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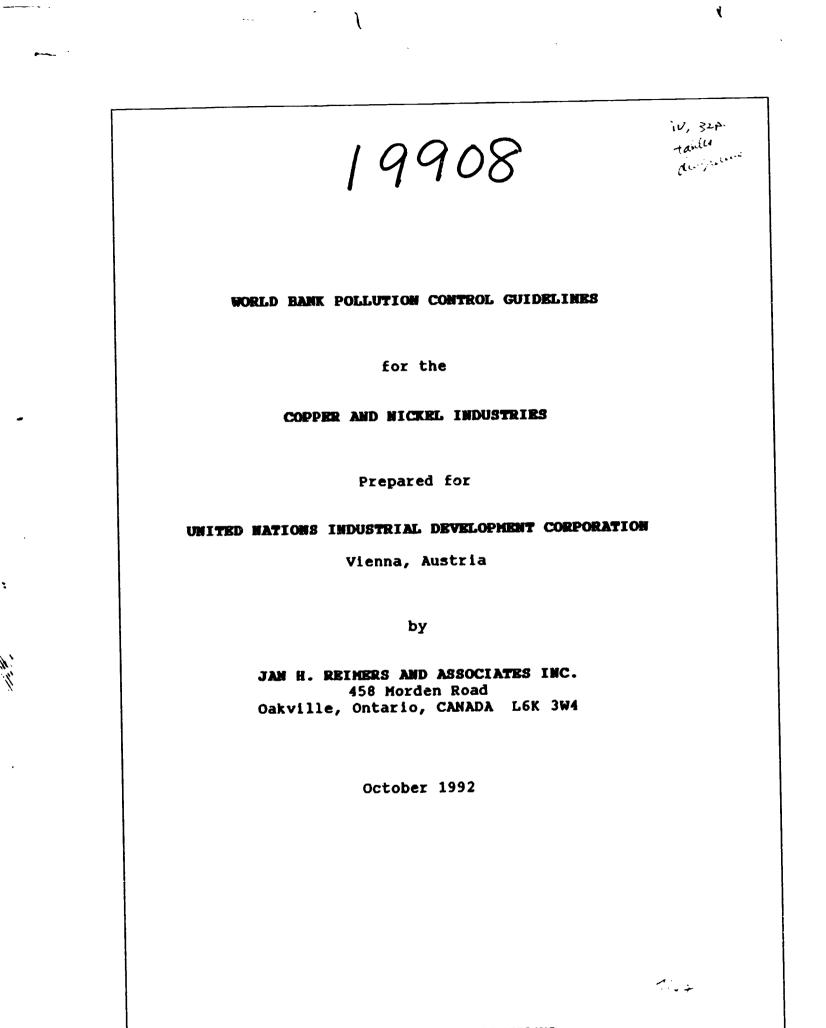
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WORLD BANK POLLUTION CONTROL GUIDELINES

for the

COPPER AND NICKEL INDUSTRIES

Prepared for

UNITED NATIONS INDUSTRIAL DEVELOPMENT CORPORATION

Vienna, Austria

by

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1.1 INTRODUCTION

1.1.1   Copper is frequently found in association with nickel in sulfide mineral deposits. Mining methods and mineral processing equipment are the same for each ore with only certain operating parameters being adjusted to accommodate the specific mineral and produce a concentrate. In addition, the basic design of the equipment used in the smelting of sulfide concentrates is the same for each metal. Only as processing proceeds through to refined metal do the processes and technology diverge.

1.1.2   This document will summarize the more common smelting and refining processes for both copper and nickel, in particular where the processes differ. In the case of sulfide ores or concentrates, the emission of sulfur dioxide (SO_2) to the atmosphere and working environment is the major environmental concern. Oxide ores do not contain significant amounts of sulfur, but dust, soil erosion and associated hazards are a concern. Where mineral dressing and hydrometallurgical processes are used in place of smelting or in conventional refining, the treatment of liquid effluents and the safe disposal of the various residues are the principal concerns.

Environmental Impacts of Copper Production

SOURCE: Office of Technology Assessment

1.2   MINING AND MINERAL PROCESSING

1.2.1   For low grade deposits of either sulfide or oxide ores, the open pit method is the most practical and lower cost system for the mining of large tonnages of ore. Large track-mounted drills prepare the ore for blasting, and the broken ore is hauled to the crushing plant by truck or conveyor. Higher grade orebodies are normally mined by underground methods. Vertical shafts are sunk below the surface adjacent to the ore deposit and tunnels are extended to the ore. Pneumatic drills and mechanized equipment drill and blast the ore which is hoisted through the shaft to the crushing plant.

1.2.2   Mineral processing (1) continues the crushing of ore received from the mine and ends with fine grinding to ensure that the copper or nickel minerals are liberated from waste materials. In cases where the next process step is leaching (most frequently in the case of oxide copper ores), the ore needs only to be ground to the extent required to expose the mineral surfaces to the leaching agent. For sulfide ores, selective flotation normally follows grinding.

1.2.3   In the flotation process, the finely ground ore is mixed with water and special reagents (some of which may be toxic), and agitated by mechanical and pneumatic devices. These produce air bubbles in the ore-water mixture, known as "slurry". The reagents provide an attraction between the surface of specific minerals and the air bubbles. As the bubbles rise to the surface they carry these minerals with them, leaving unwanted minerals to be discarded as a waste, known as "tailings". Collection of the froth from the surface of the flotation cells yields a concentrate which is dewatered and filtered to produce a low moisture filter cake for further processing in an appropriate smelter.

1.3   COPPER MANUFACTURING PROCESSES

1.3.1   Mineral processing and/or feed preparation are the first stages of the manufacturing process. The second involves either smelting or leaching and removes additional impurities, in particular iron and sulfur, further concentrating the values. The third and final stage is refining, usually electrorefining, which removes the remaining impurities, minor elements such as precious metals, and produces a 99+% pure copper.

1.3.2   The smelting of untreated or "green" concentrate is no longer acceptable from the point of view of energy efficiency or the environment, and is being phased out of industry practice.

Modern technology (2) utilizes roasting to eliminate some of the sulfur and volatile impurities such as arsenic or mercury, or the concentrate will be dried to remove excess moisture. Fuel oil, natural gas, steam or preheated process air will supply heat to the dryer. As shown in Figure 1, the concentrate is then combined with copper-bearing residues, precipitates, etc., and a controlled amount of flux and fed to the smelting furnace.

FIGURE 1.

COPPER SMELTER PROCESS FLOW DIAGRAM

1.3.3   The flash smelting process (1)(2) has now become the industry standard, although the electric furnace is still used in particular cases.   In flash smelting, the dry furnace feed mix, containing less than 1% moisture, is fed to the furnace along with preheated air, oxygen-enriched air (30 to 40% O_2), or pure oxygen. The iron and sulfur are oxidized, and the heat generated by the exothermic reactions can be sufficient to smelt concentrate to produce a liquid matte (35 to 65% Cu) and a fluid slag. Normal smelting furnace temperatures are in the range of 1250°C to 1350°C. While flash smelting is the most common process, there are others which use lances in place of burners or reactors of various types, all designed to efficiently utilize the heats of reaction and contain emissions to the atmosphere.

1.3.4   The furnace matte still contains iron and sulfur. These are oxidized in the converting step to sulfur dioxide and iron oxide by injecting air or oxygen-enriched air into the molten bath. With the addition of a flux, the iron and other oxides form a slag which floats and is skimmed from the surface, as is the case during smelting. Secondary copper (scrap) is frequently used as a coolant to control temperature. The converting process can be either batch or continuous, depending on the technology adopted. The product is normally a blister copper (98.5% Cu, 0.8% O_2).

1.3.5.   In countries where there is no significant primary production, secondary copper smelters will operate using processes and equipment similar to those employed in the primary industry to treat copper scrap and residues. The impurities, however, are usually different and many, such as lead, zinc and precious metals, are recovered in the gas cleaning system as byproducts. Organic components may be stripped prior to smelting or left in the feed to provide fuel. In either case, secondary smelters must meet the same environmental and safety regulations as primary smelters.

1.3.6   Due to the intense nature of modern smelting processes, certain auxiliaries are required to maximize the recovery of values and to protect the environment. Slags are cleaned prior to discard using slow cooling and flotation or, alternatively, an electric furnace to minimize losses and recover the copper values as a concentrate or electric furnace matte. Process gases are cooled using air-to-gas heat exchangers or waste heat boilers prior to the removal of particulates in an electrostatic precipitator or baghouse.   The offgas then receives a final scrubbing in a wet gas cleaning circuit and the sulfur is converted to acid, liquid SO_2 or other sulfur product. The precipitator or baghouse dust frequently must be treated in a separate circuit to control impurity build-up in the smelter and hydrometallurgical processes have been developed for the purpose. Disposal of some of these bleed stream products can be a problem, particularly those containing antimony, arsenic or mercury. Collection and containment of the various vent gases is necessary in a modern smelter and in some cases, they must be scrubbed with lime or other alkali to remove SO_2.

