PRELIMINARY REPORT

METALLURGICAL TECHNOLOGY

FEBRUARY 15, 1977

REGIONAL Cu-Ni STUDY

MINNESOTA EQC

PRELIMINARY REPORT
METALLURGICAL TECHNOLOGY
POLLUTION AND POLLUTION CONTROL
IN THE
NONFERROUS METALS INDUSTRY

By

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Technical Assessment

February 15, 1977

PRELIMINARY
SUBJECT TO REVIEW

REGIONAL CU-NI STUDY
MINNESOTA ENVIRONMENTAL QUALITY COUNCIL

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INTRODUCTION

Adequate control of air and water pollution is of tremendous importance when considering the development of mining systems. So important are these variables that environmental safeguards have been established to control excessive contamination of the air and water. (Refer to Appendix D for a listing of the rules and regulations developed by the MPCA which apply to the air and waters of Minnesota.)

Pollution control in the nonferrous metals industry (which includes copper, lead, zinc and aluminum) is principally confined to air pollution, water pollution being of secondary consequence. ? should be explained Specific air pollutants include:

- sulfur dioxide emissions
- particulate effluents to the atmosphere
- minor constituents and/or volatile fumes

The discussion which follows will be concerned with the principal air pollutants of the nonferrous industry (both gaseous and particulate pollutants), their origin in metallurgical processing systems, and the contemporary anti-pollution equipment which is capable of minimizing these obvious pollution emissions to the atmosphere.

GENERAL

National or world wide

The following broad categories summarize the sources of atmospheric air pollutants:

- transportation
- domestic heating
- electric power generation
- refuse burning
- industrial fuel burning and process emissions

Of the major sources of air pollution, approximately 20 percent is attributable to industrial processes, 30-35 percent when pollution from power generating facilities is included. Major industrial polluters are classified and categorized by the following list with estimated annual emission levels.[13] *

INDUSTRY	TYPE OF POLLUTION					TOTAL ANNUAL AMOUNT (Metric tons)
	Particulates	Sulfur Oxides	Carbon Monoxide	Fluorides	Hydrocarbons	
Petroleum Refining	*	*	*		*	3,809,500
Smelters Aluminum Copper Lead Zinc	*	*				3,764,200
Iron Foundaries	*		*			3,356,000
Kraft, Pulp, and Paper Mills	*	*	*			2,993,000
Coal Cleaning & Refuse	*	*	*			2,131,500
Coke (used in steel manufacturing)	*	*	*			1,995,500
Iron & Steel Mills	*		*			1,632,650
Grain Mills & Grain Handling	*					997,700
Cement Manufacturing	*					771,000
Phosphate Fertilizer Plants	*			*		283,000

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*Suprascripts are reference notations which are keyed to the Bibliography. (Tables 1 and 2 are found in Appendix D)

Too many tables much information not to the point (ie smokers] comparisons can be made in text

GASEOUS EMISSIONS

Sulfur enters the atmosphere as air pollutants in the following forms:

1. SO_2
2. H_2S
3. H_2SO_4
4. particulate sulfates
5. natural emanations as H_2S and sulfates

On an annual basis, approximately 200 X 10^6 metric tons of sulfur are routinely discharged to the atmosphere. Approximately 33 percent of this total or 66 X 10^6 metric tons originates from industrial air pollution sources principally as SO_2. The remaining 67 percent originates from natural processes of which 68 percent is H_2S. Once into the atmosphere, both H_2S and SO_2 are oxidized within a few days to a sulfate aerosol which can be removed by precipitation in rain or snow.

transferred (eg acid rain)

Table 3 indicates the type and size of the natural and pollutant sources, the estimated concentrations in the ambient atmosphere, probable scavenging reactions, and estimated residence times.

Table 4 shows the tonnage estimates of annual world-wide SO_2 emissions. Of the total, 70 percent comes from coal combustion and 16 percent from the combustion of petroleum products, mainly residual fuel oil. The remaining tonnage is accounted for by petroleum refining operations, 4 percent, and by nonferrous smelting, 10 percent. Estimates were based on 1965 world figures for coal production, petroleum refining activity and products, and smelter production combined with SO_2 emission factors per unit of production derived from U.S. industrial operations by Rohrman and Ludwig (1965) and by SRI.[12]

Table 5 indicates estimated world natural and pollution emissions of sulfur compounds. Industrial emissions account for only 35 percent of the total sulfur annually released to the atmosphere.[12]

CONTAMINANT	MAJOR POLLUTION SOURCES	NATURAL SOURCES	ESTIMATED EMISSIONS		ATMOSPHERIC BACKGROUND CONCENTRATIONS	CALCULATED ATMOSPHERIC RESIDENCE TIME	REMOVAL REACTIONS AND SINKS	PRINCIPAL REFERENCES	REMARKS
			Pollution	Natural					
SO_2	Combustion of coal and oil	Volcanoes	146 x 10^6 tons	None	0.2 ppb	4 days	Oxidation to sulfate by ozone or after absorption by solid and liquid aerosols	Ericksson (1959, 1960, 1963) Junge (1963) Lodge and Pate (1966)	Photochemical oxidation with NO_2 and HC may be the process needed to give rapid transformation of SO_2 SO_4
H_2S	Chemical processes, sewage treatment	Volcanoes, biological action in swamp areas	3 x 10^6 tons	100 x 10^6 tons	0.2 ppb	2 days	Oxidation to SO_2	Junge (1963) Smith et al, (1961)	Only one set of background concentrations available
CO	Auto exhaust and other combustion	Forest fires	220 x 10^6 tons	11 x 10^6 tons	0.1 ppm	<3 yr	None known, but large sink necessary	Bates and Witherspoon (1952) SRI Project Reports	
$NO:NO_2$	Combustion	Bacterial action in soil (?)	53 x 10^6 tons	500 x 10^6 tons	1 ppb	5 days	Oxidation to nitrate after absorption by solid and liquid aerosols, hydrocarbon photochemical reactions	Junge (1963) Leighton (1961) Lodge and Pate (1966)	Very little work done on natural processes
NH_3	Waste treatment	Biological decay	4 x 10^6 tons	5900 x 10^6 tons	6 ppb to 20 ppb	2 days	Reaction with SO_2 to form $(NH_4)_2SO_4$, oxidation to NO_3 nitrate	Ericksson (1952) Georgii (1963) Junge (1963) Lodge and Pate (1966)	No quantitative rate data on oxidation of NH_3 to NO_3 which seems to be dominant process in atmosphere
N_2O	None	Biological action in soil	None	1000 x 10^6 tons	0.25 ppm	1-3 yr	Photo dissociation in stratosphere, biological action in soil	Bates and Hays (1967)	No information on proposed absorption of N_2O by vegetation
Hydrocarbons	Combustion exhaust, chemical processes	Biological processes	88 x 10^6 tons	480 x 10^6 tons	CH_4: 1.5 ppm non CH_4: <1 ppb	16 yr (CH_4)	Photochemical reaction with NO/NO_2, O_3; large sink necessary for CH_4	Bates and Witherspoon (1952) Ehhalt (1967) Koyama (1963) SRI Project Reports	"Reactive" hydrocarbon emissions from pollution 27 x 10^6 tons
CO_2	Combustion	Biological decay, release from oceans	1.3 x 10^6 tons	10^{12} tons	320 ppm	4 yr	Biological absorption and photosynthesis, absorption in oceans	Revelle (1965)	Atmospheric concentrations increasing by 0.06 ppm per month

Table 3. Summary of sources, concentrations, and major reactions of atmospheric trace gases.

Source	Product Consumption or Production Rate	SO_2 Production Factor	SO_2 Emission, tons
Coal[a]	$3{,}074 \times 10^{6}$ T[b]	3.3 T/100 T[c]	$102. \times 10^{6}$
Petroleum Combustion			
Gasoline	379×10^{6} T[b]	9×10^{-4} T/T[c]	0.3×10^{6}
Kerosene	100×10^{6} T[b]	24×10^{-4} T/T[c]	0.2×10^{6}
Distillate	287×10^{6} T[b]	70×10^{-4} T/T[c]	2.0×10^{6}
Residual	507×10^{6} T[b]	400×10^{-4} T/T[c]	20.3×10^{6}
Petroleum Refining	$11{,}317 \times 10^{6}$ bbl[b]	50 T/10^{5} bbl[c]	5.7×10^{6}
Smelting			
Copper	6.45×10^{6} T[d]	2.0 T/T[e]	12.9×10^{6}
Lead	3.0×10^{6} T[d]	0.5 T/T[e]	1.5×10^{6}
Zinc	4.4×10^{6} T[d]	0.3 T/T[e]	1.3×10^{6}
			146.2×10^{6} tons (132.6×10^{6} Metric Tons) (1.32×10^{14} grams)

[a] Includes lignite.

[b] U.S. Statistical Abstracts, Table No. 1256, 1967.

[c] Derived from Rohrman and Ludwig (1965).

[d] U.S. Bureau of Mines, Mineral Trade Notes (1967).

[e] SRI, derived from 1967 smelter data.

Table 4. World-wide annual emissions of sulfur dioxide.

Emission	Source	Amount, tons	Amount as Sulfur, tons
SO_4 Aerosol	Sea spray	130×10^6[a]	44×10^6
H_2S	Biological decay in ocean	30×10^6[b,c]	30×10^6
	Biological decay on land	$60-80 \times 10^6$[a,b,d]	70×10^6
	Pollutants	3×10^6[b]	3×10^6
SO_2	Pollutants	146×10^6[b]	73×10^6
			220×10^6 ($200X10^6$ Metric Tons)

[a] Ericksson (1959, 1960).

[b] This study.

[c] Ericksson estimates this as high as 200×10^6 tons H_2S.

[d] Junge (1963).

Table 5. Annual world amounts of sulfur introduce into the atmosphere.

PARTICULATE MATTER EMISSIONS

Figure 1 illustrates in some detail the distribution of particulate emissions by industry. Table 6 also summarizes this data.[8]

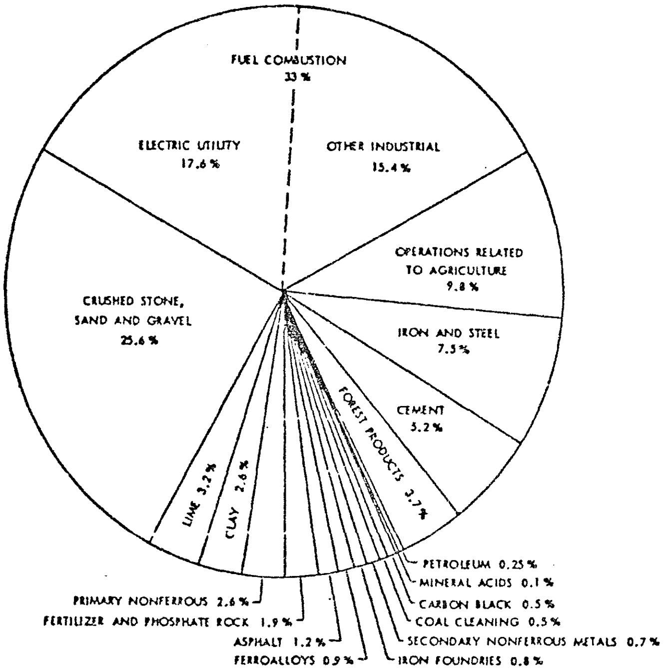

Figure 1. Distribution of particulate emissions by industrial sources.

Source	Emissions (tons/year)
Fuel Combustion	5,953,000
Crushed Stone, Sand and Gravel	4,600,000
Agricultural Operations (grain elevators, feed mills and cotton gins)	1,817,000
Iron and Steel	1,442,000
Cement	934,000
Forest Products	580,000
Lime	573,000
Clay	467,000
Primary Nonferrous (copper, aluminum, zinc and lead)	476,000
Fertilizer and Phosphate Rock	328,000
Asphalt (batch plants and roofing)	218,000
Ferroalloy	160,000
Iron Foundries	143,000
Secondary Nonferrous (copper, aluminum, zinc and lead)	127,000
Coal Cleaning	94,000
Carbon Black	93,000
Petroleum	45,000
Acids (sulfuric and phosphoric)	16,000
Total	18,066,000

Table 6. Major industrial sources of particulate pollution.

Nonindustrial sources of particulate pollutants with their corresponding emission estimates are shown in Table 7. This is included here merely for comparison purposes.

The emission of particulate pollutants to the atmosphere create numerous problems related to health, esthetics, and/or economics. The degree of severity of the various problems is related principally to:

- the total rate of emission
- the physical and chemical characteristics of the emissions
- the environment surrounding the emission source

Source	Emissions (tons/yr)	
A. Natural Dusts		63,000,000
B. Forest Fires		
1. Wildfire	37,000,000	
2. Controlled fire		
(a) slash burning	6,000,000	
(b) accumulated litter	11,000,000	
3. Agricultural burning	2,400,000	56,400,000
C. Transportation		
1. Motor vehicles		
(a) gasoline	420,000	
(b) diesel	260,000	
2. Aircraft	30,000	
3. Railroads	220,000	
4. Water transport	150,000	
5. Non-highway use		
(a) agriculture	79,000	
(b) commercial	12,000	
(c) construction	3,000	
(d) other	26,000	1,200,000
D. Incineration		
1. Municipal incineration	98,000	
2. On-site incineration	185,000	
3. Wigwam burners (excl. Forest Products disposal)	35,000	
4. Open dump	613,000	931,000
E. Other Minor Sources		
1. Rubber from tires	300,000	
2. Cigarette smoke	230,000	
3. Cosmic dust	24,000	
4. Aerosols from spray cans	390,000	
5. Ocean salt spray	340,000	1,284,000
TOTAL		122,815,000

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Table 7. Miscellaneous significant sources of particulate pollution.

A source particulate pollution may, therefore, be important because of the total amount released or because of the objectionable properties of the material emitted.[8]

The majority of atmospheric pollution existing today is in the form of smoke or dust of a size which falls out or is washed out of the atmosphere within a matter of hours or days. The remaining pollutant, however, is of a size and shape (particles a micron or smaller in diameter) which may exist in the atmosphere for long periods of time. Fine particles contribute significantly to all the major adverse aspects of air pollution and

? unit ? singular

can consequently initiate or contribute to problems related to:

- human health
- atmospheric physical properties
- economics
- natural environment

Tables 8 and 9 summarize the estimates of fine particle emissions on the basis of mass and number of emitted particles. The emission totals are based on 1968 production data and 1969-70 application of control information. Fine particle emissions from potentially significant industrial categories such as grain and feed mills, primary nonferrous metallurgy, food processing, and clay products could not be estimated because of incomplete data. Fine particle emissions from the industrial sources listed in Table 8 are estimated to be at least 3.63 X 10^6 metric tons/year. This represents approximately 20-25 percent of the total mass emissions from these sources.[8]

Table 10 presents a source priority ranking, based on the mass and number of fine particles emitted, of the industrial sources for which adequate information was available to estimate emissions. The priority ranking indicates first order sources where initial efforts should be focused to control the emission of fine particulate pollutants.

Particulate Effluent Characteristics[8]

The severity of the problems associated with the sources of particulate air pollution are dependent on the total amount or rate of emission as well as the physical and chemical characteristics of the emissions themselves. Effluent characteristics which are classified as objectionable aspects of a pollution source include:

- particle size distribution
- toxicity
- corrosivity
- sailing potential
- optical properties

Source	Fine Particle Size Ranges (Microns)					Total	Reliability Rating*
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05		
1. Stationary Combustion							
A. Coal							
1. Electric Utility							
a. Pulverized	591.6	178.6	99.2	2.9		872.3	1
b. Stoker	21.7	5.7	2.2			29.6	1
c. Cyclone	48.2	13.9	7.3	0.2		69.6	1
Total from Electric Utility						971.5	
2. Industrial							
a. Pulverized	15.1	0.5				15.6	3
b. Stoker	56.6	7.3	2.1			66	3
c. Cyclone	13.5	6.7	4.1	0.1		24.4	3
Total from Industrial Coal						106	
B. Fuel Oil							
1. Electric Utility and Industrial	126.9					126.9	3
C. Natural Gas and LPG							
1. Electric Utility and Industrial	97.2					97.2	3
Total from Fuel Oil and Gas						224.1	
Total from Fuel Combustion						1301.6	
2. Crushed Stone	740.4	92.9	34.7			868	5
3. Iron and Steel							
A. Sinter Machines	3.8	1.2	0.6			5.6	3
B. Open Hearth Furnace	60-80	20-56	8.5-234	0.1-22	0-3.6	108-376	4
C. Basic Oxygen Furnace	0.9	18.9	153.7	1.0		174.5	3
D. Electric Arc Furnace	3.8	2.5	5.2	1.3	1.5	14.3	3
Total from Iron and Steel						302.4-570.4	
4. Kraft Pulp Mills							
A. Bark Boilers	49.1	11.9	6.5	0.3		67.8	3
B. Recovery Furnace	95.3	78	74.7	1.4		249.4	3
C. Lime Kiln	1.6	0.2				1.8	4
Total from Kraft Pulp Mills						319	
5. Cement Plants, Rotary Kilns	130.8	32.7	13.5			177	2
6. Hot-Mix Asphalt Plants							
A. Rotary Dryer	96.4	36.3	21.5			154.2	3
B. Ventline	14.4	1.7	0.2			16.3	3
Total from Hot-Mix Asphalt Plants						170.5	
7. Ferroalloys							
A. Electric Furnace	18.4	27.8	81.1	17.3	7.7	152.3	3
B. Blast Furnace	0.8					0.8	3
Total from Ferroalloys						153.1	
8. Lime Plants							
A. Rotary Kilns	40.6	18.8	23.6	3.0	1.8	87.8	2
B. Crushing and Screening	25-99					25	4
Total from Lime Plants						113	
9. Secondary Nonferrous Metallurgy	127					127	5
10. Carbon Black	93					93	3
11. Coal Preparation Plants, Thermal Dryer	63.5					63.5	4
12. Petroleum FCC Units	45					45	4
13. Municipal Incinerators	10.4	6.7	11.5	3.5	4.3	36.4	2
14. Fertilizer, Granulators and Dryers	7.1	3.5	3.1			13.7	3
15. Iron Foundries, Cupolas	6.8	2.4	3.1	0.4	0.4	13.1	2
16. Acids							
A. Sulfuric	2.7					2.7	4
B. Phosphoric (thermal)	1.0					1.0	4
Total from Acids						3.7	
Total from Major Industrial Sources						3800-4068	

*Reliability rating is indicative of the relative reliability of the emission quantities. Ratings range from 1 to 5 with 1 being the most reliable.

