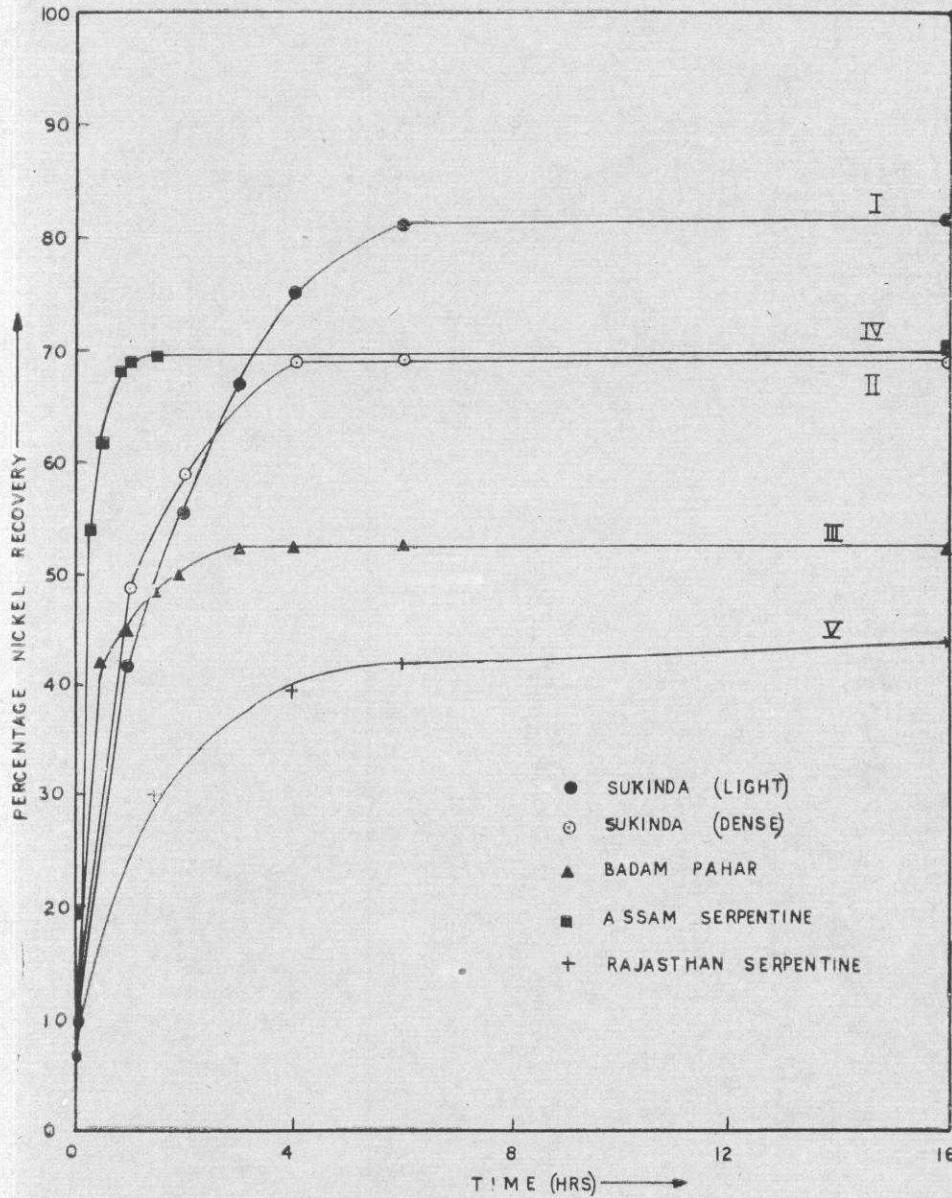
5 Maximum nickel extraction as related to nickel content of ore

-100 or -170 mesh (BSS) sizes. The serpentines, on the other hand, required a higher degree of comminution i.e. -200 mesh (BSS) for optimum nickel recoveries. There was a slight improvement in the nickel recoveries when the ores were ground to still finer sizes than those recorded in Table IV, but the optimum sizes have been established on a realistic basis where disadvantages in fine grinding are likely to somewhat counteract the slight gain in nickel recovery.

The kinetics of reduction of nickel in different oxidic ores were studied under optimum conditions of temperature and ore sizes and the results have been represented in Fig. 4. All the ores, excepting the nickeliferous serpentine from Rajasthan, have been found to

be reduced almost completely within 1 to 1½ hours. The lateritic ores have been found generally more readily reducible than the serpentinous ores right from the initial stage, while the maximum nickel recoveries are independent of the mineralogy of the ore. It is observed that the higher the initial nickel content of the ore the higher is the maximum nickel recovery recorded. Based on the experimental result, a plot of maximum nickel recovery as a function of nickel content of the ore has been made in Fig. 5. It is conclusive from Fig. 5 that for commercial feasibility, where at least 60% of the nickel should be recovered, an ore with less than 0.43% nickel content will not be suitable for the process of roast reduction and ammoniacal leaching.