1.3.7   The final smelting or first refining process is fire refining, where blister copper goes through an oxidation-reduction process to produce copper anodes (99.5% Cu) for electrolytic refining. Depending on the reductant used, afterburners may be required on the offgas system to ensure complete combustion.

1.3.8   The most common hydrometallurgical processes leach the input with ammonia or sulfuric acid to extract the copper, particularly from oxide ores. These processes can operate at atmospheric pressure or as pressure leach circuits. Leaching of low grade deposits "in-situ" or as heaps of ore, is very efficient and becoming more common in the case of copper. The hydrometallurgical processes overcome the problem of sulfur dioxide emissions, but effluent treatment of solution bleed streams and disposal of the residues are environmental concerns. Intermediate sulfur compounds can be formed and an oxy-hydrolysis circuit is required to protect the environment. In addition, the ability to recover byproduct precious metals is limited with hydrometallurgy, restricting its application to materials low in precious metals. Solvent extraction or ion exchange technologies have been improved to the point where most leach solutions can be upgraded to a level where the metal values can be recovered by electrowinning. In this process, copper is plated onto cathodes from a leach solution containing 20 to 50 grams Cu per liter (gpl) and 30-150 gpl free sulfuric acid in electrowinning cells equipped with inert anodes, usually lead.
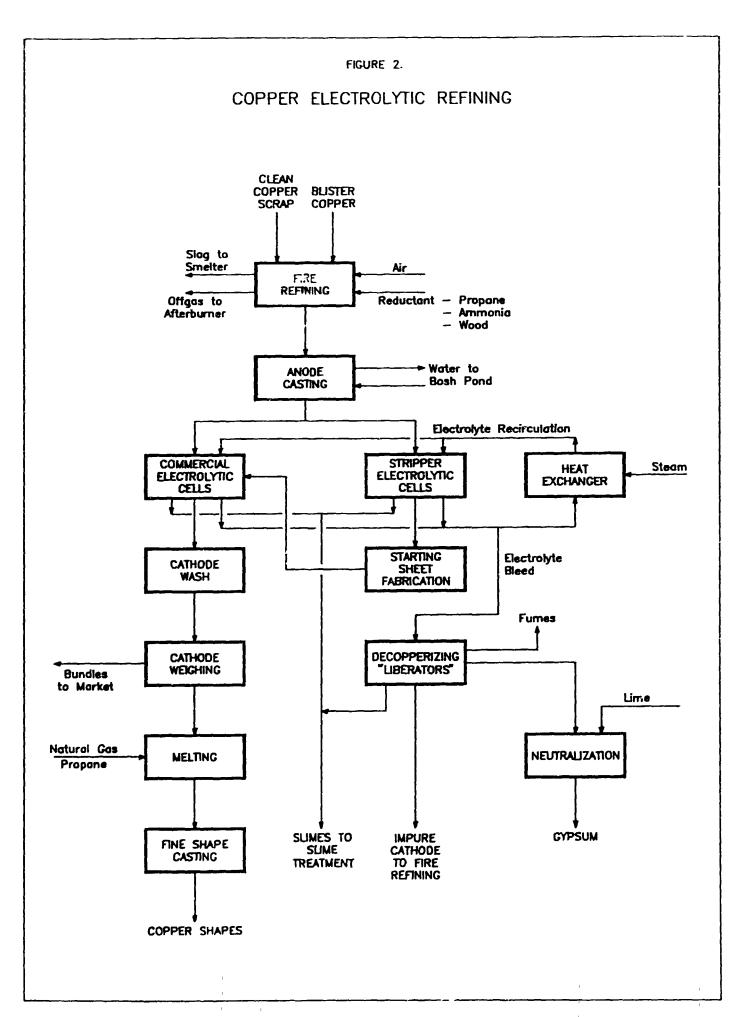
1.3.9   Most copper is refined using the electrolytic process. Here, copper is plated from impure copper anodes onto pure copper starting sheets (cathodes), both immersed in a copper sulfate-sulfuric acid solution, when an electric current passes through the solution (Figure 2). Impurities such as selenium, precious metals, etc. settle to the bottom of the electrolytic cell and are removed periodically for further treatment. In the majority of cases, cathode copper of more than 99.9% Cu purity is produced in the electrolytic process; however, it requires more careful process control to achieve the same level of purity with the electrowinning process.

1.3.10   Residues, precipitates. etc. from a refinery are usually returned to a smelter for the recovery of values, consequently, the environmental concerns are limited in most cases to the emission of fumes and the relatively small volume of liquid effluents.

FIGURE 2.

COPPER ELECTROLYTIC REFINING

1.4   NICKEL MANUFACTURING PROCESSES

1.4.1   Primary nickel is produced from two very distinct types of ore.
Sulfide deposits are very similar to, and frequently found in conjunction with,
copper ores. The second ore type is oxide, which is commonly referred to as a
"laterite" ore and is normally found where the climate is tropical. This type
of climate over time breaks the rocks down to soil or clay. The weathering
process will extract nickel, when present, and deposit it in layers at varying
depths below the surface; this process is known as "lateritic weathering". Unlike
the hard sulfide ores, laterite nickel ores are soft clay-like as a result of the
effects of weathering and form in strata near the surface of the earth.   There
are two main types of these oxide ores: the limonite type is found in the upper
levels of the laterite deposit in which ferric oxide minerals are predominant.
The second is garnerite, which is a silicate type of ore and forms in the lower
layers during the laterization process.

1.4.2   Oxide, or "laterite" nickel ores cannot be concentrated as described
previously for the sulfide ores.   Mining consists of a large earth-moving
operation using electric shovels, front-end loaders and off-road trucks – much
the same equipment as in conventional open pit mining.   Mineral processing is
confined to screening out and discarding low grade boulders leaving the remainder
of the ore as mined to be processed. Large tonnages of laterite nickel ores must
therefore be processed to achieve reasonable nickel production rates (2). The
choice of processes which can be considered for primary nickel production depends
on which of the major ore types will be used as smelter feed. The major process
steps are summarized in Figure 3.

1.4.3   Nickel Sulfide Processes

1.4.3.1   The smelting processes used for nickel sulfides are very similar to
those described previously for copper. The older nickel smelting processes, such
as the blast or reverberatory furnaces, are no longer acceptable from the point
of view of energy efficiency or the environment, and are being phased out of
industry practice. Modern technology (2) utilizes roasting to eliminate some of
the sulfur and volatile impurities such as arsenic or mercury, or the concentrate
will be dried to remove excess moisture.   Fuel oil, natural gas, steam or
preheated process air will supply heat to the dryer. The concentrate is then
combined with nickel-bearing residues, precipitates, etc., and a controlled
amount of flux and fed to the smelting furnace.

1.4.3.2   The flash smelting process (2)(3) has now become the industry
standard, although the electric furnace is used in particular cases or where
higher smelting temperatures are required. For example, some nickel concentrates
such as laterite ores can be high in magnesia and require high temperatures to
maintain a fluid slag. In flash smelting, dry sulfides containing less than 1%
moisture, are fed to the furnace along with pre-heated air, oxygen-enriched air
(30 to 40% O_2), or pure oxygen. The iron and sulfur are oxidized, and the heat
generated by the exothermic reactions can be sufficient to smelt concentrate to
produce a liquid matte (up to 45% Ni) and a fluid slag. Normal smelting furnace
temperatures are in the range of 1350°C to 1550°C. While flash smelting is the
most common process for sulfide concentrates, the electric furnace is the common
smelting unit for laterite nickel ores. Pressure leaching and other hydro-

metallurgical processes are also used in the nickel industry, particularly in operations where there is no fuel value in the feed materials and the precious metals content is negligible.

1.4.3.3   Flash or electric furnace matte still contains iron and sulfur. These are oxidized in the converting step to sulfur dioxide and iron oxide by injecting air or oxygen-enriched air into the molten bath. With the addition of a flux, the iron and other oxides form a slag which floats and is skimmed from the surface, as is the case during smelting. Secondary nickel-bearing scrap is frequently used as a coolant to control temperature. The nickel converting process is a batch process. The product is a high grade nickel matte (75%).