Note: Potentially significant sources not evaluated because of lack of sufficient data: (1) operations related to agriculture, (2) primary nonferrous metallurgy, (3) clay products, (4) food processing operations, and (5) fiberglass manufacture.

Table 8. Fine particle emissions from industrial sources (mass basis, 10^3 tons/year).

	Fine Particles Size Range (Microns)					
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
Stationary Fuel Combustion						
A. Coal						
1. Electric Utility						
a. Pulverized	5.1×10^{22}	29.5×10^{22}	250×10^{22}	480×10^{22}		765×10^{22}
b. Stoker	0.2×10^{22}	0.9×10^{22}	5.6×10^{22}			6.7×10^{22}
c. Cyclone	0.42×10^{22}	2.3×10^{22}	18.5×10^{22}	83×10^{22}		104×10^{22}
2. Industrial						
a. Pulverized	0.3×10^{22}	0.08×10^{22}				0.38×10^{22}
b. Stoker	0.5×10^{22}	1.2×10^{22}	5.6×10^{22}			7.3×10^{22}
c. Cyclone	0.12×10^{22}	1.1×10^{22}	10.4×10^{22}	42×10^{22}		53.6×10^{22}
B. Fuel Oil						
1. Electric Utility and Industrial	1.1×10^{22}					1.1×10^{22}
C. Natural Gas						
1. Electric Utility and Industrial	0.85×10^{22}					0.85×10^{22}
Total from Stationary Combustion						939×10^{22}
Crushed Stone	6.8×10^{22}	16.2×10^{22}	94.6×10^{22}			117.6×10^{22}
Iron and Steel						
A. Sinter Machines	2.74×10^{20}	16.5×10^{20}	128×10^{20}			142.7×10^{20}
B. Steel-Making Furnaces						
1. Open Hearth	$2.62-3.48 \times 10^{21}$	$16.2-45.8 \times 10^{21}$	$109-3000 \times 10^{21}$	$0.83-180 \times 10^{23}$	$0-4.6 \times 10^{25}$	$2.1-670 \times 10^{23}$
2. Basic Oxygen	5.6×10^{20}	22.2×10^{21}	2.82×10^{24}	1.08×10^{25}		3.92×10^{24}
3. Electric Arc	2.1×10^{20}	26.4×10^{20}	8.5×10^{22}	1.37×10^{24}	24.7×10^{24}	26.2×10^{24}
Total from Iron and Steel						$3-9.7 \times 10^{25}$
Kraft Pulp Mills						
A. Bark Boiler	4.25×10^{21}	19.6×10^{21}	167×10^{21}	500×10^{21}		69×10^{22}
B. Recovery Furnace	8.25×10^{21}	129×10^{21}	19.2×10^{23}	23.4×10^{23}		44×10^{23}
C. Lime Kiln	1.4×10^{20}	3.3×10^{20}				4.7×10^{20}
Total from Kraft Pulp Mills						50.9×10^{23}
Cement Plants	9.7×10^{21}	46.4×10^{21}	3×10^{23}			3.6×10^{23}
Hot-Mix Asphalt Plants						
A. Rotary Dryer	8×10^{21}	57.5×10^{21}	5.3×10^{23}			6×10^{23}
B. Secondary Sources	1.2×10^{21}	2.7×10^{21}	4.95×10^{23}			4.4×10^{21}
Total from Asphalt Plants						6×10^{23}
Ferroalloys						
A. Electric Furnace	1.33×10^{21}	37×10^{21}	17.3×10^{23}	2.3×10^{25}	16.5×10^{25}	19×10^{25}
B. Blast Furnace	5.8×10^{19}					5.8×10^{19}
Total from Ferroalloys						19×10^{25}
Lime Plants						
A. Rotary Kiln	3.14×10^{21}	27.6×10^{21}	5.4×10^{23}	4.4×10^{24}	4.1×10^{25}	46×10^{24}
B. Crushing and Screening	1.93×10^{21}					1.93×10^{21}
Total from Lime Plants						46×10^{24}
Secondary Nonferrous Metallurgy	7.85×10^{21}					7.85×10^{21}
Carbon Black	1×10^{22}					1×10^{22}
Coal Preparation Plants, Thermal Dryers	3.9×10^{21}					3.9×10^{21}
Petroleum FCC Units	3.7×10^{21}					3.7×10^{21}
Municipal Incinerators	9×10^{20}	11×10^{21}	3×10^{23}	5.8×10^{24}	11×10^{25}	11.6×10^{25}
Fertilizer	7.7×10^{20}	72×10^{20}	9.95×10^{22}			10.7×10^{22}
Iron Foundries, Cupolas	5.25×10^{20}	35.3×10^{20}	7.1×10^{22}	5.9×10^{23}	9.2×10^{24}	9.9×10^{24}
Acids						
A. Sulfuric	3.4×10^{20}					3.4×10^{20}
B. Phosphoric	1.2×10^{20}					1.2×10^{20}
Total from Acids						4.6×10^{20}
Total from Major Industrial Sources						$40.2-46.9 \times 10^{25}$

Table 9. Fine particle emissions from industrial sources (number basis, particles/year).

1. Ferroalloy Furnaces
2. Steel-Making Furnaces
3. Coal-Fired Power Plants
4. Lime Kilns
5. Kraft Pulp Mill Recovery Furnaces
6. Municipal Incinerators
7. Iron Foundry Cupolas
8. Crushed Stone Plants
9. Hot Mix Asphalt Plants
10. Cement Kilns

Table 10. Priority ranking of industrial sources of fine particulate pollutants.

Particle and carrier gas properties which are classified as important variables for control device design and/or selection include:

- particle size distribution and shape
- particle density
- electrical resistivity
- volumetric flowrate
- gas temperature
- humidity

Particle Size--Particle size is an important factor when considering the proper selection of gas cleaning equipment. Particles >10μ generally may be removed and/or eliminated by use of inertial and cyclone separators, and simple low energy wet scrubbers. Particles <10μ require the use of high efficiency (generally meaning high energy) wet scrubbers, fabric filters, and/or electrostatic precipitators.

Particle Shape--Fogs, mists and various smokes are generally composed of spherical liquids or tarry droplets. Fly ash particles, produced in the combustion of coal, are hollow spheres or cenospheres frequently having surface attachments of much smaller satellite particles. Dust particles are generally irregular in shape. Many metallurgical fumes have a star-like or plate-like arrangement, while others are needlelike and tend to form agglomerated chains. Particle shape and surface condition influence handling characteristics, chemical reactivities, absorption potentials, and flammability limits among other particulate properties.

Solids Loading--Grain loading and particle size often dictate the choice of a particular piece of control equipment. Solids loading is most often expressed as grains per cubic foot (1 grain = 1/7000 lbs.). Very high grain loadings may require the use of a series of control devices to meet air pollution regulations.

Electrical Properties--The critical electrical property of particulates is the electrical charge or conductivity of the material. Practically all natural or industrial dusts are electrically charged to an appreciable degree.

Moisture Content--Moisture content influences both selection of control equipment and particulate characteristics. Particle resistivity, flammability, and handling characteristics are strongly influenced by moisture content.

Toxicity--Toxicity characteristics of particulates and carrier gases define important health aspects of particulate emissions. The toxicity aspects of the particulates may dictate the use of a control device where it would not otherwise be required.

Flammability or Explosive Limits--Flammability and explosive factors influence selection of control equipment and define handling hazards. Ignition and explosion behavior of dust is affected by electrostatic charging, chemical composition, the size and state of the solid surface, moisture content, and dust thermal properties. Carrier-gas temperature, pressure, and chemical composition also affect these limits.

Chemical Composition--Particulate and carrier-gas chemical compositions exert an influence on the ultimate choice of pollution control devices and auxiliary handling equipment. Composition also has an influence on such parameters as electrical properties, toxicity, reactivity, wettability, and most other particle properties.

Table 11 lists those sources which are difficult to control in the metallurgical, chemical, combustion and mechanical process categories. Factors which complicate controls are noted. Metallurgical, chemical and combustion processes are inherently more difficult to control than mechanical processes.

Figure 2 outlines the more important factors to be considered with respect to the gas stream and particle characteristics of a particular industrial process.

THE COPPER INDUSTRY

Air pollution problems exist in all phases of the copper industry. Potential dust problems are foreseen in the actual open pit mining operation, also in the primary crushing and grinding of the ores, in the flotation process, in the smelting operation, and in the electrolytic refining of the metal. Problems associated with all the phases, excluding the smelting phase, seem to be easily controllable and do not create significant air pollution.

Source	Problem
Metallurgical Processes:	
Iron and steel	
Sinter machine	High temperature and high volumetric flowrate carrier-gas. SO_2 content. High particle electrical resistivity. Fluorides in effluent are corrosive.
Electric furnace	Small particle size of particulate (70 wt.% <5 micron). Particulates have a strong tendency to adhere to fabric surfaces, high angle of repose and a high electrical resistivity.
Coke ovens	Basic nature of charging and pushing steps.
Gray iron foundries	
Cupola	Small size of particulate (25 to 30 wt.% <10 micron). Variable gas-stream conditions. Fluxing agents may produce corrosive effluents.
Electric furnace	Small size of particulate.
Primary nonferrous	
Copper and lead	
Blast, reverberatory & refining furnaces	Small size of particulate (metallic fumes). Particulates are cohesive and will bridge and arch in hoppers.
Zinc	
Horizontal retort	Small size of particulate (metallic fumes). High volumetric flowrate of carrier-gas. Low outlet grain loading.
Aluminum	
Reduction cells	Small particle size of particulate. High volumetric flowrate of carrier-gas. Particulates may contain tar and fluorides. Particulates and carrier gas are corrosive.
Refining furnaces	Small particle size of particulate. Particulate and carrier-gas are corrosive.
Secondary nonferrous	
Furnaces	Small particle size of particulate. Particulates may be abrasive or corrosive. Particulates may have high electrical resistivity. High temperature carrier-gas.
Ferroalloys	
Blast furnace	Small particle size of particulate (80 wt% <1 micron). High temperature and high volumetric flowrate carrier-gas. Carrier-gas is potentially explosive because of high CO content.
Electric furnace	Small particle size of particulate. Particulates have high electrical resistivity.
Chemical Processes:	
Acid manufacture	
Sulfuric (contact process)	
Absorber	Small particle size of particulate (acid mist). Corrosive effluent.
Phosphoric (thermal process) Absorber	Small particle size of particulate (acid mist). Corrosive effluent.
Fertilizer manufacture	
Dryers and coolers	Small particle size of particulate (fluoride fumes).
Prill towers	Nature of process.
Pulp mills	
Recovery furnace	Small particle size of particulates (50 wt.% 1 micron). High volumetric flowrate.
Carbon black	
Channel process	Nature of process. Small size of particulate.
Furnace process	Small size of particulate
Combustion Sources:	
Power plants (electric utility & industrial)	Small particle size of particulate from some furnaces.
Slash and field burning	Nature of process. Multiple sources.
Incineration	Multiple sources.
Mechanical Processes:	
Crushed stone, sand and gravel	
Stockpiles	Nature of process.
Materials handling	Multiple sources.
Grain elevators	
Materials handling	Multiple sources.

Table 11. Particulate pollution sources difficult to control.

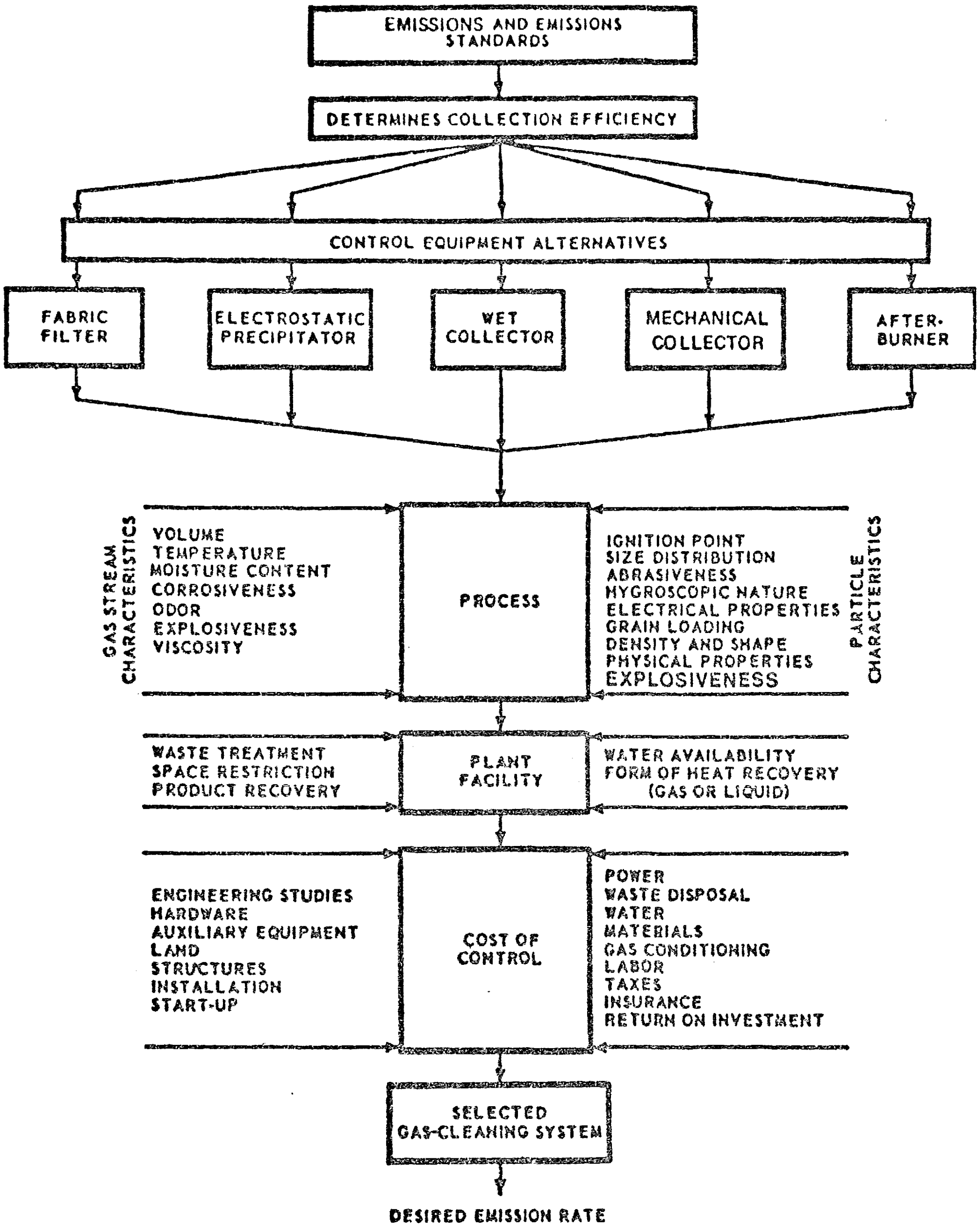


Figure 2. Criteria for selection of gas-cleaning equipment.

PRIMARY COPPER PYROMETALLURGY

Figure 3 outlines the principal processes for the extraction of copper from sulfide enriched ores. The processes are basically pyrometallurgical processes involving the major metallurgical steps of roasting, smelting and converting. Each of the three primary steps emits gases and dust as potential pollutants.