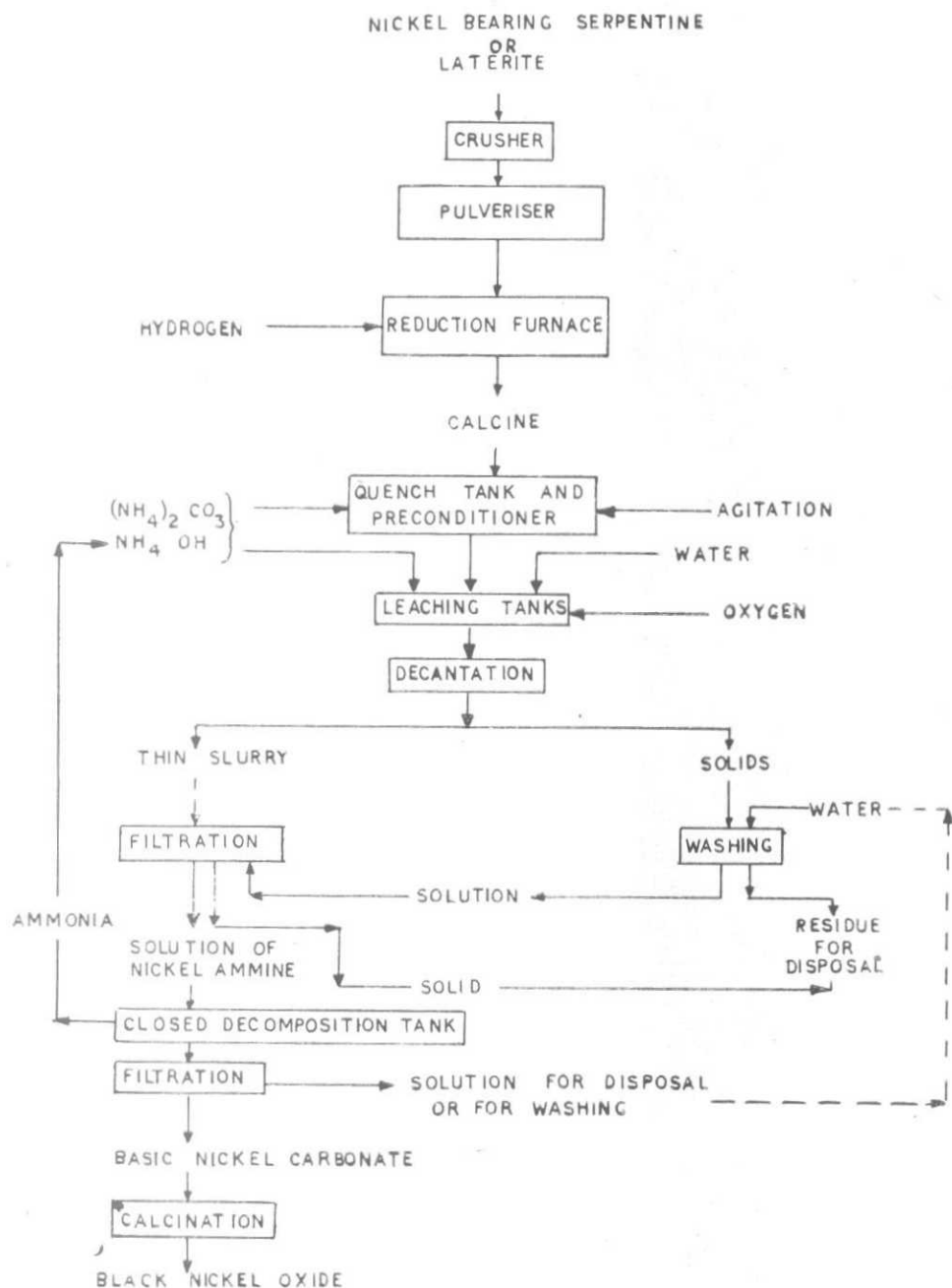


6 Kinetics of leaching of nickel ores

The reduced nickel ores containing appreciable amounts of reduced iron necessitate a pre-treatment before ammoniacal leaching where the metallic iron is converted to hydrated iron oxide by aqueous oxidation. The hydrated iron oxide thus formed is easily separated from the ore matrix in the slurry and helps dissolution of the nickel in a subsequent stage by opening up most of the sites for nickel. Aqueous oxidation of iron from various nickel ores has been studied in presence of concentrated ammonium hydroxide with a relatively thick slurry consistency. The pre-conditioning liquor usually contained 20% ammonium carbonate in  $\text{NH}_4\text{OH}$ . Slow agitation of the thick slurry brings the ore particles constantly to the surface for reaction with