1.4.3.4   Due to the intense nature of modern smelting processes, certain auxiliaries are required to maximize the recovery of values and protect the environment. Slags are cleaned prior to discard using an electric furnace to minimize losses and recover the nickel values as an electric furnace matte. In cases where there is a reasonable level of cobalt in the smelter feed, the slag cleaning circuit can be adjusted to maximize the recovery of cobalt as a separate byproduct. Process gases are cooled using air-to-gas heat exchangers or waste heat boilers prior to the removal of particulates in an electrostatic precipitator or baghouse. The offgas then receives a final scrubbing in a wet gas cleaning circuit and the sulfur is usually converted to acid. The precipitator or baghouse dust frequently must be treated in a separate circuit to control impurity build-up in the smelter and several hydrometallurgical processes have been developed for the purpose. Disposal of some bleed stream products can be a problem, particularly those containing antimony, arsenic or mercury. Collection and containment of various vent gases is necessary in a modern smelter and in some cases, they must be scrubbed with lime or other alkali to remove SO_2.
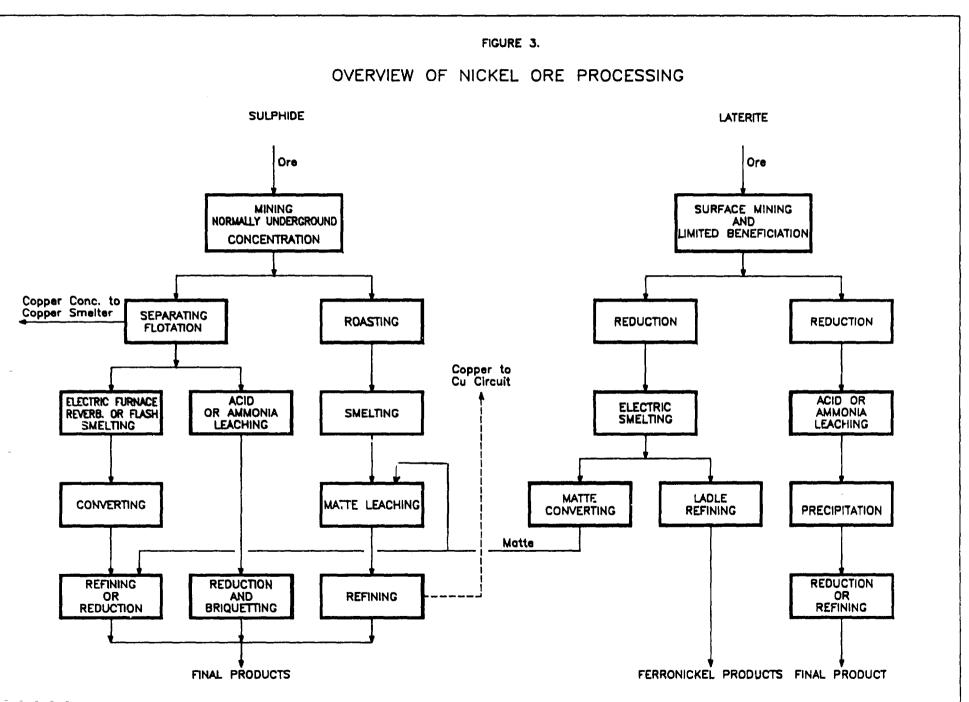
1.4.4   Laterite Nickel Processes

1.4.4.1   Laterite nickel ores have a high percentage of free and combined moisture, and the first step in their processing is the removal of the free moisture. Next, the ore is fed to the reduction furnace to remove the chemically-bound water and reduce the nickel oxide, while controlling the amount of iron oxides reduced. As noted previously, these ores have no significant fuel value and electric furnace smelting is the standard for laterite ores since the reaction heats are not significant and high temperatures in the range of 1500°C are required to accommodate the high magnesia content.

1.4.4.2   Some laterite nickel smelters add sulfur to the smelting furnace charge and produce a furnace matte which is processed in the same manner as matte from sulfide ores. Others will reduce sufficient iron to produce ferronickel products, and this is the process adopted by most laterite nickel operators.

1.4.4.3   Hydrometallurgical processes based on ammonia or sulfuric acid leach are also used in laterite nickel operations. There can be limitations, however. For example, garnerite (silicate type) ores are usually high in acid soluble magnesia, eliminating sulfuric acid leach as an option. The ammonia leach is usually applied to the ore after the reduction roast step which adds to the cost.

FIGURE 3.

OVERVIEW OF NICKEL ORE PROCESSING

SULPHIDE

Ore

MINING
NORMALLY UNDERGROUND
CONCENTRATION

Copper Conc. to
Copper Smelter

SEPARATING
FLOTATION

ROASTING

ELECTRIC FURNACE
REVERB. OR FLASH
SMELTING

ACID
OR AMMONIA
LEACHING

SMELTING

Copper to
Cu Circuit

CONVERTING

MATTE LEACHING

REFINING
OR
REDUCTION

REDUCTION
AND
BRIQUETTING

REFINING

Matte

FINAL PRODUCTS

LATERITE

Ore

SURFACE MINING
AND
LIMITED BENEFICIATION

REDUCTION

REDUCTION

ELECTRIC
SMELTING

ACID OR
AMMONIA
LEACHING

MATTE
CONVERTING

LADLE
REFINING

PRECIPITATION

REDUCTION
OR
REFINING

FERRONICKEL PRODUCTS   FINAL PRODUCT

1.4.5   Nickel Refining

1.4.5.1   Various processes are used to refine nickel matte (4) (5). Fluid bed roasting and a chlorine-hydrogen reduction will produce high grade nickel oxides (95+% Ni). Vapour processes, such as the Carbonyl process, can be used to produce high purity nickel pellets, but nickel carbonyl is very toxic and requires complex systems to ensure safe operation. In this process, copper and precious metals remain as a pyrophoric residue requiring separate treatment. In electrorefining, the process is very similar to that for copper but the electrodes are separated by diaphragm compartments to prevent the passage of impurities from anode to cathode. The electrowinning process, that is, the removal of nickel from solution in cells equipped with inert anodes, is more common with nickel than with copper. In one process a chloride electrolyte is used in the electrowinning cell; the majority, however, are sulfuric acid solutions resulting from leach or solvent extraction processes. In the production of ferronickel (the more common product from laterite operations), refining is a pyrometallurgical process and directed towards the removal of such impurities as sulfur, carbon and phosphorous.

1.5   ECONOMIC AND ENVIRONMENTAL FACTORS IN PROCESS SELECTION

1.5.1   The mineralogy and composition of an orebody and the proposed smelter location all have a significant bearing on which processes can be considered. With respect to location, the following are key economic considerations:

a)   Energy supply and cost, particularly where electric furnace processes or high levels of oxygen enrichment (90%+) are being considered.

b)   Environmental regulations governing the disposal of residues and slag, and the containment of emissions such as sulfur, arsenic, etc.

c)   Design capacity. The capital costs of some of the newer smelting processes are such that a smelting rate of at least 1000 MTPD concentrate is required to be economic.

d)   Byproduct recovery can improve project economics through the sale of aggregate, acid, precious metals and energy.

1.5.2   In connection with Item 1.5.1 (b), some regulations proposed in the past were technically unrealistic and would, if instituted, make many modern processes uneconomic. Care must be taken to avoid extremes of this type.

1.6   PRIMARY RAW MATERIALS

1.6.1   The primary raw materials feeding a copper or nickel smelter are concentrates and fluxes as follows:

TABLE I. TYPICAL RANGE OF ANALYSIS FOR SMELTER RAW MATERIALS

	Percent	Sulfide Concentrates Copper	Nickel	Oxide Ores Nickel	Flux Silica	Limestone
Copper	20-30	1 - 5		-	-	-
Nickel	-	3 - 12		1.6-2.9	-	-
Iron	22-32	25 - 43		13-21	0.5-2.0	0.5
Sulfur	30-34	19 - 31		-	-	-
Silica	-	-		-	85-95	-
Lime	-	-		-	0.5-1.0	50-55
Moisture	6-12	9 - 15		20-32	-	-
Mesh Size	80-90% -200	70 - 80% -200		-65 mm		

1.6.2   Appropriate scrap metal, residues and recycle dusts, process scrap, etc. will be added along with the above materials. The amount and type of materials which can be processed will depend upon plant capacity, impurity levels and the smelting process. In general, smelting processes are more flexible with respect to feed materials than leaching.

1.7   TYPICAL CONSUMPTION DATA

1.7.1   A reliable supply and sufficient capacity of electric power is essential for any metallurgical plant. Power failures create hazardous operating conditions and excessive emissions to the environment. For smelting processes, excluding the electric furnace process, typical power consumption would be in the range of 420 to 520 kWh/MT of concentrate, including oxygen and sulfuric acid plants. The electrolytic refining of copper will require between 250 and 300 kWh/MT cathode copper; electrowinning processes require considerably more power, in the range of 2200 kWh/MT cathode copper.