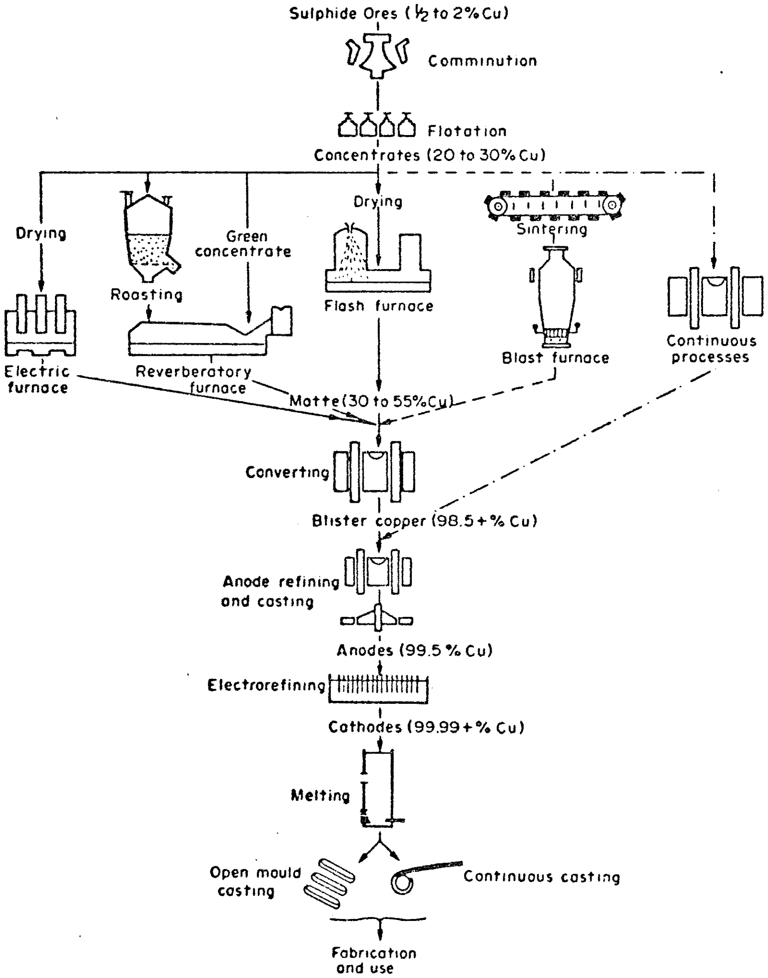


Figure 3. Principal processes for extracting copper from sulfide ores. Parallel lines indicate alternative processes.
(—— Established; ---- Rare; -- · -- · -- · Under development)

Roasting[2]

In roasting, the concentrated sulfide ore is dried and heated until the sulfur begins to combine with oxygen to form sulfur dioxide gas (SO_2) which is removed in a gaseous stream. Ores rich in sulfur are roasted to lower the sulfur content to a level adequate for smelting which is the next operation to follow (ores low in sulfur content generally bypass the roasting stage). The process is usually autogenous, Jergon however, some hydrocarbon fuel may be required if the concentrates are excessively moist. Temperatures generally range from 500-700°C in the roasting chambers (temperatures of 500-550°C are maintained with iron enriched ores in order to avoid the formation of iron oxides.) Roasting is not applicable to blast-furnace, flash, or single-step smelting all of which incorporate the roasting reactions in the smelting step.

Roasting produces SO_2 and volatile oxides of arsenic, antimony, lead and other trace elements. Roasting, therefore, involves a net elimination of sulfur and leads to a smelting product (matte) which is of considerably higher copper grade than the original concentrate.

Dust content generated during the roasting reactions depend principally on:

- characteristics of the copper concentrates what kind of characteristics
- volume of air aspirated by the roasting furnace
- extent to which concentrates remain continuously in suspension in traveling from hearth to hearth
- size and number of the aperatures in the hearth

Multiple-hearth roasters (Figure 4) used in the roasting of copper ores, operate at temperatures approaching 650°C. The SO_2 in the offgas ranges between 5 and 10 percent, a consequence of low efficiencies in the furnace and dilution by air. Hearth roasters treat approximately 0.5-1.0 metric

sp?

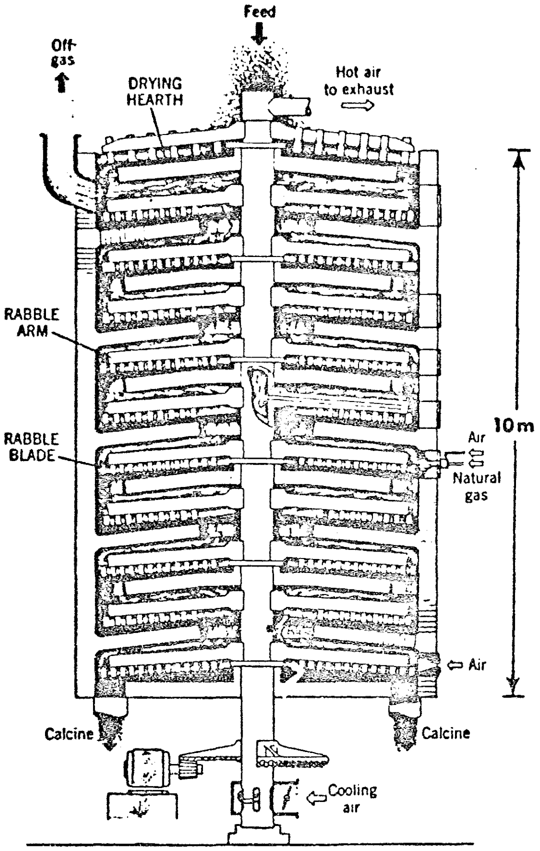
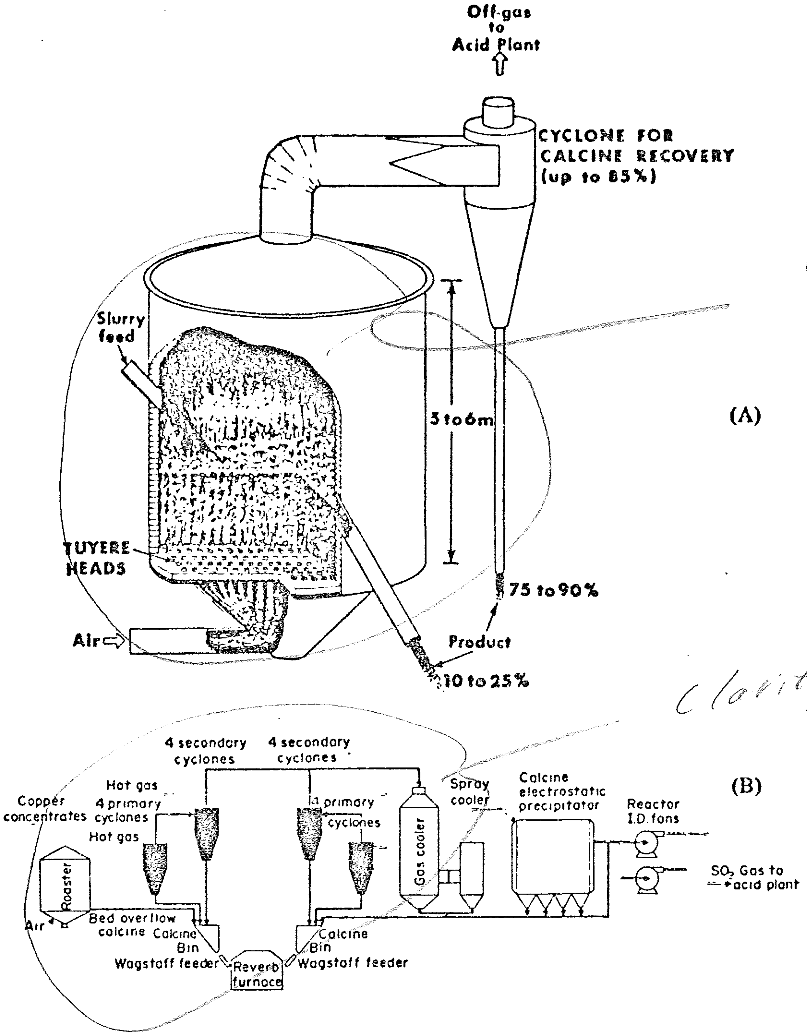


Figure 4. Cutaway view of a multiple hearth roaster.

meter^2

tons of charge per M^2 of hearth per day, which is equivalent to eliminating 0.1-0.2 metric tons of sulfur per M^2 per day. Dust loads in the offgas are often 3 to 6 percent of the weight of the feed.

Fluid-bed roasters (Figure 5) operate in the same temperature region as the multiple-hearth units. Oxidation of the sulfide particles occur while they are suspended in an evenly distributed stream of air. The rates of reaction are considered to be instantaneous. While at high gas velocities, 75-90 percent of the feed is carried off in the gas stream, however, the majority is immediately recovered in cyclone collectors and recycled back to the roaster.



Can resolution be increased

Clarity ?

Figure 5. (A) Cutaway view of a fluid-bed roaster, and (B) Roaster-reverberatory furnace flowsheet.

The fluid bed roaster is considered to be the best device for the roasting of sulfide ores. It has a high production rate, excellent temperature control, and produces a gas of 10-15 percent SO_2, which is an excellent feedstock for a contact sulfuric acid plant.

Smelting[2]

Matte smelting is a process for metal extraction involving the reduction of feed to molten metal or matte (matte is an artificially created sulfide), which easily separates from a siliceous iron slag which also forms in the melt. Gangue material usually melts at higher temperatures than the matte, so it is necessary to add fluxes which allow this gangue to become sufficiently liquid at the furnace temperature to form the slag. The major metals simultaneously combine with sulfur to form the valuable matte.

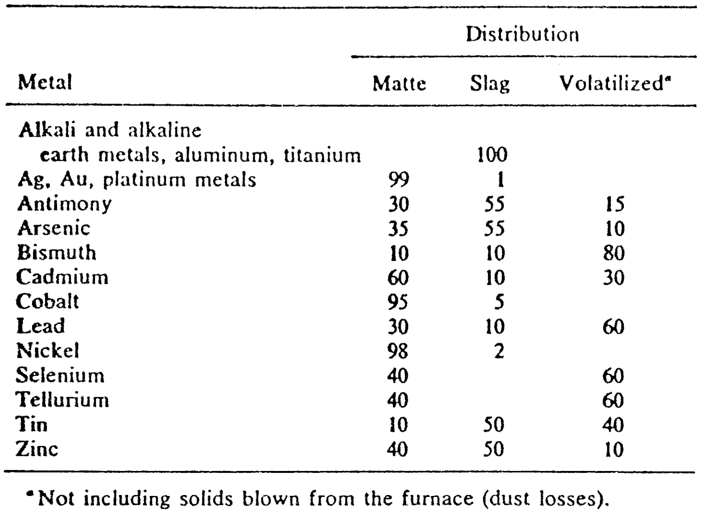
Smelting produces SO_2 and volatile oxides of arsenic, antimony, lead, selenium, tellurium and other trace elements. Depending on the material being processed, the dusts emitted in smelting may have commercial value when collected or may pose pollution problems when emitted to the environment.

The behavior of metals other than copper and iron during matte smelting is estimated in Table 12. These data serve only as a guide and the precise distribution of minor elements depends upon the smelting conditions and the type of process. The most important points are:

a) Gold, silver, the platinum metals, cobalt and nickel enter the matte almost completely, these metals are carried forward to the converting operation and they are finally recovered as by-products during the electrorefining of anode copper.

b) Significant quantities of impurities harmful to copper also enter the matte; specifically antimony, arsenic, bismuth, lead, selenium and tellurium. Some of these are also recovered as by-products during subsequent converting and refining operations.

c) Much of the zinc reports in the slag from which it can be recovered by "slag fuming" (reduction) if it is present in sufficient quantities (Mast and Kent, 1955).



Metal	Distribution		
	Matte	Slag	Volatilized*
Alkali and alkaline earth metals, aluminum, titanium		100	
Ag, Au, platinum metals	99	1	
Antimony	30	55	15
Arsenic	35	55	10
Bismuth	10	10	80
Cadmium	60	10	30
Cobalt	95	5	
Lead	30	10	60
Nickel	98	2	
Selenium	40		60
Tellurium	40		60
Tin	10	50	40
Zinc	40	50	10

*Not including solids blown from the furnace (dust losses).

Table 12. Estimated distribution of elements other than copper and iron during matte smelting.

Blast-Furnace Matte Smelting--Blast-furnace smelting (Figure 6) was used extensively in the past for producing large quantities of matte from lump sulphide ores. It was also used at one time to produce a crude, iron-contaminated "black copper" from oxide ores. However, depletion of rich lump ores and the increasing prevalence of froth flotation concentrates have gradually eliminated the blast furnace from matte smelting. The blast furnace is unable to directly treat finely ground flotation concentrates because they are quickly blown out of the furnace by the rising combustion gases. However, the blast furnace still finds some use (usually with a sintered charge) in Africa where mixed oxide-sulphide ores are treated, in Canada for Cu-Ni concentrates, and in Japan. World-wide there were fewer than 10 matte blast furnaces remaining in operation by 1974.

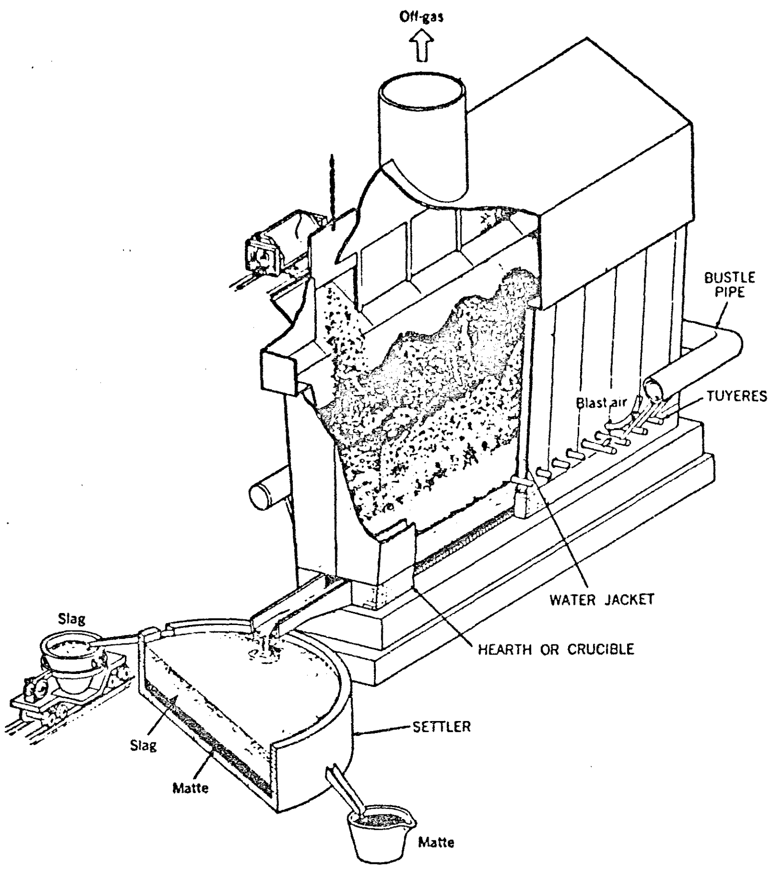


Figure 6. Cutaway view of a blast furnace for producing copper matte from sulfide ores.

Typical charge to the blast furnace consists of sintered concentrates, lump ores, silica fluxes, converter slags, and metallurgical cokes. The products of the furnace include:

- a copper-rich liquid matte (∿ 50 percent Cu)
- a liquid slag
- gases containing approximately 5 percent SO_2. (gases are generally laden with dust)

<u>Reverberatory-Furnace Matte Smelting</u>--The reverberatory furnace is the most widely used unit for matte smelting. It is a fuel-fired hearth furnace in which

concentrates or roaster calcines are melted to produce separate layers of liquid matte and slag. The dimensions of reverberatory furnaces vary considerably, but modern furnaces (Figure 7) are typically 33 m long (inside), 10 m wide and 4 m high (hearth to roof). Furnaces of these dimensions produce in the order of 500-800 metric tons of matte (35-40 percent Cu) and 500-900 metric tons of discard slag per day. A smelter usually has from one to three such furnaces. The reverberatory furnace is also used (simultaneously with smelting) to recover copper from recycled, molten converter slag.

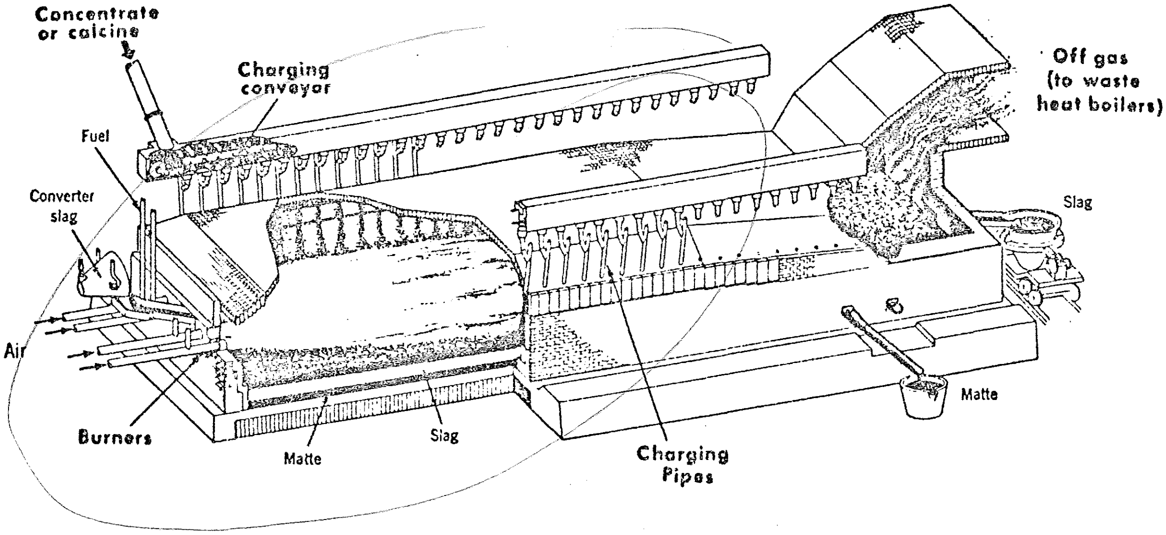


Figure 7. Cutaway view of a reverberatory furnace for the production of copper matte from sulfide concentrates or roasted calcines.