air. The kinetics of iron oxidation and nickel dissolution during the pre-conditioning stage have been studied for various nickel ores and it was observed that within half an hour most of the metallic iron is oxidised to hydrated iron oxide, while nickel dissolution is restricted to only less than 10% during this stage.

The pre-conditioned slurry was leached in presence of oxygen, in a thinner slurry consistency with a leachant consisting of 7.5% ammonium hydroxide. The solid/liquid ratio of the slurry during leaching is maintained at 1:8 and the kinetics of leaching for the different ores have been shown in Fig. 6. It is observed that leaching is complete within six hours. The serpentine ore from Assam could be leached in less than two



7 Flowsheet for nickel extraction using indigenous low grade ores

hours, the lateritic ore from Badam Pahar took three hours, the dense grade Sukinda laterite took four hours, while the Rajasthan serpentine and Sukinda light grade laterite took six hours for almost complete leaching.

The leach liquor containing the nickel ammonium complex precipitates basic nickel carbonate on boiling the solution for the removal of ammonia. A complete nickel separation is attained at this stage. The nickel carbonate thus obtained has been calcined to nickel oxide, which could be briquetted with coke and reduced

to metallic nickel. Treatment of leach liquor is common irrespective of the nickel ore treated. Investigations have also been made to precipitate metallic nickel in powder form by hydrogen reduction of the leach liquor under pressurised condition and nickel recoveries of above 99% have been attained during the experimental runs.

On the basis of laboratory scale studies on the indigenous ores a flow sheet has been made for pilot scale trial. The flow sheet is shown in Fig. 7.

Besides the studies on ammoniacal leaching, sulphate

tion<sup>20</sup> as well as chlorination<sup>21</sup> studies have also been carried out at the National Metallurgical Laboratory. Recoveries obtained by sulphation of the different lateritic ores were similar to those obtained by ammoniacal leaching. Chlorination of the serpentine ore was carried out with hydrogen chloride and nickel could be extracted with substantial quantities of iron at 1000°C. In view of the short supply of sulphur in India the adoption of ammonia leaching in place of sulphation appears more logical, while chlorination at as high as 1000°C, which is not selective for nickel extraction, cannot be thought to compete with ammoniacal leaching.

#### **Sulphide ore**

Sulphide concentrates from the UCI plant at Jaduguda are also being examined for extraction of Cu, Ni, and Mo. Different methods are under investigation including roasting and leaching under atmospheric as well as higher pressures and encouraging results have been obtained. Further work is in progress.

#### **Nickel recovery from other wastes**

Besides the indigenous ores there are numerous other nickel bearing materials and wastes from which the metal can be extracted. Among these wastes may be included the anode sludge from copper refineries, the spent nickel catalysts used in various chemical plants and nickel bearing metallurgical scraps from heat resistant, electrical resistance, as well as chemical corrosion resistant alloys. Work done at National Metallurgical Laboratory indicated the possibility of nickel extraction from the anode sludge of copper refineries. Considerable tonnage of nickel catalysts are imported for the chemical industries; the deactivated catalyst should either be re-used after re-activation or should be converted to nickel salts for the electro-plating industry. The scraps and swarfs of nickel can be converted to specified utility alloys and already entrepreneurs are coming forward to help in this direction.

#### **Conclusion**

While India is not in a very happy position with respect to its nickel resources, the discovery of a few deposits of workable nature provides sufficient incentive to initiate indigenous nickel production. The nickel deposits have not been properly scaled as yet but preliminary estimates have shown the occurrence of over 8 million tonnes of laterite ores in the chrome ore belt of Sukinda, Orissa and an equally vast reserve of serpentine in Assam. The nickel ores of Rajasthan have been found too poor in nickel but if further explorations find sizable deposits of ores containing over 0.43% nickel, it will be worthwhile considering the utilisation of such ores for exploitation.