1.7.2   Fuels of various types are required to make up for heat deficiencies in the feed materials, preheat ladles, maintain flow in launders, etc. When equipped with the appropriate environmental controls, modern smelting furnaces can utilize a range of "dirty" fuels such as high sulfur coal or oil, scrap plastics, etc. In these smelters, the offgases are cleaned and industry experience indicates that the temperature is sufficiently high to destroy any noxious combustion products which may result. Once the metal is refined, clean fuels such as propane, natural gas or light industrial fuel oil are used to avoid contamination in the melting, casting and other processes.

1.7.3   Water is required for refractory cooling, make-up for solutions bled from the circuit for impurity control, gas cooling and scrubbing, cathode washing, etc. Normally treated effluents, excess process water, etc. are collected in a large settling pond and can be recycled to the process. A typical smelter-refinery complex, with flotation slag cleaning and a sulfuric acid plant, would require approximately 7 to 9 m^3 of water per MT of concentrate.

1.8   SMELTER WASTE SOURCES AND CHARACTERIZATION

1.8.1   The smelter input and discard or waste products are summarized in Figure 4 to provide an overview of the following sections.

1.8.2   Atmospheric Emissions:

1.8.2.1   These are of particular concern where sulfide ores are being treated pyrometallurgically. The sulfur dioxide (SO_2) concentration in the process gases will depend on the level of oxygen enrichment, and higher enrichment levels are being used to increase the sulfur dioxide strength, as indicated below, and reduce the total volume of the process gas stream to reduce the equipment size and cost of gas cleaning.

TABLE II.   TYPICAL SO_2 LEVELS IN PROCESS GAS STREAMS BEFORE SULFUR FIXATION

Smelting Furnace	% SO_2 by Volume
Fluid Bed Roasters	2.0 to 5.0
Electric Furnaces	0.5 to 2.0
Flash Furnace – Outokumpu Design	15 to 30
– Inco Design	70 to 80
Noranda Reactor	6 to 10
Mitsubishi Continuous Process	15 to 25

Source: Reference 2

As an additional benefit, very little if any NO_x is produced by the newer processes. Offgases contain fine dust particles and volatile impurities such as arsenic, fluorine and mercury. These are removed from the gas stream ahead of the sulfur fixation plant in wet gas cleaning or other specialized circuit (Fig. 1).
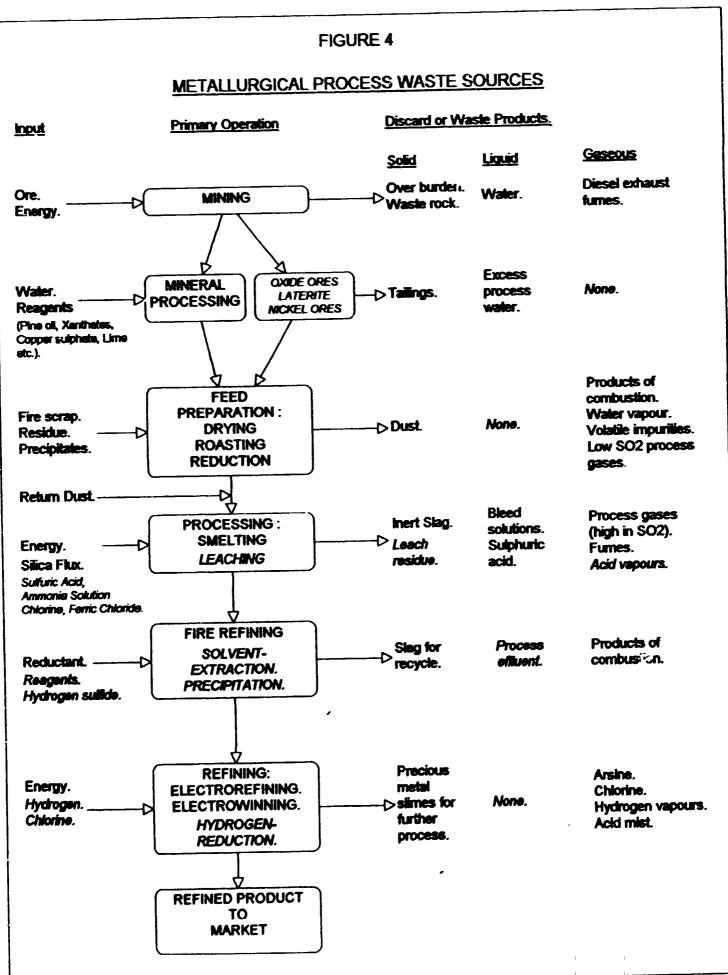
1.8.2.2   Fugitive emissions will occur at furnace openings, from launders, casting moulds and ladles carrying molten materials, which allow sulfur dioxide and volatile elements to be emitted to the working environment. When fine ores or concentrates are being transported, there can be wind or material handling losses at each transfer point totalling as much as 0.5% of the weight of the material handled, depending on the plant design, level of maintenance and care in operation. Where the material contains free silica, this dust loss can be a health concern particularly in connection with silicosis. Proper enclosure of transfer points, launders, bins and tanks will contain these emissions which can then be ducted to gas cleaning equipment specifically designed for the purpose.

1.8.2.3   Some vapors are produced in hydrometallurgy and the various refining processes. Chlorine, hydrogen and acid mist can be emitted from electrorefining cells and, when present in solution, arsenic in the form of arsine can be emitted when the concentration of copper is reduced in electrolyte purification or effluent treatment circuits. Emissions of this type are contained with the use of vented hoods, blankets or other systems designed to protect the workplace from undesirable vapors as well as reduce solution and heat losses.

FIGURE 4

METALLURGICAL PROCESS WASTE SOURCES

Input	Primary Operation	Discard or Waste Products.		
		Solid	**Liquid**	**Gaseous**
Ore. Energy.	MINING	Over burden. Waste rock.	Water.	Diesel exhaust fumes.
Water. Reagents (Pine oil, Xanthates, Copper sulphate, Lime etc.).	MINERAL PROCESSING / OXIDE ORES LATERITE NICKEL ORES	Tailings.	Excess process water.	None.
Fire scrap. Residue. Precipitates.	FEED PREPARATION : DRYING ROASTING REDUCTION	Dust.	None.	Products of combustion. Water vapour. Volatile impurities. Low SO2 process gases.
Return Dust				
Energy. Silica Flux. Sulfuric Acid, Ammonia Solution Chlorine, Ferric Chloride.	PROCESSING : SMELTING LEACHING	Inert Slag. Leach residue.	Bleed solutions. Sulphuric acid.	Process gases (high in SO2). Fumes. Acid vapours.
Reductant. Reagents. Hydrogen sulfide.	FIRE REFINING SOLVENT-EXTRACTION. PRECIPITATION.	Slag for recycle.	Process effluent.	Products of combustion.
Energy. Hydrogen. Chlorine.	REFINING: ELECTROREFINING. ELECTROWINNING. HYDROGEN-REDUCTION.	Precious metal slimes for further process.	None.	Arsine. Chlorine. Hydrogen vapours. Acid mist.
	REFINED PRODUCT TO MARKET			

1.8.3 Liquid Wastes

1.8.3.1 Liquid wastes and effluents vary widely from plant to plant, and with the location of the plant. In flotation processes, large volumes of water will be used to convey the solid wastes to the tailings pond which will act as a reservoir for the storage and recycle of plant process water. Runoff from the plant site for the first half hour during periods of heavy rain is frequently collected in a separate pond to recover the entrained solids and allow for water treatment prior to discha_ge of any excess to the water shed.

1.8.3.2 The build-up of impurities in various process solutions, granulation circuits, boiler and cooling water systems result in bleed streams to control the impurity levels within permissible limits. These are not large volume streams but must still be treated before discharge. In copper electrorefining, a proportion of the electrolyte (up to 0.5 m^3 electrolyte per MT cathode) is bled continuously and circulated through the purification circuit to remove arsenic, antimony, selenium, etc. prior to its return to the main circuit. Usually, one element will be the major or controlling impurity determining the size of this stream and only a small portion would be bled off for treatment and discard. Solutions bled from certain leach processes can be larger volume and may contain undesirable intermediate compounds which must be destroyed prior to discharge.

1.8.3.3 Wash water from the backwash of filters, final washing of products, including the excess from quench tanks, is usually circulated back directly to the individual operation. Where there is an excess, however, it will be discharged to the central pond as part of the plant process water supply.

1.8.4 Solid Wastes and Sludges

1.8.4.1 In the extractive metallurgical industry, the largest tonnage of solid wastes is flotation tailings, usually discharged as a slurry from the flotation circuit, and discard slag from the smelter. The latter is a dense silicate and can be either in lump form, coarse granules, or as fine flotation tailings, depending on the method of slag cleaning. These solid wastes are the major sources of metal loss and consequently have a significant bearing on the recovery of values. Discard slags usually contain between 0.5 and 0.7% Cu, or 0.2 to 0.9% Ni (2), are normally non-hazardous and are frequently used as aggregate, clean fill, and for sandblasting. Tailings produced during the concentration of ores are not inert and must be impounded in lined ponds with appropriate systems to monitor potential leakage.