The extensive use of reverberatory furnaces is due to their high degree of versatility. The heat for smelting is provided by burning fuel in the furnace and by passing the hot combustion gases over the charge. All types of material, lumpy or fine, wet or dry, can be readily smelted. There are approximately 100 reverberatory furnaces in use world-wide (1975).

During the melting phase in a reverberatory furnace, approximately 20-50 percent of the sulfur in the charge is oxidized. The range of sulfur dioxide concentration in the wet offgas is 0.5 to 2.5 percent depending on the feed and operating conditions. Of the sulfur in the charge, 70-80 percent is removed in the matte, 18-30 percent in the flue gas, and 1-2 percent in the slag.

Dust from the reverberatory furnace is a substantial problem. Heavier particles settle below the waste heat boilers and into the hoppers of the balloon flues or settling chambers. Practically all of the copper smelters use drag or screw conveyors for the removal of dust from places of accumulation. Collected dusts are returned to the system.

Generated dusts depend on:

- fineness of the charge
- degree of agitation in charging and working
- specific gravity

<u>Electric-Furnace Matte Smelting</u>--The electric furnace (Figure 8) is an electrically heated hearth furnace which performs the same functions as that of the reverberatory furnace. It is used where electrical energy is inexpensive and where SO_2 evolution from the smelter must be tightly controlled. The electric furnace and the reverberatory furnace are equally suitable for obtaining the relatively low temperatures (1200^oC) of copper matte smelting.

The electric furnace has two environmental advantages over the reverberatory furnace:

a) it produces smaller quantities of effluent gases, due to the absence of gaseous combustion products.

b) the SO_2 concentrations of its effluent gases are readily controlled by adjusting the amount of air infiltration into

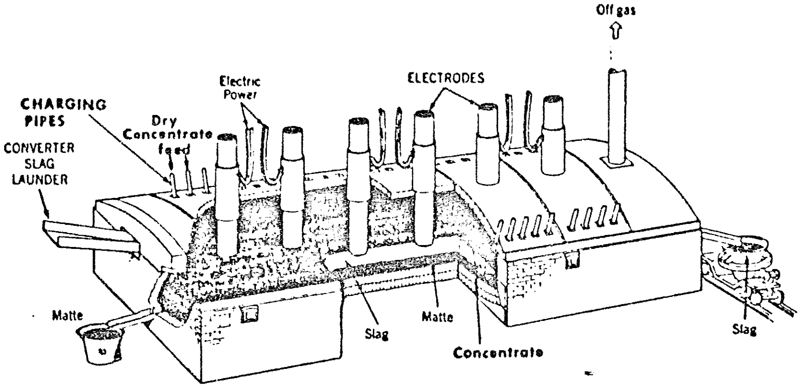


Figure 8. Cutaway view of a submerged arc electric furnace for the production of matte from dry sulfide concentrates or roasted calcines.

> the furnace. With a minimum amount of air infiltration, the SO_2 concentration may be as low as 0.4 percent, for venting directly to the atmosphere (Mostert, 1973), while extensive air infiltration and sulphide oxidation leads to SO_2 concentrations in the order of 5 percent (Rodolff and Marble, 1972). This latter gas is blended with converter gases and the SO_2 is extracted from both as sulphric acid.

The electric furnace has the same versatility as the reverberatory furnace, and this factor plus the environmental advantages have led to its adoption for new smelting capacity in several environmentally sensitive areas (Dayton, 1974). Worldwide there are approximately 15 electric matte smelting furnaces in operation including those used for producing Cu-Ni mattes.

Mattes and slags produced in electric furnaces are similar in nature to the mattes and slags from the reverberatory furnace. SO_2 gas emissions generally range from 2-4 percent with minimal dust losses, a consequence of low gas velocities. Figure 9 illustrates, in generalized form, a typical flowsheet of a smelting system utilizing an electric furnace for matte production.

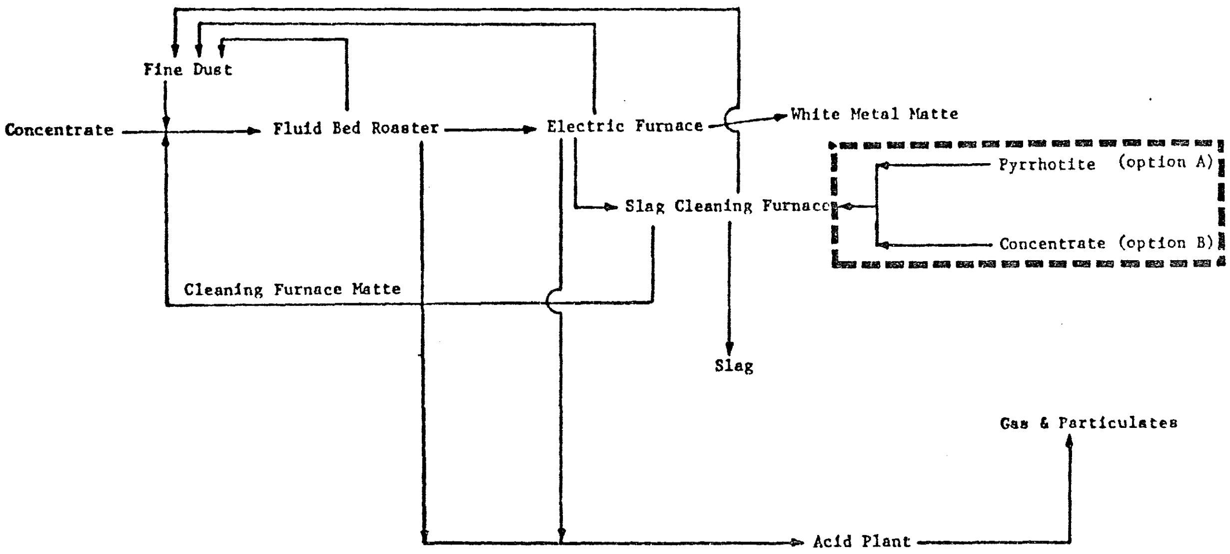


Figure 9. Combination fluid bed - electric furnace for the production of commercial grade Cu-Ni metal.

Table 13 and 13A summarize the material balance of the major metals, trace elements, and principal impurities of a typical Cu-Ni concentrate utilizing the above system. Calculations are based on the production of 100,000 metric tons/year of commercial grade Cu-Ni metal. Figure 9A summarizes particulate emissions based on varying efficiency factors.

Input Products	Cu	Ni	Fe	S	Co	SiO_2	CaO	MgO	Al_2O_3	As	Pb	Zn	Cd	Ag	Au	Rh	Pt	Pd
Concentrate & Dust	69263	14842	143474	113789	693	74210	6085	21768	11973	15.34	39.58	1880	19.79	23.06	.71	.0087	.88	2.09
Flux			19170															
Cleaning F. Matte	8672	4947	22249	9531														
Pyrrhotite Conc.			6082	3496														
INTERMEDIATE CALCINE	74818	18998	177496	27309														
Output Products																		
White Metal Matte	63790	13219	3478	19002	485									22.26	.69	.0080	.85	2.01
Cleaning F. Matte	8672	4947	22249	9531														
Clean or Dump Slag	877	461	157326	835			6085	21768	11973	1.54	35.65	1598	1.98	0.80	.02	.0007	.03	.08
Dusts (fluid bed)4%	3118	792	7396	4933														
Dusts (electric F.)2%	1302	270	71	388														
Dusts (electric F.)2%	177	101	454	194														
Total Dusts	4597	1163	7921	5515	208													
Flue Dust (recycle)	4136	1047	7129	4964	187					12.42	3.57	254	16.03					
Particulate Emissions	461	116	792	551	21					1.38	.36	28	1.78					
Gas Emissions				4514														

Unreadable

BULK CONCENTRATE ANALYSIS

ELEMENT	WT %
Cu	14.0
Ni	3.0
Fe	29.0
S	23.0
SiO_2	15.0
CaO	1.23
MgO	4.4
Al_2O_3	2.42
As	0.0031
Pb	0.008
Zn	0.38
Cd	0.004
Ag	0.00467
Au	0.000145
Rh	0.00000176
Pt	0.000178
Pd	0.000422

ASSUMPTIONS

1) Common constituents of volatile fumes and/or particulates

Bismuth (Bi)	*Zinc (Zn)	Tin (Sn)
*Arsenic (As)	*Nickel (Ni)	*Cobalt (Co)
Antimony (Sb)	Selenium (Se)	*Cadmium (Cd)
*Lead (Pb)	Tellurium (Te)	

*Considered in the material balance.

2) Exhaust gases contain some molten or semi-molten dust particles. Volatile compounds tend to be concentrated in the dust.

3) Zinc: Major portion of zinc constituent is oxidized and distributed into slag. A portion partly volatilized.

85% into slag — Concentrates high in zinc
15% into dust — Volatilization rate = 20-30%

4) Lead: Major portion goes to matte. Pbs in matte is then oxidized partly to PbO in the converting furnace and distributed into slag.

90% into matte — Concentrates high in zinc
10% into dust — Volatilization rate = 60%

5) CaO: MgO: Al_2O_3: Reports principally to the slag.

6) As: 90% of total goes in dust or particulate fraction — Volatilization Rate = 10%
10% of total into slag

7) Cd: 90% of total goes in dust particulate fraction — Volatilization rate = 10%
10% of total into slag

8) Co: 70% into matte
30% as dust or particulate fraction — Volatilization rate = 10%

Table 13. Metallurgical material balance of the principal constituents of a typical Cu-Ni concentrate. (Electric Furnace)
(Units are in metric tons/year)

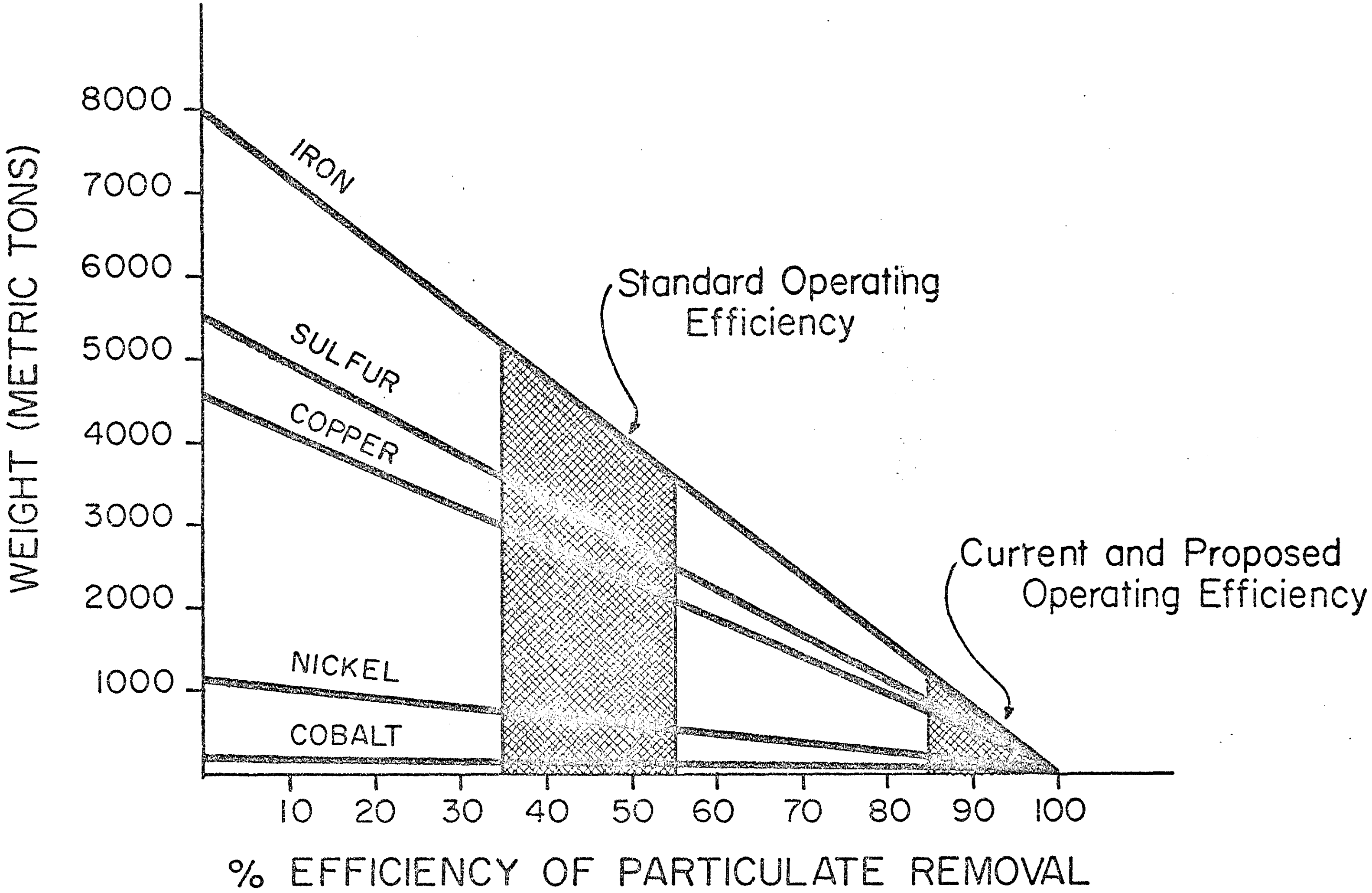
	Input Products	Cu	Ni	Fe	S	Co	SiO_2	CaO	MgO	Al_2O_3	As	Pb	Zn	Cd	Ag	Au	Rh	Pt	Pd
	Concentrate & Dust	89	75	75	90	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Flux			10															
	Cleaning F. Matte	11	25	12	8														
	Pyerhotite Conc.			3	3														
	INTERMEDIATE CALCINE	96	96	93	22														
	Output Products																		
1	White Metal Matte	82	67	2	15	70									97	97	92	97	96
2	Cleaning F. Matte	11	25	12	8			100	100	100	10	90	85	10	3	3	8	3	4
3	Clean or Dump Slag	1	2	82	1														
	Dusts (fluid bed)4%	4	4	4	4														
	Dusts (electric F.)2%	2	1	.04	.31														
	Dusts (electric F.)2%	.23	1	.24	.15														
	Total Dusts	6	6	4.28	4.46	30													
4	Flue Dust (recycle)	5	5	4	4	27					81	9	14	81					
5	Particulate Emissions	1	1		.43	3					9	1	1	9					
	Gas Emissions				4														

1 + 2 + 3 + 4 + 5 = 100%

Table 13A. Metallurgical material balance of the principal constituents of a typical Cu-Ni concentrate. (Electric Furnace) (Numbers are as percents)

FIGURE 9A

PARTICULATE EMISSIONS TO THE ATMOSPHERE PER YEAR AS A FUNCTION OF THE DEGREE OF EFFICIENCY



Absolute Quantities of a Particular Element will Change as the Assumptions to the Material Balance Change.

Flash-Furnace Matte Smelting--Flash furnaces (Figures 10 and 11) utilize the heat evolved from oxidizing part of their sulfide charge to provide much or all of the energy required for smelting. The principal advantage of the flash smelting processes is that their energy costs are considerably lower than those of reverberatory and electric-furnace smelting. Flash furnaces are also excellent from an environmental point of view because they produce SO_2-rich effluent gases from which the SO_2 can be efficiently removed as sulfuric acid or liquid SO_2. For these reasons, flash furnaces have accounted for most of the new matte smelting capacity since 1965. The principal product of flash-furnace smelting is a high-grade (45-50 percent Cu) liquid matte.

There are two basic types of flash smelting.

(a) The INCO process which uses commercial oxygen and which is completely autogenous.

(b) The Outokumpu process which uses preheated air or preheated oxygen enriched air. This process is not autogenous. Hydrocarbon fuel (and in one case electrical energy + fuel, Kitamura et al., 1973) is used to make up the thermal deficit.

Currently (1975) there are twenty Outokumpu flash furnaces in operation (17 built since 1965) and one INCO oxygen flash furnace. Flash furnaces are usually operated singly as the only smelting unit in a smelter.

The gaseous product of the sulfide oxidation reactions is SO_2 and considerable quantities are produced by the flash smelting reactions. The effluent gases produced by the INCO process contain approximately 80 percent SO_2. The SO_2 from the Outokumpu reactions is diluted by nitrogen (from the incoming air) and by hydrocarbon combustion products. Outokumpu effluent gases contain 10-15 percent SO_2. SO_2 is efficiently removed from flash-furnace gases as liquid SO_2 (the INCO process) or as sulfuric acid (the Outokumpu process).