The country's need for nickel is growing because of the strategic importance of this metal and also due to the expanding industrialization of the country. To be self-sufficient in nickel the first step would be to exploit the eastern zone nickel deposits of both oxidic and sulphidic nature. The future expansion of such an industry may require imported ores. The world is witnessing today the speed with which the producers in advanced countries are expanding their capacities on the basis of foreign low-grade deposits. Japanese, entrepreneurs are collecting Indonesian, Australian or New Caledonian ores; Canadian producers have concentrated their supplies from South and North America as well as from New Caledonian deposits. Now that India has found her own resources, it will pay the country richly to have its own nickel refinery. National Metallurgical Laboratory has initiated studies on such project and it is hoped that in the not too distant future, the foundation stone will be laid on Indian soil for the Nickel Industry.

#### **Acknowledgement**

The authors are thankful to Dr T. Banerjee, Scientist-in-Charge, National Metallurgical Laboratory, for his help in preparing this paper. Thanks are also due to their collaborators, Miss S. Samanta and Mr M. S. Mahanty for their experimental work in various stages of the project.

## Discussions

Mr M. Totlani (Bhabha Atomic Research Centre, Bombay) :

1. The conditions in a batch scale operation are quite different from those in a continuous operation. I would like to know whether any studies were carried out on a continuous operation to test the data collected from batch scale studies and on what scale the batch scale studies were carried out.
2. The term lateritic deposit, is a generic term, applied to the deposits that are formed by the process 'Laterite weathering'. These deposits generally contain two types of ores; a limonite type that occurs in the upper zone of a lateritic deposit and the silicate type formed at greater depths during laterization process. In view of this, I would request the authors to give some more details on the type of silicate ores they are referring to while they state that lateritic ores were found to be more reducible than the silicate ores.

Mr P. P. Bhatnagar (Author) :

1. It is true that for commercial exploitation of the process continuous operation tests have to be carried out. We have done only batch scale tests using 50-100 grams of the sample. It is planned to carry out continuous operation tests in the near future.
2. We do agree with Mr Totlani on his comments but we would like to mention that the lateritic ores and silicate ores referred to in the text are from different deposits and not from the same ore body. They do not relate to the type of occurrence as suggested by Mr Totlani. The lateritic ores referred to are from Sukinda and Badam Pahar and contained 7-17%  $\text{SiO}_2$ . The nickel in lateritic ores has been presumed to occur as  $(\text{Fe, Ni}) \text{O}(\text{OH}) \cdot n\text{H}_2\text{O}$  as already mentioned in the text. The silicate ores referred to are from Assam and Rajasthan and contained 38%  $\text{SiO}_2$  on the average. The nickel in silicate ores can be regarded to occur in combination with  $\text{SiO}_2$  as a silicate and of the general formula  $\text{NiSiO}_3, m\text{MgSiO}_3, n\text{H}_2\text{O}$ . The silicate ore from Assam was taken from ultra-basic origin. The rock consisted chiefly of lenticular and fibrous antigorite traversed by veinlets of chrysotile whilst the ore from Rajasthan was in the form of greenish white lumps with visible scattered brownish veins on the lump surface.

Mr Sunil Dey (Chemical and Metallurgical Design Co. P. Ltd., New Delhi) :

1. Does Sukinda ore contain an average of 1.8% NiO?
2. Have the authors examined beneficiation of lateritic ore by washing or froth flotation?
3. Hydrogen gas reduction would be expensive. Were trials made with reformed gas containing  $\text{CO} + \text{H}_2$  for reduction?
4. What is the purity of nickel powder obtained at NML during the hydrogen reduction of nickel ammine sulphate?
5. Was any catalytic agent used for hydrogen reduction of nickel ammine sulphate?

Mr P. P. Bhatnagar (Author) :

1. 1.8% NiO content is not the average in Sukinda ore. The two representative lateritic samples received by us from Sukinda of which one is light and the other a dense variety, analysed 1.8% NiO and 0.7% NiO respectively. The average will work out to be 1.25% NiO.
2. Physical beneficiation of lateritic ores was tried by the ore dressing division of the National Metallurgical Laboratory and was not successful in view of the uniformly close occurrence of nickel in the entire ore matrix and eventual inter-locking of metallic particles.
3. Thermodynamic data revealed that carbon monoxide is the best reducing agent at lower temperatures though it has been experimentally observed that hydrogen results in maximum recoveries. The improved recoveries due to hydrogen reduction are evidently due to its faster diffusion rate when it is alone than when it is mixed with carbon monoxide. Further, carbon deposition on the particle surface during the use of coke oven gas, either due to decomposition of carbon monoxide to carbon dioxide and carbon or due to cracking of hydro-carbons, interferes with the gaseous reduction.
4. Nickel powder obtained after hydrogen reduction of the nickel ammine solution resulted in 99% purity.
5. The effect of different catalytic agents during hydrogen reduction of nickel ammine solution is being investigated at National Metallurgical Laboratory.