1.8.4.2 Residues resulting from leaching processes and sludges from effluent treatment systems also have to be impounded in sealed ponds. The various treated water systems, such as boiler feed water, cooling water, etc. all have bleed streams to control impurity build-up which must be treated to adjust pH and precipitate heavy metals prior to discharge. Weak acid from the wet gas cleaning circuit and effluents from leaching and refining circuits are usually neutralized with lime, which results in a gypsum precipitate containing the copper, nickel and other heavy metals. Depending on the particular impurities present, this sludge can be recycled to a smelter; alternatively, disposal with tailings can be a benefit.

1.8.4.3 Some leach processes fix sulfur as a gypsum sludge; these, along with chloride wastes, can be difficult to handle physically, and can be a disposal problem due to the substantial tonnages involved.

1.8.5 Hazardous Wastes

1.8.5.1 Hazardous wastes are determined by various tests or criteria, some of which are unrealistic. In actual practice, a hazardous waste is one that endangers health or contaminates the environment, consequently it can be site-specific and dependent on a number of factors.

1.8.5.2 Dusts bled from the smelter hot gas cleaning system to control impurity build-up can contain arsenic, lead, mercury, selenium and other hazardous elements. They will be in the form of oxides, sulfides, or similar compounds which will weather and leach when stockpiled outside. The tonnage is usually small, less than 0.2% of the smelter feed, and is frequently processed in a separate plant to recover any values present and produce an inert slag.

1.8.5.3 Due to their very nature, almost all sludges and leach residues are hazardous wastes and must be treated further or contained in sealed ponds equipped with groundwater monitoring systems to detect any leakage.

1.8.5.4 Based on current process technology for copper or nickel, slag or similar fused products are the only truly inert or non-hazardous wastes. The ultimate solution to the disposal of some hazardous wastes is through a pyrometallurgical process which produces a silicate slag.

1.8.6 Upset Conditions

1.8.6.1 All metallurgical operations, particularly pyrometallurgical processes, benefit from cont'nuous smooth operation, free of sudden changes, process upsets or emergencies. Power failures and the resulting crash shutdowns damage equipment, which leads to spills of chemical solutions, molten materials and the uncontrolled emission of pollutants, and potentially hazardous conditions.

1.8.6.2 Since process upsets and emergency conditions can and will occur, most frequently during start-up and early operation, modern plant design calls for the provision of about 1500 KW standby diesel electric power. This must be sufficient to energize emergency shut-off valves, allow cranes, furnaces, etc. to move to safe positions, power the ventilation system which removes noxious gases and fumes, and power the emergency light and alarm system.

1.8.6.3 The area under launders, furnaces and other equipment which contains molten materials, particularly matte, must be clear of all power cables and service lines and barricaded in such a manner that a molten spill cannot flow into water or contact structural steel components.

1.9 <u>WASTE MINIMIZATION OPPORTUNITIES</u>

1.9.1 Waste minimization efforts usually concentrate on the earlier steps in the smelting or hydrometallurgical process. As extraction proceeds and

approaches the refining stage, the solutions, residues, etc. are too high in values to be discarded and must be recycled to reduce the loss of values and maintain a reasonable recovery.

1.9.2 Byproducts

1.9.2.1 In smelting and refining copper or nickel, opportunities to reduce wastes by changes in the range of products are limited. Primary and secondary products are normally determined by the process and equipment used. Wherever practical, a smelter and refinery will produce byproducts which can be used elsewhere simply to reduce or eliminate disposal and impoundment costs. For example, in ammonia leach processes, where a market exists, there is the option of removing sulfur as an ammonium sulfate fertilizer rather than as gypsum.

1.9.2.2 In certain countries where natural resources are limited, gypsum from vent and weak gas scrubbers has been used for wallboard or cement production. In other cases, particularly when there are some values contained, gypsum has been returned to the smelting furnace feed where up to 5% CaO can improve slag characteristics.

1.9.2.3 While liquid sulfur dioxide can be produced from smelter process gases containing over 65% sulfur dioxide, sulfuric acid is the normal sulfur byproduct from smelters treating sulfide concentrates. Depending on smelter location, byproduct sulfuric acid can be a profitable item. Smelters located close to phosphate fertilizer plants or uranium mills are particularly well suited in this respect, as are those located on tidewater where acid can be shipped to offshore markets.

1.9.2.4 Silicate slag can be granulated, crushed or cast into lumps and thus provide a wide range of aggregate products for sandblasting, coarse fill, bedding for railroads, or spun into fibres for insulation.

1.9.3 Process Changes

1.9.3.1 The basic process is usually fixed to a large extent by the feed materials, primarily the concentrate, and the plant location. The opportunity to minimize waste products is therefore limited to the technology selected; even then, the process considerations will be the governing factor.

1.9.3.2 Oxygen enrichment is being used to an increasing extent to raise the sulfur dioxide content of process gas streams in order to reduce their volume and permit efficient fixation of sulfur dioxide. This is considered preferable to the use of various absorption-desorbtion systems to increase the strength of the sulfur dioxide gas streams.

1.9.3.3 Hot air and certain process gases can be recycled to air preheaters or used as combustion air for dryers, etc., saving energy and providing an efficient removal of any entrained particulates. Similarly, condensate, rainwater and excess process water can be recycled to the circuit for washing, dust control, gas scrubbing and other process applications where water quality is not a particular concern.

1.9.3.4   Good housekeeping is the key to safe operation, minimum loss of values, reduced maintenance and a reduction in waste products.   To control dusting and minimize handling losses, concentrate storage and blending are carried out in enclosed buildings; conveyors, transfer points, etc. are covered and vented to dust collection equipment. In hot, dry climates, the roadways are sprayed with water to control dusting. The plant yard around buildings and roadways is usually paved and the run-off water ducted to a central settling pond. In some plants, as much as 500 metric tons per year of metal-bearing material is collected from ponds of this type. At vehicle exits, wash stations clean the wheel wells and undercarriage of all vehicles leaving the plant.

1.9.4   On-Site Recycling

1.9.4.1   As noted in the previous sections, on-site recycling has long been a standard procedure in smelting and refining as a means of maintaining an acceptable recovery of values. Many process intermediate products, particularly from the refinery, are therefore returned to the smelter feed system.

1.10   <u>CONTAMINANTS OF CONCERN</u>

1.10.1   The contaminants which cause concern in the processing of copper and nickel concentrates are dependent on the contaminants in the original ore. In general, sulfide ores contain a wider range of these contaminants than do oxide or laterite nickel ores.

1.10.2   Arsenic

1.10.2.1   Arsenic will be volatilized early in the smelting process and collected as an oxide as the temperature is reduced in the gas cleaning circuit. With recycle of the dust to the smelting furnace, a circulating load builds up and some dust must be removed from the circuit to prevent downstream contamination of the product, and hazardous conditions such as emissions from molten streams, generation of arsine, etc. Arsenic compounds are toxic and can be ingested, inhaled or absorbed through the skin.

1.10.3   Lead

1.10.3.1   Lead is more frequently associated with copper ores than with nickel, and is distributed among the dust, slag and matte or blister copper during smelting. Lead will be emitted to atmosphere while molten matte and copper are being transferred, and the fume will be concentrated in sections of the gas cleaning circuit. Lead is toxic with extended ingestion; special protection must be used and blood levels monitored closely. In the discard of wastes, lead sulfates, oxides, etc. are of concern and special impoundment measures required.

1.10.4   Mercury

1.10.4.1   Mercury is in the order of five times as toxic as lead and can accumulate in the food chain and cause medical problems. For example, at concentrations of 20 ppm in the brain, neurological problems can occur. In pyrometallurgical processes, mercury is driven off very early in the process and leaves in the process gas. Since sulfuric acid is a very efficient mercury

collector, one of a number of mercury removal processes is required ahead of the acid plant to ensure that the product acid contains less than 1 ppm mercury.

1.10.5 Nickel

1.10.5.1 Although nickel is an essential metal in modern technology, nickel carbonyl is very toxic and respiratory cancers have been reported in processes where nickel matte from sulfide ores is roasted to produce nickel oxides. It should be noted that there is considerable ongoing work in connection with the toxicity of nickel and all its inorganic compounds (5). Various operating techniques and processes have been developed which overcome potential hazards, and these are taken into consideration with proper plant design.