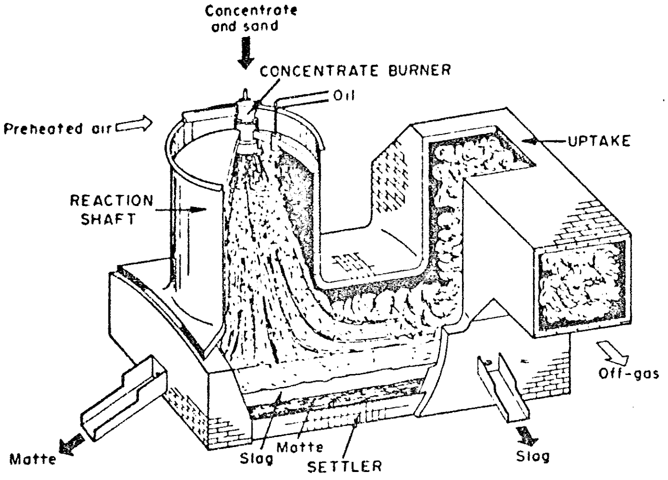


Figure 10. Cutaway view of Outokumpu preheated air flash-smelting furnace.

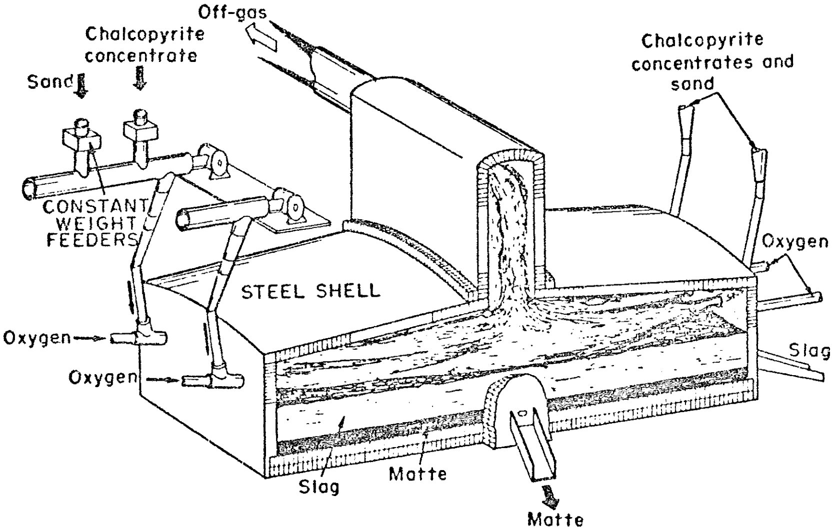


Figure 11. Cutaway view of INCO oxygen flash smelting furnace.

Figure 12 illustrates in generalized form a typical flowsheet of a smelting system utilizing a flash smelting furnace for matte production. Table 14 and 14A summarize the material balance of the major metals, trace elements, and principal impurities of a typical Cu-Ni concentrate utilizing the above system. Calculations are based on the production of 100,000 metric tons/year of commercial grade Cu-Ni metal. Figure 12A summarizes particulate emissions based on varying efficiency factors.

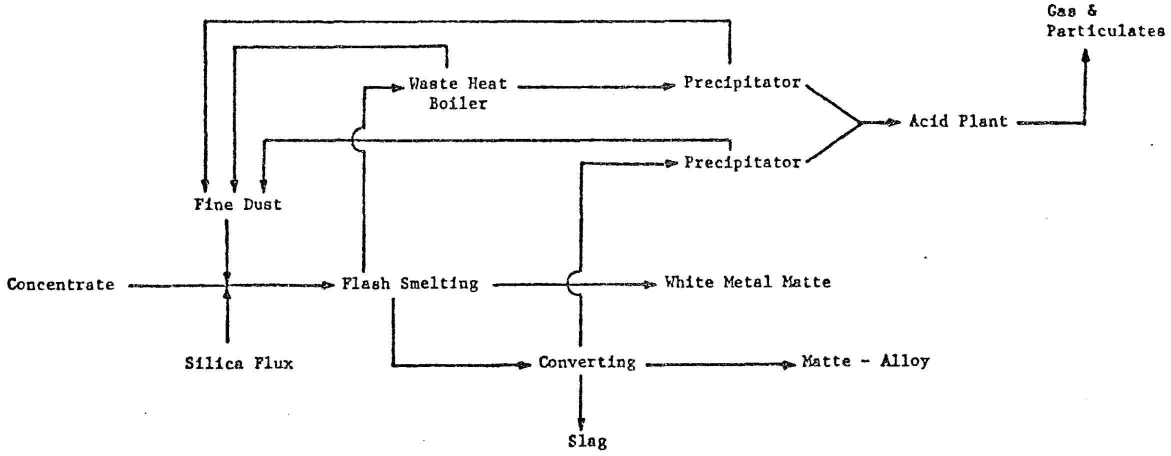


Figure 12. Process flash smelting for the production of commercial grade Cu-Ni metal.

ut Products	Cu	Ni	Fe	S	Co	SiO_2	CaO	MgO	Al_2O_3	As	Pb	Zn	Cd	Ag	Au	Rh	Pt	Pd
centrate & Flux	79785	17092	165280	123707	741	89252	6488	23221	12766	16.07	42.02	2002	21.01	23.06	.71	.0087	.88	2.09
ica Flux						47048												
put Products																		
te Metal Matte	65462	9516	3275	21442	61.79									22.26	.69	.0080	.85	2.01
te - Alloy	7217	5710	1421	2472	457													
p Slag	1207	604	148337	1730		126203	6488	23221	12766	1.61	37.82	1702	2.10	.80	.02	.0007	.03	.08
e Dust (recycle)	5317	1134	11022	2102	208	9083				12.98	3.83	271	17.05					
ticualte Emissions	582	128	1225	234	14.21	1014				1.48	0.37	29	1.86					
Emissions				4793														

BULK CONCENTRATE ANALYSIS

ELEMENT	WT %
Cu	14.0
Ni	3.0
Fe	29.0
S	23.0
SiO_2	15.0
CaO	1.23
MgO	4.4
Al_2O_3	2.42
As	0.0031
Pb	0.008
Zn	0.35
Cd	0.006
Ag	0.00467
Au	0.000145
Rh	0.00000176
Pt	0.000178
Pd	0.000422

ASSUMPTIONS

1) Common constituents of volatile fumes and/or particulates

Bismuth (Bi)	*Zinc (Zn)	Tin (Sn)
*Arsenic (As)	*Nickel (Ni)	*Cobalt (Co)
Antimony (Sb)	Selenium (Se)	*Cadmium (Cd)
*Lead (Pb)	Tellurium (Te)	

*Considered in the material balance.

2) Exhaust gases contain some molten or semi-molten dust particles. Volatile compounds tend to be concentrated in the dust.

3) Zinc: Major portion of zinc constituent is oxidized and distributed into slag. A portion partly volatilized.

85% into slag	Concentrates high in zinc
15% into dust	Volatilization rate = 20-30%

4) Lead: Major portion goes to matte. PbS in matte is then oxidized partly to PbO in the converting furnace and distributed into slag.

90% into matte	Concentrates high in zinc
10% into dust	Volatilization rate = 60%

5) CaO: MgO: Al_2O_3: Reports principally to the slag.

6) As: 90% of total goes in dust or particulate fraction — Volatilization Rate = 10%
10% of total into slag

7) Cd: 90% of total goes in dust particulate fraction — Volatilization rate = 10%
10% of total into slag

8) Co: 70% into matte
30% as dust or particulate fraction — Volatilization rate = 10%

Table 14. Metallurgical material balance of the principal constituents of a typical Cu-Ni concentrate (Flash Smelter-Outokumpu Style). (Units are in metric tons/year)

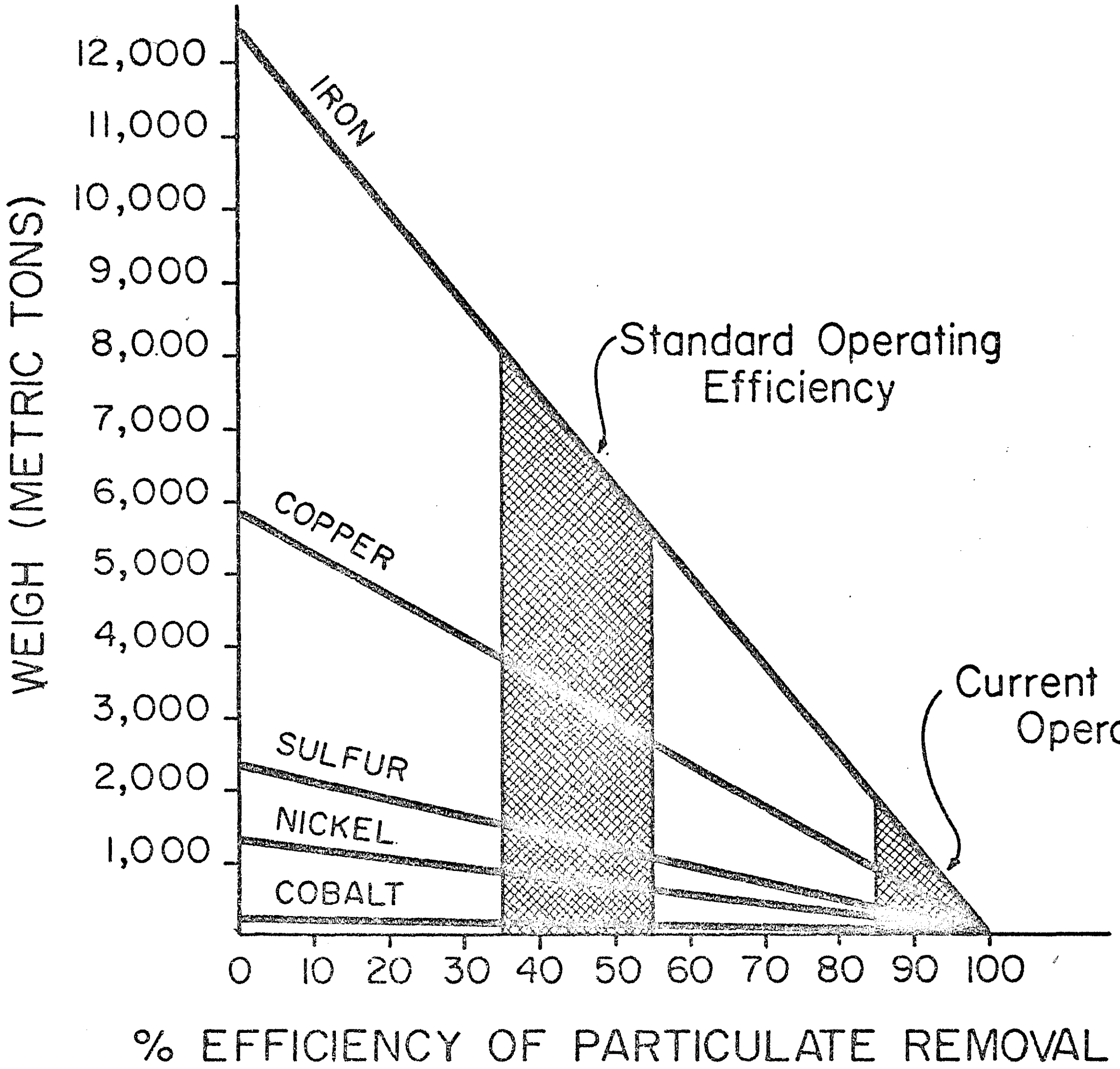
Input Products	Cu	Ni	Fe	S	Co	SiO_2	CaO	MgO	Al_2O_3	As	Pb	Zn	Cd	Ag	Au	Rh	Pt	Pd
Concentrate & Flux	100	100	100	100	100	65	100	100	100	100	100	100	100	100	100	100	100	100
Silica Flux						35												
Output Products																		
1 White Metal Matte	82	56	2	17	8									97	97	92	97	96
2 Matte - Alloy	8	32	1	2	62													
3 Dump Slag	2	4	89	1		92	100	100	100	10	90	85	10	3	3	8	3	4
4 Flue Dust (recycle)	7	7	7	2	28	7				81	9	14	81					
5 Particulate Emissions	1	1	1	.2	2	1				9	1	1	9					
Gas Emissions				4														

1 + 2 + 3 + 4 + 5 = 100%

Table 14A. Metallurgical material balance of the principal constituents of a typical Cu-Ni concentrate (Flash Smelter- Outokumpu Style). (Numbers are as percents)

FIGURE 12 A

PARTICULATE EMISSIONS TO THE ATMOSPHERE PER YEAR AS A FUNCTION OF THE DEGREE OF EFFICIENCY



Absolute Quantities of a Particular Element will Change as the Assumptions to the Material Balance Change.

Continuous Production of Blister Copper: Single-Step and Multistep Processes--

Continuous process smelting (Figures 13, 14 and 15) combines the steps of roasting, smelting and converting into a continuous (and perhaps autogenous) single-step operation for producing blister copper directly from concentrates. Input materials to the process would be concentrates, fluxes and air; and the products would be blister copper, a gas of high SO_2 strength, and a slag sufficiently low in copper to be directly discarded.

The potential advantages of such a single-step process for producing blister copper would be:

(a) A reduced amount of material handling due to the absence of intermediate steps.

(b) A low or zero energy requirement, due to efficient use of the energy obtained by oxidizing sulfides continuously in a single vessel.

(c) The production of a single stream of high SO_2 strength gas suitable for sulfuric acid or elemental sulfur recovery.

(d) The ability to apply on-line, automatic computer control to the entire copper-making process.

(e) Low capital cost requirements of a single unit as compared to multiple-unit operations.

The Noranda and Mitsubishi processes are operating on an industrial scale and further installations of both are planned. The WORCRA pilot plant was shut down in 1970 and it has not operated since. Why? Where?

Converting[2]

When the matte has been drained from beneath the slag, it is further processed in the last major operation, that of converting. Converting is essentially an oxidation process, no extraneous fuels necessary. The sulfur from the metallic sulfides is driven off as a SO_2 gas and the

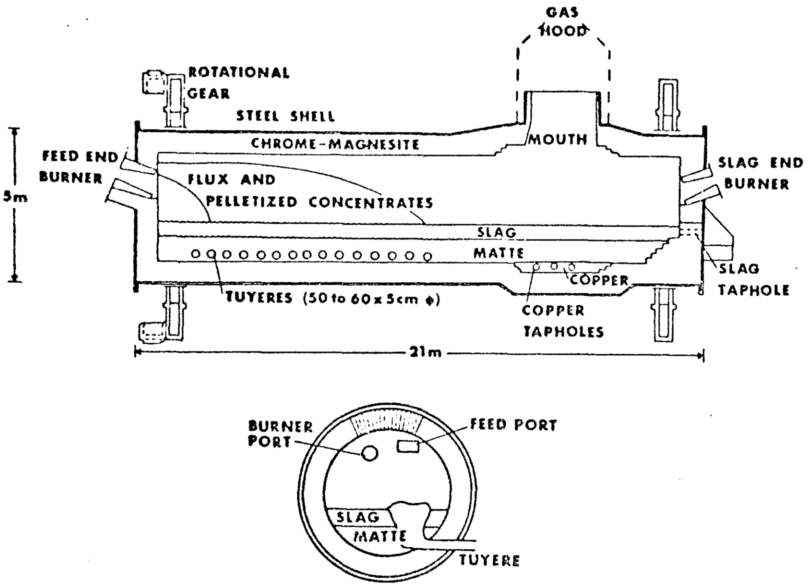
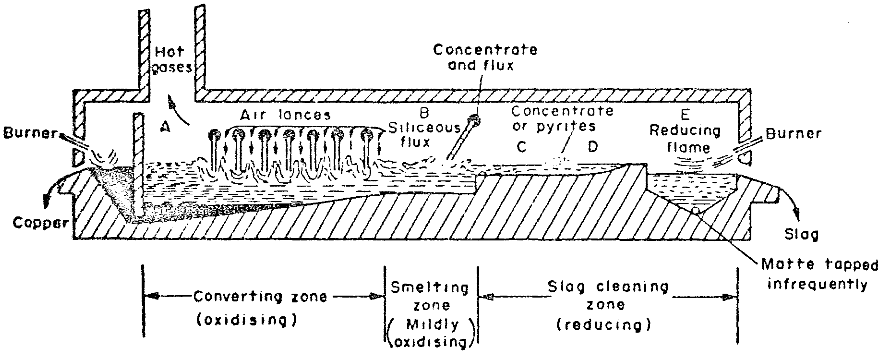
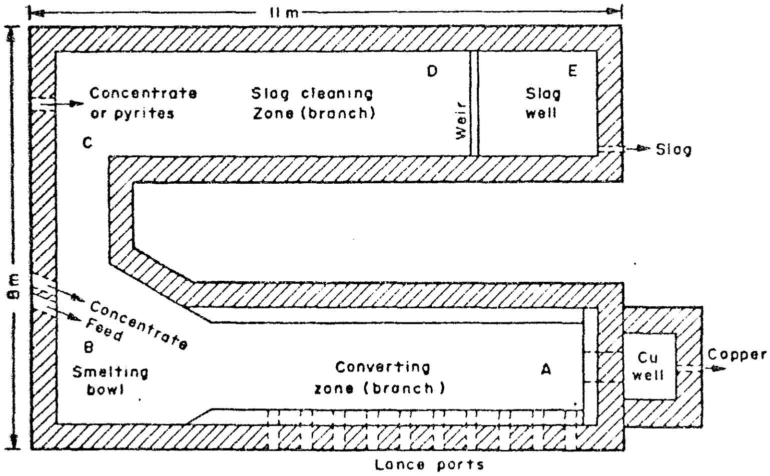


Figure 13. Schematic longitudinal and end views of the industrial Noranda single-step reactor.



(a) Elevation view†



(b) Plan view

Figure 14. Plan and elevation views of the WORCRA process pilot reactor.

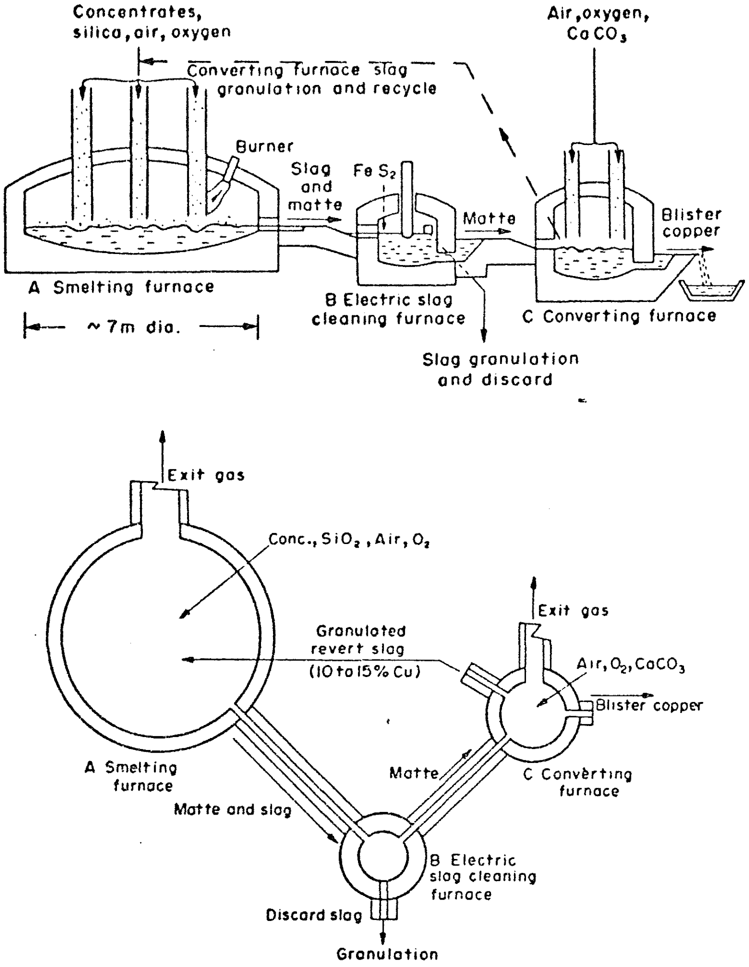


Figure 15. Schematic plan and elevation views of the Mitsubishi continuous smelting system.

remaining iron in the system is oxidized. The iron silicate slag which forms is poured off leaving the nearly pure metal or metals in a liquid form. Refining by electrolytic or other means reduces the metal or metals to the required purity.

The converting of copper matte is almost universally carried out in the cylindrical Pierce-Smith type converter (Figure 16). The converting reactions are exothermic and the process is autogenous. Typical converters

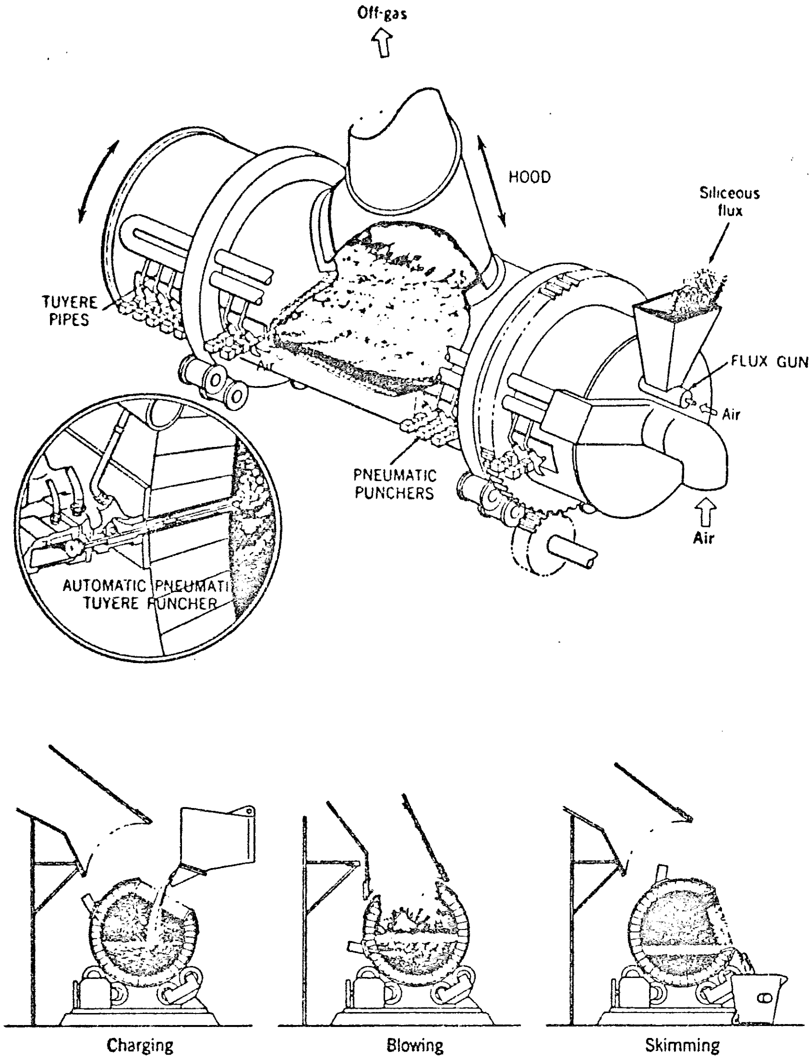


Figure 16. Cutaway view of a horizontal side-blown Pierce-Smith converter for producing blister copper from matte.

treat 300-400 metric tons of matte per day to produce 100-200 metric tons of copper. A smelter will normally have from three to six converters (with one or more of these being relined or on standby) depending upon the capacity of the smelting furnace.

Converters emit principally SO_2 as a potential gaseous pollutant. Dust loads in converter gases (also considered as a pollutant) may amount to

10-20 tons/day/unit. Seventy-five to 85 percent of the solids generated settle in the flue system. The remaining 15-25 percent, composed of smaller particles, is removed in dust collectors. The dust content depends principally on the chemical composition of the copper matte. An increase in the operating temperature of the converter causes higher volatilization of the metals and, hence, higher dust content in the offgases.

The distribution of elements among blister copper, vapor, and slag are estimated in Table 15. This table indicates that, generally speaking, As, Bi, Cd, Ge, Hg, Pb, Sb and Sn are extensively removed as vapors during converting while most of the Zn is removed along with the iron in the slag. The precious metals, nickel, and cobalt are carried over with the blister copper and are recovered during electrorefining.

	Blister copper	Vapour[a]	Slag[b]
Ag	90	0	10
Au	90	0	10
Pt metals	90	0	10
As	15	75	10
Bi	5	95	0
Cd	0	80	20
Co	80	0	20
Fe	0	0	100
Ge	0	100	0
Hg	10	90	0
Ni	75	0	25
Pb	5	85	10
Sb	20	60	20
Se	60	10	30
Sn	10	65	25
Te	60	10	30
Zn	0	30	70

[a] Not including ejected droplets of matte and slag.
[b] Including entrained matte.

Table 15. Distribution (estimated) of impurity elements during converting.

Converter gases often have entrained droplets of matte and slag which have the approximate composition of the liquids at the time of ejection. The solidified droplets are caught in the flue system (generally in the balloon flues and the electrostatic precipitators) and are recycled to the converters. The dusts and vapors from the converters are of sufficient concentration (contain sufficient copper) to be recycled to the smelting furnace or to the converter itself.

Table 16 compares the production features attributable to existing matte smelting operations. Table 17 summarizes the salient features of pyrometallurgical process equipment.

Seperate by following tables 16 & 17

POLLUTION AND POLLUTION CONTROL

Air pollution problems of the nonferrous metals industry are varied and complex. One typical characteristic exists, however, in almost all the nonferrous metals processes, the particles emitted are metallic fumes generally submicron in size. Table 18 summarizes particulate emissions.

The chemical and physical properties of effluents from primary copper smelters are summarized in Table 19. Particulate emissions from the furnaces are predominantly metallic fumes of submicron size. The fumes are difficult to wet and readily agglomerate. In addition, they are cohesive and will bridge and arch in hoppers and other collection lines.

Technology has been developed to provide equipment which, when operated efficiently, minimizes the negative effects inherent in a particular metallurgical system. Pollutants must be efficiently recovered in a form which is either marketable or inert under atmospheric conditions for regulated disposal.

TYPE	BLAST	REVERBERATORY	ELECTRIC	FLASH	CONTINUOUS
Hearth Area (M^2)	6.6-11.4	315-360	84-350	133-140	----
Solid Charge Rate (Total Metric tons/day)	250-1300	400-1300	250-1650	1100-1600	115-1075
Matte (Metric tons/day)	110-650	250-800	150-1100	550-850	20-180 (Blister Cu, ~98% Cu)
Matte Grade (% Cu)	46-63	34-47	22.5-40	47-49	----
Slag (Metric tons/day)	120-700	260-900	160-1360	300-550	65-700
Slag Grade (% Cu)	0.15-1.0	0.38-0.60	0.16-0.63	0.55-1.0	0.50-12.0
Productivity (Metric tons of charge per day/M^2)	35-130	1.2-3.6	3.0-5.8	7.9-11.6	3.0-9.0
Total Energy in Fuel (Kcal/Metric ton of charge)	$6x10^5$-$8x10^5$	$10x10^5$-$16x10^5$	$3.5x10^5$-$5.9x10^5$	$1.1x10^5$- $6.1x10^5$	$6x10^5$-$13x10^5$
Total Energy as an Average (Kcal/metric ton of charge)	$6.75x10^5$	$13.33x10^5$	$4.18x10^5$	$4.45x10^5$	$10x10^5$ (without air enrichment)

Table 16. Production details of matte smelting furnaces.

Table 17. Salient features of pyrometallurgical equipment and apparatus.

APPARATUS	DESCRIPTION AND DIMENSIONS	CAPACITY	GAS GRADES	MAJOR DISADVANTAGES	MAJOR ADVANTAGES
Multiple Hearth Roaster	Cylindrical-brick-lined vessel		2-6% SO_2	More expensive to operate in comparison to other calcining operations. Calcine Carryover of 6% in outlet gases.	
Fluid Bed Roaster	Cylindrical-refractory-lined steel shell	1600 TPD Concentrate	12-14% SO_2	Processing difficulties. Excessive calcine carryover of 80% in outlet gases.	No moving parts in the combustion chamber. Maintenance requirements are at a minimum. Uniform bed temperatures and composition are maintained in the fluid bed. Little excess air is required.
Sintering Machine	Traveling straight line grate 25 ft. - 35 ft. long 5 ft. - 8 ft. wide		1.5-2% SO_2	Requires a very careful adjustment of the physical and chemical conditions of the charge. Sulfur control is not very practical.	Excellent hearth efficiency.
Conventional Blast Furnace	Rectangular in plan with vertical sides at the top, inwardly sloping sides in the center section, and a vertically sided hearth at the bottom 1.5 m x 7 m x 5 m	1000 TPD Concentrate	5% SO_2	The blast furnace is unable to treat finely ground flotation concentrates.	The blast furnace has a high productivity rating. The typical blast furnace uses a relatively small amount of fuel.
Momoda Blast Furnace		500 TPD charge	7.3% SO_2 9.5% CO_2 3.1% O_2	Lacks capacity for larger smelter operations.	Lower BTU requirements per ton of charge when compared with the BTU requirements per ton of wet charge in reverberatory.
Reverberatory Furnace	A long horizontal furnace with a roof designed to reflect flame down onto a charge on the hearth 120-150 ft. long; 30-40 ft. wide High temperatures 1400-1700°C Tapping temperature 1100-1300°C Gas temperatures 1100°C	1600 TPD charge	.5-1.0% SO_2 11-20% of sulfur content removed	Thermal efficiency of the reverberatory is low.	Furnace possesses flexibility with respect to feed. Capable of handling large tonnages of hot charge per day.
Electric Furnace	Rectangular in cross-section with a firebrick spring-arch roof and a basic-brick inverted-arch bottom		2-4% SO_2	High hydrostatic heads attributable to deep layered slags constitute a definite furnace operating hazard. Bath runaways are a major hazard.	It is completely versatile and it can be used to smelt any and all materials. It produces small volumes of effluent gas (consisting of N_2 from infiltrated air, CO

Table 17. (contd.)

Column titles should repeat

Electric Furnace (cont.)				Copper matte is more difficult to produce than nickel matte. Furnace makes little use of the energy which is potentially available from oxidizing the sulfide minerals of the charge. The operating costs tend to be high due to the high price of electrical energy.	and CO_2 from electrode-slag reactions and SO_2 from sulfide oxidation). The SO_2 concentration of its effluent gas is readily controlled by adjusting the amount of air which is infiltrated into the furnace. It makes efficient use of electrical energy.
Flash Furnace (Outokumpu) (not autogenous) Requires ½ the fuel of an equivalent (dry) reverberatory smelting process.	20 m x 7 m x 3 m	1200 TPD-1400 TPD Concentrate	14% SO_2	Slags are too high in copper content to be discarded. An additional electric furnace is needed to treat both flash furnace slag and converter slag.	Its small physical size supports a large throughput. It is very economical in its use of fuel, the greater portion used for air heating, and therefore, of low quality. The gas produced is a good feedstock for an acid plant. Direct production of elemental sulfur in the flash-smelting emission system is being developed.
Flash Furnace (INCO) (autogenous)	Small hearth-type furnace 23 m x 6 m x 5 m	1600 TPD dry charge	75-80% SO_2	Slags are too high in copper content to be discarded. Additional treatment is needed for both flash furnace slag and converter slag.	It has a much lower overall energy requirement. Its volume of effluent gas (per ton of charge) is small due to the absence of nitrogen and hydrocarbon combustion products, which means that its gas-collection equipment requirement is small. The SO_2 concentration in its effluent gas is very high (80%) which simplifies SO_2 removal as sulfuric acid, liquid SO_2, or elemental sulfur. Dust losses are low due to a relatively small volumetric gas-flow rate. Its productivity (tons of charge per day/M^2 of hearth area) is approximately 30% higher than that of the Outokumpu process.
Pierce-Smith Sideblown Converter	Cylindrical steel vessel lined with basic refractory bricks. 13 ft. diameter; 30 ft. length		2-6% SO_2	Relatively low concentration of SO_2 in outlet gas.	Very efficient as a smelting machine under certain modified conditions.

Table 17. (contd.)

Hoboken Horizontal Siphon-Type Converter	56.5 TPD blister copper	8% SO_2	Capital costs are high than Pierce-Smith converter Capacity per unit size is lower than comparable units. Efficiency as a smelting machine is low.	
Mitsubishi Process (Continuous)	500 TPD-1500 TPD concentrates	12-15% SO_2	The Mitsubishi process may not be suitable for treating high impurity concentrates. (Concentration of impurities in the blister copper is likely to be high.) The multi-step Mitsubishi process produces SO_2-bearing gas in each of its three furnaces and a more extensive gas-collection system is required.	The system is pollution free, all exit gases have a SO_2 content greater than 10% which will permit recovery of sulfur as sulfuric acid. Capital investment is 70% of that needed to build a conventional smelter. Operating costs are reduced due to a smaller work force. Blister copper requires relatively little fire refining due to its relatively low (.1-.9% S) sulfur content. Slag recycle to the melting furnace is kept to a minimum by the small production of slag.
WORCRA Process (Continuous) (Utilizes submerged lances)		9-12% SO_2	The heat from the oxidation reactions is not available to the settling branch. As a consequence, hydrocarbon fuel must be burnt in the settling branch and large volumes of combustion gas, dilute in SO_2 (1 or 2%) are produced. Only a small part of the furnace is devoted to copper-making reactions and hence the productivity of the furnace is low, 2-3 tons of charge per M^2 of hearth area.	Capital costs 20-30% below that of reverberatory converter plants. Lower operating costs, with savings dependent upon local costs for fuel, power and labor. Economic viability at low annual throughputs-possible 10,000 to 20,000 tons/year of copper. Efficient recovery of byproduct sulfur from continuous SO_2 emission. Process makes metal rather than matte directly from concentrates. Most of the exothermic oxidation reactions are generated and continued within the liquid bath. Injection of oxygen-containing gases via lances creates turbulence and continuous flow in the smelting and converting zones. In the converting zone, slag moves by gravity, generally countercurrent to matte and metal. Copper content of the slag is reduced to throwaway levels as the slag flows through the smelting and slag-cleaning zones; there is no revert slag.

Table 17. (contd.)