1.10.6 Silica

1.10.6.1 The processing of ores containing free silica will produce fine dust which, if not contained and collected, can be inhaled and with time cause silicosis. However, the use of proper ventilation, respirators and annual chest X-Rays will control the hazard. When the X-rays are positive, the workers are transferred to areas of the plant which are free of dust.

1.10.7 Sulfur

1.10.7.1 The main contaminant in sulfide ores is the sulfur removed as sulfur dioxide or intermediate sulfur compounds. In all cases, sulfur fixation processes are required and the effluents from hydrometallurgical processes must be treated.

1.11 ENVIRONMENTAL IMPACT ON RECEPTORS

1.11.1 Dust collection and recycle is given a high priority in smelting and refining operations to protect the environment and is a key factor in the recovery of values, consequently the impact on the surrounding environment from particulates is relatively small. Once deposited on the ground or in the water system, they can accumulate and enter the food chain. Plant life, for example, will absorb heavy metals from the soil and has been analyzed by geologists in some cases as a means of determining the metal content of that soil.

1.11.2 Arsenic, lead and similar contaminants contained in bleed dusts and stockpiled outside will be leached with time. Without proper containment measures to prevent dust losses and leaching action, these contaminants can enter the water table and create a health hazard. Efficient dust collection and containment and good worker hygiene, including the use of dust masks, will protect the employees from potentially hazardous dusts and fumes, including silica. Where these materials cannot be treated, they must be stored in sealed containers which prevent leakage to the environment.

1.11.3 Of the gaseous emissions, sulfur dioxide is the principal contaminant. Emissions generated in some processes, such as arsine, hydrogen sulfide, chlorine, etc. are very small in volume but toxic and must be vented to atmosphere at source. In the processing of sulfide ores, however, substantial tonnages of sulfur dioxide are produced which can amount to between 40 and 60%

of the weight of concentrate smelted. Large volumes of high strength sulfur dioxide will damage vegetation, cause acidity in surface waters and promote the leaching of other contaminants from the environment. The high strength gases are normally processed to produce a market grade sulfuric acid. Weaker gas streams, usually less than 1% sulfur dioxide, are scrubbed and the sulfur removed as gypsum, sodium or ammonium sulfate.

1.11.4   Some processes produce intermediate sulfur compounds which are hazardous to the environment. Leach circuits can produce intermediate sulfur compounds such as thionates, sulfamates and thiosulfates which destroy vegetation and must be destroyed in an oxyhydrolysis circuit prior to discharge. Similarly, intermediate gaseous compounds must be incinerated prior to discharge to protect the environment.

1.12   OCCUPATIONAL HEALTH AND SAFETY ISSUES

1.12.1   The measures used to protect workers from contaminants include such engineering designs as enclosure of control rooms and individual processes, ventilation and mechanical dust recovery. Other systems include personal protective equipment and administrative controls. Medical surveillance and monitoring serve to check the effectiveness of the various measures. Personal hygiene and separate work clothes are key features in avoiding ingestion of arsenic, mercury and toxic chemicals. A wide range of chemicals are used in the industry as reagents and some require very specific handling procedures.

1.12.2   Threshold Limit Values are expressed as time-weighted averages (TWA), which is the time-weighted average concentration of a contaminant for a normal 8-hour day/40-hour week, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect. TWAs permit excursions above the limit, provided they are compensated for by equivalent excursions below the limit during a workday. The current TWA standard set by the American Conference of Government Industrial Hygienists (6) for a number of substances which can appear in copper and nickel smelters and refineries are given below. For substances which do not appear on this list, the reader should consult the latest complete document (6).

TABLE III.   THRESHOLD LIMIT VALUES FOR SUBSTANCES FOUND IN COPPER-NICKEL PLANTS

Substances of Concern	ppm	mg/m³
Ammonia	25	17
Antimony and Compounds, as Sb	—	0.5
Arsenic and Soluble Compounds, as As	—	0.2
Arsine	0.05	0.16
Cadmium, dusts and salts; as Cd	—	0.05
Cadmium oxide fume, as Cd	—	0.05
Carbon black	—	1.5
Carbon monoxide	50	57
Chlorine	0.5	1.5
Cobalt, dust and fume	—	0.05
Copper fume	—	0.2
dust and mist	—	1
Cyanides as CN	—	5
Hydrogen sulfide	10	14
Lead inorganic dusts and fumes; as Pb	—	0.15
Mercury, all forms except alkali	—	0.05
Nickel, metal and insoluble compounds	—	1
soluble compounds as Ni	—	0.1
Nickel carbonyl	0.05	0.12
Nitrogen Oxide	3	5.6
Particulates not otherwise classified	—	10
Sulfur dioxide	2	5.2
Sulfuric acid	—	1
Uranium soluble and insoluble compounds, as U	—	0.2

Source: Reference 6

It should be noted that the above data are continually reviewed and updated to incorporate new information. On the other hand, some authorities apply stricter limits; for example, the American Occupational Health and Safety Administration (OSHA) adopted a much lower standard for nickel carbonyl at 0.001 ppm, or 0.007 mg/m³ (5). Nickel carbonyl is very toxic when inhaled, but acute toxicity by ingestion of nickel in most other forms is rare.

1.12.3   Ingestion of fine fume, noxious gases and similar emissions is controlled with the use of properly fitted respirators. This usually prohibits the wearing of full-face beards which prevent the respirator from making a tight fit to the face. The health effect of increased levels of sulfur dioxide is summarized below:

TABLE IV. WORKPLACE SULFUR DIOXIDE LEVEL

ppm, SO_2 Concentration	General Health Effect
3 - 5	Odor threshold.
8 - 12	Throat irritation, coughing, constriction in the chest, tearing and smarting of the eyes.
10 - 50	Exposure 5 - 15 minutes: increased irritation of the eyes, nose, throat, choking, coughing and in some cases wheezing as a sign of narrowing of the airways (which increases the resistance of the airflow).
150	Short-term endurance due to severe eye irritation and because of the effects on the membranes of the nose, throat and lungs.
500	Highly dangerous after exposure of 30 to 60 minutes.
1000-2000	May be fatal with continued exposure.

Source: Reference 5

A well-designed smelter will keep contaminants below occupational exposure limits. For example, the time-weighted average exposure to SO_2 over a normal 8-hour day, 40-hour week, should not exceed 2.0 ppm (5)(6).

1.12.4   In pyrometallurgical operations, radiant heat, hot surfaces and the splash or spill of molten materials, particularly sulfides, can be hazardous. When large quantities of molten matte suddenly contact water or a cold surface, the reaction can be violent. To protect against minor splash or spill, clothing of a protective material or natural fibre is worn and covers all body areas. In hydrometallurgical plants, acid-resistant materials will be used and emergency showers placed at strategic locations throughout the plant. Finally, a supply of cool water and well ventilated rest areas away from the hot working areas are provided to permit workers to rest as required to avoid heat exhaustion (6).

1.13   HAZARDOUS MATERIAL HANDLING

1.13.1   Regulations have been developed for most industrially developed areas which govern spillage, on-site storage, transport and off-site disposal of hazardous wastes. Solid hazardous wastes are classed as inert when the leachate produced under defined conditions contains less than the limits listed below

TABLE V.   HAZARDOUS LEACH TEST

Leach Acid	U.S. EPA Register 261.22 to 261.24 Acetic Acid	Japanese EPA Ordinance 13 Hydrochloric
Leachate Limit for:		
Arsenic	5.0 mg/L	1.5 mg/L
Cadmium	1.0 "	0.3 "
Chromium	5.0 "	1.5 "
Lead	5.0 "	1.0 "
Mercury	–	0.005 "
Silver	5.0 "	–

Source: Reference (5)(8)

In some cases the dusts, residues and precipitates fed to a copper or nickel smelter may be hazardous and require special handling and storage procedures.

1.13.2   The regulations in North America are quite complex but in brief, they require hazardous wastes to be shipped and stored in approved containers properly marked as to contents and potential hazards. At present, residues and sludges can be impounded in sealed ponds equipped with systems to measure groundwater quality; however, in the near future the use of ponds for final disposal may not be approved.

1.13.3   Noxious or toxic gases and fumes are normally scrubbed and collected as a sludge or residue prior to discharge of the gas stream. Where possible, this residue will be returned to the smelter or leach circuit for recovery of values, or it is sent to a hazardous waste facility. One of the advantages of pyrometallurgy is its ability to absorb some hazardous wastes and produce inert, or non-hazardous, products.

1.13.4   Process gas streams containing over 5% sulfur dioxide are processed to sulfuric acid in plants of either the single catalysis or double catalysis design. From an environmental point of view, the double catalysis system is preferred since it can provide a 99.5% conversion efficiency and a tailgas containing about 500 ppm sulfur dioxide. This would result in between 96 and 98% of the sulfur in a typical smelter feed being fixed in some form so as not to be emitted to the atmosphere.