WORCRA Process (cont.)				Offgases generated in the smelting and converting stages are combined and leave the furnace continuously. SO_2 concentration is mostly in the 9 to 12% range.
Noranda Process (Continuous) (Uses submerged tuyeres and a rotatable reactor)	Horizontal cylindrical furnace with a raised hearth at one end, and a depression near the middle in which the copper collects. 13 ft. diameter; 60 ft. length	800 TPD-1600 TPD concentrate	The sulfur content of Noranda process blister copper (1-2% S) is considerably higher than that of conventional converter copper and hence requires more air and a much lower oxidation period in the anode furnace. The Noranda process may not be suitable for treating high impurity concentrates. (Concentration of impurities in the blister copper is likely to be high.)	
Kennecott Converter-Smelter Vessel		400-500 TPD concentrate		

	Quantity of Material	Emission Factor	Efficiency of Control, C_c	Application of Control, C_t	Net Control, $C_c \cdot C_t$	Emission tons/yr.
I. Aluminum						
A. Preparation of Alumina						
1. Grinding of Bauxite	13,000,000 tons bauxite	6 lb./ton bauxite	-	-	0.80	8,000
2. Calcining of Hydroxide	5,840,000 tons alumina	200 lb./ton alumina	-	-	0.90	58,000
B. Aluminum Mills						
1. Soderberg Cells						
(a) Horizontal stud	800,000 tons aluminum	144 lb./ton aluminum	0.40	1.0	0.40	35,000
(b) Vertical stud	700,000 tons aluminum	84 lb./ton aluminum	0.64	1.0	0.64	10,000
2. Prebake Cells	1,755,000 tons aluminum	63 lb./ton aluminum	0.64	1.0	0.64	20,000
C. Materials Handling	3,300,000 tons aluminum	10 lb./ton aluminum	0.90	0.35	0.32	11,000
			Total from primary aluminum industry			142,000
II. Copper						
A. Ore Crushing	170,000,000 tons ore	2 lb./ton ore	0.0	0.0	0.0	170,000
B. Roasting	40% of 1,437,000 tons copper	168 lb./ton copper	0.85	1.0	0.85	7,000
C. Reverberatory Furnace	1,437,000 tons copper	206 lb./ton copper	0.95	0.85	0.81	28,000
D. Converter	1,437,000 tons copper	235 lb./ton copper	0.95	0.85	0.81	33,000
E. Fire Refining						
F. Slag Furnaces						
G. Materials Handling: Ore, Limestone, Slag, etc.	1,437,000 tons copper	10 lb./ton copper	0.90	0.35	0.32	5,000
			Total from primary copper industry			243,000
III. Zinc						
A. Ore Crushing	18,000,000 tons ore	2 lb./ton ore	0.0	0.0	0.0	18,000
B. Roasting						
1. Fluidized Bed, Suspension	75% of 1,020,000 tons zinc	2,000 lb./ton zinc	0.98	1.0	0.98	15,000
2. Ropp, Multiple Hearth	15% of 1,020,000 tons zinc	333 lb./ton zinc	0.85	1.0	0.85	4,000
C. Sintering and Sinter Crushing	60% of 1,020,000 tons zinc	180 lb./ton zinc	0.95	1.0	0.95	3,000
D. Distillation	60% of 1,020,000 tons zinc		0.0	0.0	0.0	15,000
E. Materials Handling	1,020,000 tons zinc	7 lb./ton zinc	0.90	0.35	0.32	2,000
			Total from primary zinc industry			57,000
IV. Lead						
A. Ore Crushing	4,500,000 tons ore	2 lb./ton ore	0.0	0.0	0.0	4,000
B. Sintering	467,000 tons lead	520 lb./ton lead	0.95	0.90	0.86	17,000
C. Blast Furnace	467,000 tons lead	250 lb./ton lead	0.85	0.98	0.83	10,000
D. Drossing Kettle		-				
E. Softening Furnace		-				
F. Desilvering Kettles		-				
G. Cupeling Furnaces		-				
H. Refining Kettles		-				
I. Dross Reverberatory Furnace	467,000 tons lead	20 lb./ton lead	-	-	0.50	2,000
J. Materials Handling	467,000 tons lead	5 lb./ton lead	0.90	0.35	0.32	1,000
			Total from primary lead industry			34,000
			Total from nonferrous metals industries			476,000

Table 18. Particulate emissions - primary nonferrous metals industries.

Particulate

Source	Particle Size	Solids Loading	Chemical Composition
Roasting furnace	$15 < 10$	6 - 24	Cu: 9, S: 10, Fe: 26
Blast furnace	--	6.6	Cu: 4.4, Zn: 12.5, S: 7.3
Reverberatory furnace	$51 < 37$	1 - 6	Cu: 6.2, Zn: 13.0, S: 13.6 Oxides of arsenic, antimony, aluminum silicon sulfates (traces).
Copper matte converter	--	5.3	Cu: 1.2, Zn: 18.0, S: 10 (also see reverberatory furnace)
Copper refining (coal dust fired)	$50 < 44$	--	Cu: 7, S: 1.5

Carrier Gas

Source	Flow Rate	Temperature	Moisture Content	Chemical Composition
Roasting furnace	a. 60 - 131 b. 47.3	600 - 890	--	SO_2: 8
Blast furnace	a. 21.2 b. 76.5	248	--	CO_2: 6.5
Reverberatory furnace	a. 50 - 460 b. 71	350 - 750	4 - 10	O_2: 5 - 6, CO_2: 10 - 17, N_2: 72 - 76, CO: 0 - 0.2, SO_2: 1 - 2
Copper matte converter	a. 102 - 750 b. 364	300 - 650	--	SO_2: 4
Copper refining furnace (coal dust fired)	a. 16	410	--	--

Coding Key for Tables of Effluent Characteristics

I. General Note: All data for uncontrolled sources unless otherwise noted.

II. Specific Notes:

A. Particulates

1. Particle size:
   $x < y$, $x > y$.
   x = weight percent, y = particle size (μ).
   Measuring technique noted. If no notation is listed, measuring technique was not reported or is unknown.
2. Solids loading: grains/scf, unless otherwise noted.
3. Chemical Composition: solids - weight percent (unless otherwise noted).
4. Particle density: g./cm.^{3}.
5. Electrical resistivity: ohm-cm, laboratory measurements unless otherwise noted.
6. Moisture content: weight percent, unless otherwise noted.
7. Toxicity:
   a) N.T. - not toxic.
   b) numerical value - threshold limit, mg./m.^{3}.
8. Solubility:
   s. - soluble.
   s. sl. - slightly soluble.
   d. - decomposes.
9. Wettability, hygroscopic, flammability, handling, optical, and odor characteristics: only a descriptive comment generally given; if numerical value is presented, units will be indicated.

B. Carrier Gas

1. Flow rate: flow-rate data presented in two forms:
   a) thousands of standard cubic feet per minute, M scfm, unless otherwise noted.
   b) thousands of standard cubic feet per ton of product processed, M scf/ton, unless otherwise noted.
2. Temperature: °F.
3. Moisture content: volume percent, unless otherwise noted. Dew point is in °F. if listed under moisture content.
4. Chemical composition: volume percent, unless otherwise noted.
5. Toxicity:
   a) N.T. - not toxic.
   b) numerical value - threshold limit, mg./m.^{3}.
6. Corrosivity, odor, flammability, and optical properties: only a descriptive comment generally given; if numerical value is presented, units will be indicated.

PRELIMINARY
SUBJECT TO REVIEW

Table 19. Effluent characteristics - primary copper production.

The selection of suitable control devices requires a careful consideration of the characteristics of the pollutants and the equipment. Poor system performance in many cases is indicative of poor equipment selection.

Control equipment is often classified into two categories:

- equipment capable of removing particulates
- equipment capable of removing gaseous pollutants from an airstream

Equipment available for each of these two broad categories include:

Particulates (Including Aerosols)	Gaseous Pollutants
settling chambers	gas scrubbers
cyclones	absorbers
impingement separators	incinerators
centrifugal separators	direct incineration
bag filters	catalytic combustion
wet collectors	condensors
electrostatic precipitators	

table 18 & 19

Particulate Matter Removal[13]

The evaluation of a pollution problem followed by the design of a control system to meet the particular need is a long and involved process. A well designed program involving pollution evaluation, engineering study, and engineering construction is necessary in all situations where a pollution problem is evident. This means that all potential anti-pollution devices are studied with respect to a particular situation.

There are certain fundamentals which are applicable to all practical collectors of particulate matter. These fundamentals are:

(a) All collectors clean the gas by continuously removing the dust from a moving stream of gas.

(b) The size of collector and its cost are directly proportional to the gas quantity to be cleaned.

(c) The collection efficiency is calculated by the following formula (expressed as a percentage)

$$\%\text{ collection efficiency} = \frac{\text{wt. of input dust - wt. of output dust}}{\text{wt. of input dust}} \times 100$$

(d) Fine dust is considerably harder to collect than coarse dust in all types of particulate collectors. Many dusts are a collection of fine and coarse with the proportion of fines dictating the collector efficiency. Heavier concentrations of dust are usually easier to collect than low-grain loadings.

Table 20 summarizes the basic types and subtypes of particulate collectors.

Basic Type	Specific Type	Basic Operating Force	Basic Measure and Unit of Capacity	Typical Capacity in cfm of Gas per Basic Measure of Capacity	Typical Required Plan Area for Collector to Clean 100,000 cfm[e]	Typical Energy Required and % Collection Efficiency on Fine Dust[c]		COST IN $1000 FOR A COLLECTOR TO CLEAN 100,000 CFM: Cost to Purchase fob Shop and Install		COST IN $1000 FOR A COLLECTOR TO CLEAN 100,000 CFM: Annual Cost for Maintenance and Power		Effect On Collection of Operation at Over or Under Capacity[d]	
					sq. ft.	Inches w.g.	%	fob shop[a]	in-stall	main-tenance	pow-er[b]	over	under
Mechanical Collectors	settling chamber	gravity	casing volume (cu ft)	20	2600	0.2	25	10	3	1	0.5	down	up
	baffle	intertia	inlet area (sq ft)	1200–3600	300	0.5	40	13	4	2	1.3	up	down
	high-efficiency cyclones	centrifugal	inlet area (sq ft)	3000–3600	125	4	80	20	5	2	10	up	down
Fabric Filters	manual cleaning	filter cake filtration	fabric area (sq ft)	1–4	1000	4	99	35	20	7	10	down	no change
	automatic shaker cleaning	filter cake filtration	fabric area (sq ft)	1–4	1000	5	99	60	30	10	13	down	no change
	automatic reverse jet cleaning	felt fabric filtration	fabric area (sq ft)	3–8	600	8	99	80	35	15	20	no change	no change
Wet Scrubbers	impingement baffle	liquid capture	baffle cross-sectional area (sq ft)	500–600	300	4	80	30	15	7	10	up	down
	packed tower	liquid capture	bed cross-sectional area (sq ft)	500–700	250	7	90	40	20	9	17	down	up
	venturi	liquid capture	throat area (sq ft)	7,000 to 30,000	100	30	99	50	50	11	75	up	down
Electric Precipitators	single field	electric	collectrode area (sq ft)	5	270	0.5	95	75	55	4	1.3	down	up
	multiple field	electric	collectrode area (sq ft)	3	500	0.5	99	100	70	5	1.3	down	up

[a] Fob shop costs, installation and maintenance costs are based on 1970 mild steel construction costs, and do not include auxiliary equipment such as supporting structure, connecting flues, thermal insulation, foundations, stacks, etc. They are subject to substantial variation due to the specific requirements of each installation including geographic location. Use only for general comparison purposes.

[b] Energy costs are based on electric power at $0.015/kwh.

[c] Fine dust is considered to be 70% by weight minus 10 μ.

[d] Some collectors can be modified to maintain collection efficiency at over or under capacity.

[e] Plan areas do not include connecting flues.

Table 20. Fundamental operating characteristics of commercial particulate collectors.

Mechanical Collectors--Mechanical collectors are designed mechanisms which take advantage of differences in specific gravity between typical industrial dusts and the gases in which they are entrained, separating the heavier dust from the lighter gas. Refer to Table 21 for a summary of the types of equipment which fall into this category.

TYPE	CHARACTERISTICS	UNIQUE DISADVANTAGES
Gravity settling chamber	Physical Size-very large Installed Cost-low Energy Cost-very low Maintenance Cost- low Collection Efficiency-very low Reliability-excellent Efficiency At Low-increases loads Efficiency At -decreases overloads	Low collection efficiencies on fine and moderately fine dusts
Recirculating baffle collector	Physical Size-small Installed Cost-low Energy Cost-low Collection Efficiency-low Reliability-excellent Efficiency At Low-lowers slowly loads Efficiency At -increases slightly overloads	Collection efficiency not sufficient to meet current emission control requirements
High Efficiency Cyclones		Fractional efficiency (efficiency drops off rapidly below a certain size of dust) Draft losses (proportional to the square of the inlet velocity)
Chip trap or cinder tray		
trap louvre separator		
Dynamic Precipitator		
Centrifugal Inertial Separator		
Ordinary Cyclone		
Wet Cyclone		
Cyclonic Drouplet Collector		
Ultra High-Efficiency Collector		

Table 21. Mechanical collectors.

Fabric Filters--Fabric filters are versatile collectors used in the removal of dry, solid particulate matter from an air or gas stream. Dust bearing gas is passed unidirectionally through a fabric filter medium of woven or felted cloth. The principal function of the fabric filter includes the trapping of dust on the dirty-gas side of the fabric while allowing the gas to pass through the interstices between the woven threads of the fabric. Interstices as large as 100μ in typical commercial bag filters (woven fabric media) trap dust particles as small as 0.5μ.

The capability of the woven fabric filter to collect fine dust is a direct consequence of the buildup of a fragile, porous layer of dust on the dirty-gas side of the cloth. This layer, better known as the filter cake, blocks the larger interstices preventing the finer dust particles from passing through. The thicker felted fabrics are less dependent on the formation of the filter cake. They, however, cannot be cleaned effectively by shaking and must be cleaned frequently with high-pressure reverse jets.

The mechanisms responsible for the formation of filter cake include:

- agglomeration of upstream particles
- impaction of larger particles on the fiber
- electrostatic attraction and repulsion
- thermal effects
- coarse sieving by cloth
- fine sieving by filter cake layer

Table 22 shows a typical operating cycle of one compartment of a compartmented, automatic fabric filter. Dust collection efficiency is also indicated.

The major advantage of the fabric filter is its high efficiency at all loads from maximum gas flow down to zero gas flow. Disadvantages include large size and high maintenance due to the cost of bag replacement.

Cycle Number	Filter Cycle	Cloth Status	Filter Cake Thickness	Air-to-Cloth Ratio or Filtering Velocity (ft/min)	Draft Loss (in./W.G.)	Collection Efficiency
1	new	clean	zero	2–3	< 0.5	no dust
2	precoat	clean to coated	zero to minimum	2–3	< 0.5 to 2–3	low to high
3	filtering	coated	partial	2–3	3–5	high
4	filtering	full coated	maximum	2–3	4–6	high
5	cleaning	shaking	maximum to minimum	dampered off	Zero	not operating
6	filtering	coated	minimum	2–3	2–3	high
7	filtering	full coated	maximum	2–3	4–6	high

The following comments are keyed to cycle numbers:

(1) When new and clean, the draft loss across the fabric filter media is much below 0.5 in. W.G.

(2) During the precoat cycle the draft loss will gradually increase as the layer of filter cake is built up. The efficiency will increase to operating levels of plus 99 percent; the gas discharge will become clear.

(3–4) During the filtering cycle the draft loss will increase to the maximum acceptable level as the layer of filter cake thickens.

(5) The conventional bag house will damper off the compartment being cleaned. Maximum filter cake is shaken off the cloth and drops into a hopper under the influence of gravity. The vigor and duration of shaking must be adequate to reduce filter cake thickness from maximum to minimum. Excessive shaking may reduce collector efficiency by reducing filter cake thickness below minimum.

(6) Compartment is restored to filtering cycle. Cycles (5), (6), and (7) are repeated for each compartment by a predetermined program so that no more than one compartment is removed from service at one time.

Table 22. Operating cycle of one compartment of conventional compartmented bag house with woven fabric.

Additional problems result from the exposure of the bags to elevated temperatures causing destruction of the bags, or exposure to moisture resulting from operation below the dew point causing blinding or plugging.

Table 23 summarizes the basic types of fabric filters available for commercial use.

Wet Scrubbers--Wet scrubbers are mechanical type devices which use a liquid, usually water, to capture, then remove particulate matter from a moving stream of gas.

Basic Type of Baghouse	*Type of Bag*	NORMAL DIRECTION OF GAS FLOW DURING FILTERING CYCLE		CLEANING TUBES		*Air to Cloth Ratios (ft/min)*	*Space Requirement*	*Cost per Square Foot of Filter Media*
		Thru Collector	*Thru Tube*	*Method*	*Cycle*			
Intermittent	woven cloth tube	up	inside to outside	manual or powered shaking	periodically during shutdown	1-4	very large	low
Conventional	woven cloth tube	up	inside to outside	automatic mechanical or pneumatic shaking	intermittent by isolated compartment	1-4	very large	low
Reverse air flow cleaning	woven cloth tube	up	inside to outside	automatic tube collapse by low pressure reverse flow	intermittent by isolated compartment	1-4	very large	low
Reverse ring jet cleaning	felted cloth tube	down	inside to outside	travelling compressed air ring	continuous on heavy dust loadings or intermittent on light dust loadings while gas flows	3-8	large	high
Reverse pulse jet cleaning	felted cloth tube	up	outside to inside	high pressure pulsed jet	programmed by manifolds while gas flows	3-8	large	high

Table 23. Basic types of fabric filters using cloth tubes.