1.14   EFFLUENT GUIDELINES

1.14.1   Atmospheric Emissions

1.14.1.1   In North America, the State or Provincial environmental agencies have the final say on air quality standards, provided they are in line with the Federal Guide levels. For example, in the case of atmospheric emissions:

TABLE VI.   CANADIAN PROVINCIAL REGULATION - Ontario 1984

	½ hour average at Point of Impingement $\mu g/m3$
Arsenic	75
Arsine	10
Cadmium	5.0
Carbon Monoxide	6,000
Copper	100
Dust fall	8,000 $\mu g/m^2$
Lead	10
Mercury	5.0
Nickel	5.0
Sulfur Dioxide	830
Sulfuric Acid	100
Zinc	100

Source: Reference (5)

The U.S. National Ambient Air Quality Standards (NAAQS) sets forth the following limits for sulfur dioxide at the point of impingement:

TABLE VII.   SULFUR DIOXIDE EMISSION STANDARDS

	United States NAAQS $\mu g/m^3$	Canada British Columbia $\mu g/m^3$
Annual Arithmetic Mean	80	25 to 75
Concentration over - 24 hr.	365 (permissible	160 to 260
- 3 hr.	1300 once a yr.)	375 to 665
- 1 hr.	-	450 to 900

The objectives shown for the British Columbia Ministry of the Environment take into account the needs of particular receiving environments. Overall, they are lower than the U.S. limits due to a large extent to the role of the forests and salmon spawning grounds in the Province.

1.14.1.2   The 1992 statutory guidelines for Sweden are summarized below, based on a copper smelter production of 350,000 metric tons per year of primary product; a nickel smelter in Sweden would have to meet similar levels.

TABLE VIII.   SWEDISH EMISSION LIMITS TO ATMOSPHERE - 1992 to 1993

	Annual Metric Ton/Year	Specific g/Metric Ton product
Arsenic	8	20
Cadmium	0.8	2
Copper	10	30
Lead	30	85
Mercury	0.35	1
Dust	250	700
Sulfur Dioxide *	5,000	14,300
Zinc	40	110

* Swedish Environmental Protection Agency recommended ground level concentrations of 100 $\mu g/m^3$ and 50 $\mu g/m^3$ during the winter half-year.

Source: Reference (7)

Studies are under way in Sweden directed towards the further reduction of arsenic, cadmium and mercury emissions.

1.14.2   Liquid Effluents

1.14.2.1   Smelters and refineries are normally required to meet effluent criteria for the area or industrial complex within which they are located, which in some cases could be those applicable to mines and mills. The limits are not a function of the metallurgical process, but apply to any liquid discharge; consequently, the effluent from leach circuits would also have to comply with the criteria. Examples of permissible effluent levels are as follows:

TABLE IX.   PERMISSIBLE LIQUID EFFLUENT LEVELS

	Germany Smelter Effluent Random Tests mg/L	Canada Maximum Monthly Mean Concentration mg/L	Japan Maximum Concentration mg/L
Arsenic	0.1	0.5	0.5
Cadmium	0.2	-	0.1
Copper	0.5	0.3	-
Lead	0.5	0.2	1.0
Nickel	0.5	0.5	-
Total Mercury	0.05	-	0.005
Zinc	2.0	-	-
Suspended Solids	-	25	-
pH	-	6.0	5.8 to 8.6

Source: Reference (5)

Both Canada and Japan have particularly sensitive aquatic environments and therefore emphasize the mercury and pH components.

1.14.2.2   As is the case with atmospheric emission guidelines, the Swedish liquid effluent emission guidelines are expressed in annual and specific terms. For the copper smelter described previously, the 1992-1993 emission limits are as follows:

TABLE X.   SWEDISH EMISSION LIMITS TO WATERSHED

	Annual Metric Ton/year	Specific g/MT Product
Arsenic	20	10
Cadmium	0.4	0.05
Copper	2	0.1
Lead	2	0.1
Mercury	-	0.1
Zinc	8	2.0

Source: Reference (7)

1.14.3   Noise Levels

1.14.3.1   In a mine, mill or smelter, there can be a considerable amount of noise. In Sweden, the noise from industrial activities is regulated not to exceed the following levels at the nearest domestic residence:

TABLE XI.   SWEDISH INDUSTRIAL NOISE LIMITS

Time Period-Hours	Maximum Noise Level - dBA
0700 to 1800	55
1800 to 2200	50
2200 to 0700	45
Maximum Momentary Pulse	60

Source: Reference (7)

In a mine or smelter it is the oxygen plant blower, air compressors and similar equipment which are the major contributors to the noise level in the surrounding area.

1.14.3.2   In the workplace there are several pieces of equipment and processes which contribute to the noise level. The following are the Threshold Limit Values (TLVs) proposed by the American Conference of Industrial Hygienists:

TABLE XII. TLV - NOISE LIMITS

Duration per Day Hours	Sound Level dBA
16	80
8	85
4	90
2	95
1	100

Source: Reference 6

The guidelines stipulate that there should be no exposure of any duration of 140 decibels. In areas where the levels exceed the above TLVs, personal hearing protection is a job requirement.

1.15   ENVIRONMENTAL MONITORING

1.15.1   Monitoring regulations will vary with each jurisdiction but, in general, they are similar to those outlined in the EPA Regulations 40 CFR Ch 1 (7-1-89 Edition), Sec. 60.165. In brief, they require the smelter operator to maintain a monthly record of the total input of arsenic, antimony, lead and zinc, continuously monitor and record the opacity of dryer discharge gases and the concentration of sulfur dioxide emitted.

1.15.2   Effluent ponds are monitored by a system of deep wells surrounding the pond area. The water is analyzed on a regular basis for any leakage which might occur in the pond liner and seal system. Similarly, treated effluents are sampled prior to discharge to the water shed on a regular basis. In each case, records are kept.

1.15.3   Emission of sulfur dioxide to atmosphere is usually determined on the basis of a material balance, where all sulfur not fixed in products is considered to be emitted to atmosphere.

1.16   PREFERRED GUIDELINES

1.16.1   It is important when adopting emission limits and establishing environmental controls, that an overall waste management (8) plan has been developed and that the final result reflects the particular features of the local environment. For example, control and final limits for mercury and sulfur dioxide emissions will be more severe for plants located in heavily forested areas and where fish are sensitive, than would be the case in a desert location where the control of other process effluents, particularly acids, can be the governing factor. Finally, it is important to ensure that the final guidelines or regulations do not impede the recycle of hazardous materials to a smelter where high temperatures can render most of those materials inert.

1.16.2   With modern smelting technology, it should be possible to fix in products at least 96% of the sulfur contained in feed materials and design to meet the following ambient air criteria:

TABLE XIII.   PROPOSED AMBIENT AIR CRITERIA

Sulfur Dioxide: Annual arithmetic mean	80-100 µg/m³
Maximum 24-hour arithmetic mean	340-370 "
Dust Loading: Annual geometric mean of	
24-hour concentrations	75 "
24-hour average not to be exceeded	
more than once per year	260 "

These figures are based on data in a UNEP report (5) and some recent U.S. National Ambient Air Quality standards.

1.16.3   The target levels for smelter-refinery effluents, including those from hydrometallurgical processes, should also be realistic and compatible with ambient water quality. In general, however, where specific regulations or base data are not available, the following maximum limits would be reasonable and achievable:

TABLE XIV.   PROPOSED SMELTER-REFINERY EFFLUENT LIMITS

Element	Concentration Limits, mg/L
Arsenic	1.0
Copper	1.0
Iron	5.0
Lead	0.5
Nickel	0.5
Selenium	1.0
Zinc	10.0

1.16.4   Monitoring of environmental guidelines usually consists of accurate records being maintained and reported by the operator on a regular basis. The sampling, analysis and calculations will follow agreed procedures and be checked on a spot basis by independent consultants or agents representing the government regulatory agency.

1.17   TREATMENT TECHNOLOGY OVERVIEW

1.17.1   Once again, as noted in Section 1.16.1, when selecting the technology best suited to protect the environment specific to the smelter location, it is essential that a comprehensive waste management plan (8) be developed taking local conditions into account. Similarly, ground conditions, susceptibility to earthquakes, soil erosion, etc. must all be considered and should govern the treatment technology selection.

1.17.2   Emissions to the Atmosphere

1.17.2.1   Airborne particulate emissions are reduced to acceptable levels with the use of cyclones, electrostatic precipitators or baghouses and scrubbers. Gaseous contaminants are removed from a gas stream using an acid plant when the concentration is high in sulfur dioxide or various alkali, and dual alkali scrubbers for the lower strength gases. Vapors such as mercury are removed using one of a number of dedicated scrubbing processes.

1.17.2.2   The U.S. Clean Air Act lists some technologies which the EPA believes can be considered to reduce airborne emissions. Changes in smelting technology which utilize oxygen enrichment, the production of sulfuric acid using double catalysis technology and certain gas scrubbing systems would be classed as Best Available Technology (BAT); however, they may not necessarily be economic.

1.17.3   Liquid Effluents

1.17.3.1   Liquid effluents result from bleed streams required to control impurity build-up which have been adjusted for pH, usually 6.0+. Heavy metals are precipitated along with the sludge in the waste water treatment plant. Various systems are used, but most add lime for neutralization and produce a gypsum residue. Depending on the impurity balance in the smelter-refinery, the sludge can be returned to the smelter for recovery of values and to fix impurities in an inert slag.

1.17.3.2   The treated effluent may be stored in a pond to be used as make-up water or discharged to the watershed, in which case it must meet local water quality specifications. This can usually be achieved with a standard alkali neutralization, normally lime, settling and final pressure filtration now considered BAT.

1.17.3.3   In cases where yard dusting is prevalent, such as in laterite operations or hot dry climates, the treated effluent can be used to wet down roads and control dusting.

1.17.4   Solid Wastes

1.17.4.1   The main solid waste from copper or nickel smelters is discard slag. In almost all cases, this material is inert and non-hazardous and can be used for landfill, sandblasting, or aggregate.

1.17.4.2   The much smaller quantities of dusts, purification sludges and residues are recycled to the smelter where possible, and would be considered BAT. However, it is frequently necessary to bleed some impurities from the circuit to avoid building up a circulating load of undesirable elements. In these cases, the wastes are impounded in sealed containers or in sealed ponds which currently would be considered the Best Practical Technology (BPT).

1.18   ALTERNATIVE TREATMENT TECHNOLOGIES

1.18.1   Gaseous Emissions

1.18.1.1   Sulfuric acid production is the most common process for containment of sulfur dioxide; however, various plant designs are available.   All metallurgical acid plants incorporate a wet gas cleaning system to remove particulates, fume and sulfur trioxide from the gas stream. The single catalysis plant has a lower conversion efficiency than the standard double catalysis design, and will emit a tailgas containing 1500 to 2000 ppm SO_2. In some cases, the tailgas is fed to a weak gas scrubbing system and sulfur dioxide emission level reduced to less than 500 ppm SO_2 normal for the double catalysis design.

1.18.1.2   For the weaker gas streams containing less than 1% sulfur dioxide, various scrubbing systems have been developed. For metallurgical gas streams where the ratio of CO_2/SO_2 is usually low, limestone is not a particularly efficient scrubbing medium. Lime, sodium sulfate regenerated with slaked lime, magnesium oxide and several other reagents are used to fix the sulfur, usually as gypsum. The latter can be used in wallboard manufacture, the cement industry, or impoundment in tight ponds.

1.18.1.3   Under very special conditions, the higher strength gases, usually over 70% sulfur dioxide, can be used to produce liquid SO_2 or elemental sulfur. This sulfur will contain a number of impurities and require refining before it is marketable. Consequently, it is a very expensive alternative and can rarely compete with natural sulfur.

1.18.2   Solid Wastes

1.18.2.1   The dusts bled from the smelter to control impurity build-up and the residues resulting from the effluent treatment circuits are rarely inert and usually classed as hazardous wastes (8).   A number of processes are being developed to treat these materials and recover values while producing an inert slag.

1.18.2.2   Plasma technology is being adapted by a number of developers. For example, Tetronics has used plasma arc to produce a nickel-chromium ferroalloy containing 85% of the nickel and chromium in the bleed dust (9). Zinc, lead and cadmium are collected in a baghouse for further processing in a zinc plant, and the discard slag is non-hazardous.

1.18.2.3   Various cyclone reactors are being developed. The St. Joe Flame Reactor (10) and Lurgi's Flame Cyclone (11) are two designs which have been piloted. All these processes operate at high temperatures (up to 1800°C) with short retention times, while metal recoveries in the range of 90 to 99% are achievable.

1.19 CAPITAL AND O & M COSTS

1.19.1 Capital Costs

1.19.1.1 The direct capital cost for a smelter-refinery complex will depend to a large extent on its location. For example, in warm climates, lower cost, open-sided buildings can be used. Within the total cost there can be a number of trade-offs; for instance, high levels of oxygen enrichment increase the size and cost of the oxygen plant itself, but the resulting lower volume, high-strength furnace offgas reduces the size of the gas cooling and cleaning equipment. In most cases, one will offset the other, particularly where an acid plant is used.

1.19.1.2 In terms of capital costs, hydrometallurgical plants are usually lower cost than equivalent pyrometallurgical plants; however, the selection of the final process technology is invariably based on technical factors rather than cost. The requirement to produce inert, non-hazardous waste products to protect the environment favors pyrometallurgy. The smelting furnace area itself usually accounts for less than 20% of total capital cost, so the savings resulting from one furnace design over another does not significantly affect project economics. Environmental controls, including the sulfur fixation plant, will be 30 to 35% of the total capital cost for a smelter-refinery complex.

1.19.1.3 For a plant smelting 1100 MTPD of sulfide concentrate and producing 100,000 MTPY of refined copper or 30,000 MTPY of nickel, the total installed cost of major plant areas, in U.S. dollars at the April 1992 cost level, would be in the range of:

a) Smelter, incl. feed preparation — $85 to $98 million

b) Electrolytic refinery — $55 to $70 million

c) Cryogenic oxygen plant — $19 to $22 million

d) Sulfuric acid plant — $45 to $60 million

e) Auxiliary facilities, incl.
   environmental controls — $46 to $52 million

Laterite nickel plants must handle large tonnages of relatively low grade ores, consequently their capital costs will be considerably higher, over twice those shown above for sulfide concentrates. However, normally they do not include oxygen or sulfuric acid plants.

1.19.1.4. In any smelter project, the sulfuric acid plant will account for about 30% of the cost of the smelter. Metallurgical type acid plants include a wet gas cleaning circuit consisting of scrubbers and mist precipitators to ensure that the feed gas is clean. The final cost of the sulfuric acid plant will depend on the process gas volume and sulfur dioxide content. For this reason, modern sulfide smelters utilize oxygen enrichment to increase the process gas strength and reduce the volume, thereby minimizing acid plant costs. Other environmental costs are covered under Auxiliary Facilities and include the

collection and scrubbing of the low strength fugitive emissions from ladles, launders, tap holes, etc., and the effluent treatment plants.

1.19.2   Operating and Maintenance Costs

1.19.2.1   The main components in the cost of operating a metallurgical plant are labor and energy, primarily electrical energy. The cost of power and fuel are the major cost items in electrolytic refining and in the smelting of laterite nickel ores.   Labor costs vary widely throughout the world, but so does productivity; in general, where labor costs are low more employees are required, and in the final analysis the total operating labor cost component may not represent a major cost saving. In laterite nickel operations, the cost of labor is small in comparison to the energy cost, consequently the operating costs for laterite nickel are generally higher than for sulfide nickel operations.

1.19.2.2   Significant differences in labor, power and fuel costs result in a wide spread in direct operating costs between plants. In general, the total direct operating cost for copper smelting will be in the range of 26.5-39.87¢/kg (12-18¢/lb.) of copper, of which some 30-35% will be for maintenance. For electrorefining, the cost would be in the range of 6.6-11.0¢/kg (3-5¢/lb.) of copper, with only about 17% required for maintenance.

1.19.2.3   Operating costs for nickel will vary considerably, depending on the type of ore, process used, and whether the final product is refined nickel, nickel oxide, or ferronickel. Unlike copper, there is very little cost information published for nickel; the production of primary nickel is very competitive. Nevertheless, based on estimates from various sources, the current direct operating cost of the metallurgical plant is in the range of $1.98 to $3.31 US/kg ($0.90 to $1.50 US per pound) of nickel in product. This includes maintenance of the smelter and refining facility, which could be in the range of 18 to 25%.

1.20   CONCLUSIONS

1.20.1   The efficient processing of copper and nickel feed materials requires the use of modern process technology designed to provide a high level of recycle of intermediate products, and the containment of gaseous and particulate emissions.

1.20.2   Hydrometallurgical processes eliminate the emission of sulfur dioxide but frequently produce hazardous wastes and effluents, whereas pyrometallurgical processes can produce large volumes of sulfur dioxide. They also produce a non-hazardous slag which frequently renders hazardous elements inert.

1.20.3   Copper and nickel ores and concentrates can be processed safely to marketable products and still meet realistic environmental limits. Byproducts such as cobalt, zinc, sulfuric acid or precious metals will frequently be produced, which improve the economics.

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