The collection efficiency of all well designed wet scrubbers is related to the total energy expended. Low energy collectors have low efficiency, correspondingly, high energy collectors have high efficiency. The energy is introduced either in the water cycle or the gas cycle. For most commercial collectors, the energy is usually introduced in the gas cycle.

The major advantage of the wet scrubber is the great variety of types which allows the selection of a collector suitable for almost any collection problem including collection efficiencies as high as 99 percent.

Primary disadvantages include:

- disposal problems associated with wet sludges
- high energy costs associated with the high efficiency scrubber
- increased material costs where chemical corrosion is evident
- potential problems of plugged nozzles
- unavailability of scrubbing liquids of sufficient clarity
- the presence of a visible plume discharging to the atmosphere

Table 24 summarizes the basic types of scrubbers available in this category.

		WATER VS. GAS FLOW	WATER CIRCULATION	DRAFT LOSS	PERCENT COLLECTION EFFICIENCY ON FINE DUST		
Basic Type	*Specific Type*	*Concurrent or counter or cross*	*gpm per 1,000 cfm*	*Inches water gauge*	*Low*	*Moderate*	*High*
Impingement baffle	tangential inlet wet cyclone	concurrent or cross	3–5	1–4	X	X	
	spiral baffle wet cyclone	concurrent	1–2	4–6	X	X	
	single plate	concurrent	2–4	1–8	X	X	
	multiple plate	concurrent	3–5	6–12		X	
Packed tower	fixed bed	concurrent or counter	10–20	2–4	X		
	fluidized bed	counter	15–30	4–12	X	X	
	flooded bed	concurrent	2–4	4–8		X	
	multiple bed	counter	20–40	4–12		X	
Submerged Orifice	wide slot	concurrent	15–30	2–15	X	X	
	circular slot	concurrent	15–30	2–15	X	X	
	multiple slot	concurrent	15–30	2–15	X	X	
Venturi	high-pressure	cross or concurrent	5–7	30–100			X
	medium-pressure		3–5	10–30		X	X
	low-pressure		2–4	3–10	X	X	
	flooded disc		5–6	30–70		X	X
Miscellaneous and combination scrubbers	cross-flow packed	cross	1–4	2–4	X	X	
	centrifugal fan	concurrent	1–2	[a]	X	X	
	multiple venturi	concurrent	4–6	20–80		X	X
	combination venturi	concurrent	5–7	15–60		X	X
	combination fan type	concurrent	2–3	[a]		X	

[a] ½ hp per 1,000 cfm.

Table 24. Basic types of wet scrubbers.

Electrostatic Precipitators--The industrial electric precipitator, invented by Frederic Gardner Cottrell in 1910, separates entrained particulate matter from gas streams by:

- charging the dust to a negative voltage (x 50,000 V)
- precipitating the dust onto grounded collecting electrodes
- dropping the agglomerated dust into a hopper

The energy consumption is low and the draft loss is the lowest of all high-efficiency collectors.

In commercial units, the dirty gas is passed horizontally through narrow, vertical gas passages formed by parallel rows of grounded collecting electrodes. Electrically insulated high-voltage wires are spaced precisely on the center lines of each gas passage, thereby causing the dirty gas to pass between the high-voltage wires and the grounded plates.

Dust particles carried through the gas passages by the entraining gas, collide with negative gas ions and are charged negatively. The negatively charged dust particles move rapidly toward the grounded (positive) plates and are held by powerful electric forces.

The dust particles build a thickening layer on the collectors, and the negative charge gradually bleeds from the dust into the grounded electrode. As the layer thickens, the charges on the recently precipitated dust must be conducted through the layer of that previously precipitated. The resistance of the dust layer to this current flow is termed "dust resistivity." Precipitators are successfully operating on dusts whose resistivity is in the range of 10^7 - 10^{11} Ω/cm.

After a 1/16 - 1/4 inch layer of dust has been precipitated, the dust particles next to the collectrode have lost much of their charge to the grounded plate. The electrode attraction has been weakened. The recently arrived dust particles still hold much of their charge, being electrically insulated from the plate by the dust layer, thereby holding the entire layer against the collectrode. A sharp rap causes the dust layer to shear away from the collectrode. The force of rapping is restrained so as to allow the layer to be shattered into relatively large agglomerations of dust particles, but not back into the original submicron particles.

The relatively large agglomerates fall into the hoppers under the influence of gravity just as in the gravity settling chamber. Most electric precipitators are operated at gas velocities in the range of 3-6 ft/sec to allow ample settling time. The high voltage remains on to recharge and reprecipitate any fine particles which may become re-entrained during the rapping cycle.

The major advantage of the electric precipitator is its high collection efficiency with a minimum of operating cost. Other advantages include:

- minimum energy requirements of all high-efficiency collectors
- reduced maintenance requirements
- high reliability at any required collection efficiency from maximum to zero gas flow

Among the disadvantages are:

- high installation costs
- unpredictable collection efficiency on certain high-resistivity dusts
- loss of collection efficiency at gas flows above the designed rating

Figure 17 compares a variety of natural and man-made particulates by their size ranges. Figure 18 illustrates the general guidelines which are used in the preliminary evaluation of control equipment.

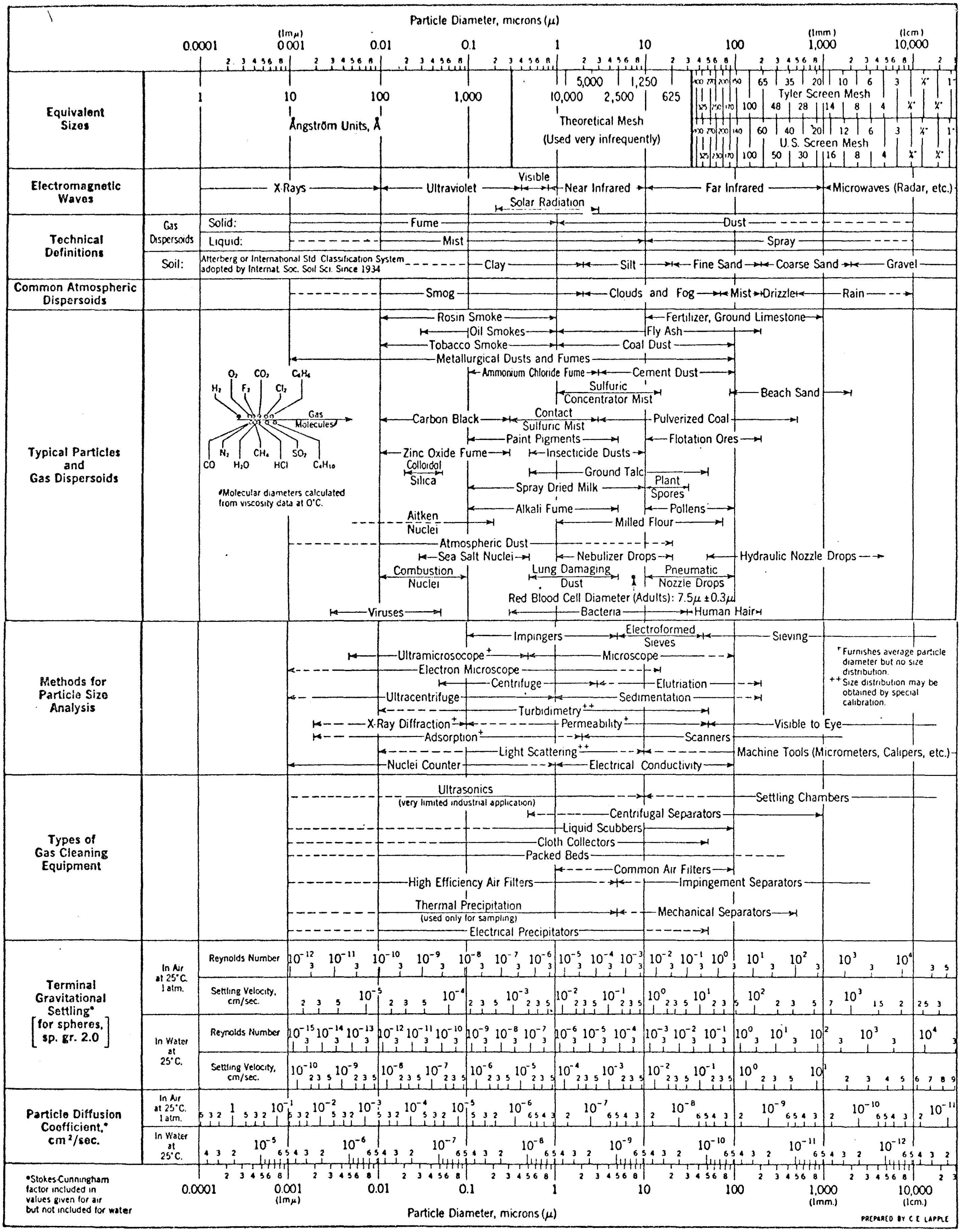
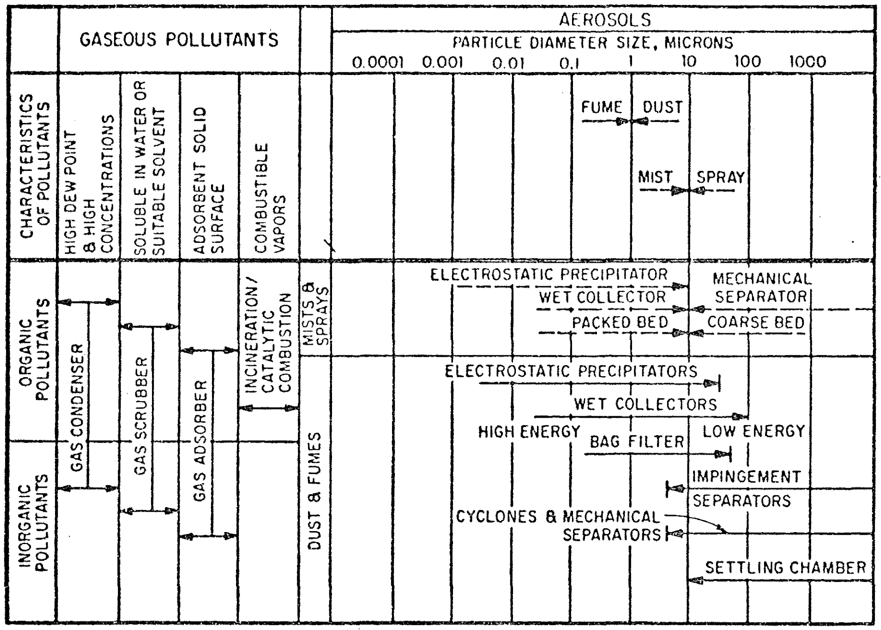


Figure 17. Characteristics of particles and particle dispersoids.

PRELIMINARY
SUBJECT TO REVIEW



(1) The selection of equipment for removing aerosols from air streams depends on the properties of the particles.

(a) Low concentration mists can be collected with an electrostatic precipitator, a wet collector, a high density fibrous filter, or a packed bed mist eliminator.
(b) Sprays can be removed with mechanical separators or coarse-packed beds.
(c) Fumes can be collected with high-energy wet collectors, bag filters, or electrostatic precipitators.
(d) Dusts can be removed from an airstream with wet collectors, inertia or impingement separators.
(e) Coarse particles can be removed from exhausts with settling chambers or cyclones.
(f) A primary cleaner, cyclone, or settling chamber should be considered for exhaust loadings greater than 10 grains/ft^3 to reduce the load on the principal abatement equipment.
(g) Abrasive particles can be collected with wet collectors or bag filters operated at reduced flow velocities. Electrostatic precipitators can be used, but the unit must be sized to reduce erosion wear.
(h) Adhesive or hygroscopic materials are best collected with wet collectors. Bag filters, electrostatic precipitators and cyclones are not effective control devices.
(i) Dusts with low resistivity characteristics are effectively collected with electrostatic precipitators.

(2) The selection of control equipment for gaseous pollutants is dependent on the chemical nature of the contaminant. Some guidelines for organic pollutants can be summarized as follows:

(a) Vapors present in high concentrations and with high dew-point temperatures can be removed by condensation either by direct cooling or compression.
(b) Highly soluble organics can be removed from the exhaust by scrubbing with liquid or a suitable solvent.
(c) Pollutants which have molecular weights higher than the normal components of air can be removed by adsorption. Generally, adsorption is practical for removal of organic vapors which can easily be evaporated from the adsorbent at low pressure steam temperatures.
(d) Combustible vapors can be burned in direct or catalytic units.
(e) Vapors which are highly explosive or flammable, and soluble in water, are best collected in wet systems.

(3) Inorganic gaseous pollutants can be removed from airstreams by condensation, scrubbing, and with adsorbents such as silica gel, alumina, or activated carbon. The use of adsorbents for inorganics has limited application so that scrubbing and sometimes condensation remain the principal treatment methods.

Figure 18. Control equipment guidelines.

Table 25 lists the particular choices made by the operator for specific applications in a variety of industries. For many applications, the choice of the type of collector is well established by operational precedent.

Refer to Appendix B for a summary of the particulate removal pollution equipment.

The Sulfur Problem and Possible Solutions[2]

Over 90 percent of the world's primary copper originates in sulfide minerals so that sulfur in some form is a by-product of most copper processing. Furthermore, most of the sulfur is emitted as SO_2 gas which is harmful to fauna and flora if present in the air to even a limited extent. Some effects of SO_2 are shown in Figure 19.

In the past and even today, SO_2 has been vented directly into the atmosphere, however, this practice is now prohibited in many areas of the world. The standards for clean air vary from country to country but representative requirements for controlling copper smelter emissions are (U.S. Environmental Protection Agency):

(a) not more than 10 percent of the sulfur entering the smelter can be emitted to the atmosphere;

(b) the yearly average SO_2 content anywhere at ground level must not exceed 0.03 ppm (by volume);

(c) the average SO_2 content anywhere at ground level on any one day must not exceed 0.14 ppm.

There has been a tendency to build increasingly taller chimney stacks (380 m, INCO, Sudbury) which might possibly meet criteria (b) and (c), but these will not satisfy requirement (a).

INDUSTRY AND SPECIFIC APPLICATION	TYPES OF COLLECTORS*		
	Most used	*Also used*	*Seldom used*
ROCK PRODUCTS			
Wet process cement kiln	MC, EP	CC, WS	FF
Dry process cement kiln	MC, EP, FF	CC	WS
Cement mills	FF	EP, MC	WS, CC
Cement silos	FF		
Raw material preparation	MC, FF	EP	WS, CC
Asphalt plant dryer	MC, WS	EP, FF	CC
Coal drying	MC, WS		FF, EP
Coal mills	FF	MC, WS	EP, CC
Alumina kiln	MC, FF, EP	WS	CC
Bauxite kiln	MC, EP	FF, WS	CC
Gypsum kiln	MC, FF, EP	WS	CC
Magnesium oxide	MC	FF, WS, EP	
Lime kiln	MC, EP	FF, WS	
Phosphate kiln	MC, WS, EP	FF	
Finishing	FF	MC, EP	WS, CC
IRON AND STEEL			
Blast furnance	WS, EP	MC	FF
Open hearth	WS, EP	FF	MC, CC
Basic oxygen furnance	WS, EP		
Electric furnance	FF, WS	EP	MC, CC
Sintering	MC, FF, EP	WS, CC	
Cupolas	WS	MC, FF, EP	CC
Ore beneficiation	MC	FF, EP, WS	
Ore pellitizing	MC	WS, EP	
Ore roasting	MC, WS, EP		FF, CC
Taconite	MC	FF, WS, EP	CC
Pyrites roasting	MC, WS, EP		FF, CC
Hot scarfing	WS, EP		MC, FF, CC
Coke ovens	EP	WS	MC, FF, CC
Ferro-manganese blast furnace	MC, EP	CC, WS	FF
Scrap preheating	WS		MC, FF, EP
MINING AND METALLURGY			
Ore preparation and beneficiation	MC, FF, WS	EP	CC
Aluminum pots	FF, WS, EP	MC	CC
Elemental phosphorous	EP	WS	FF, WS
Copper converter	EP	FF, WS, CC	MC
Copper reveratory furnace	EP	WS	MC, FF, CC
Copper roaster	MC, EP	WS, CC	FF
Ilmenite ore dryer	MC, EP	CC	FF, WS
Molybdenum	WS	EP	FF, MC, CC
Precious metals	FF, EP	MC, WS	CC
Lithium kiln	EP		
Lead furnace	FF, WS		MC, EP
Titanium dioxide	FF, WS	EP	MC, CC
Zinc cupola	EP	WS	
Zinc roaster	MC, EP	FF, WS	CC
Zinc smelter	FF, WS, EP		MC, CC
FOUNDRY AND INDUSTRIAL			
Ferrous cupola	WS	MC, EP	FF, CC
Non-ferrous cupola	FF, EP	MC, WS	CC
Foundry cleaning room	FF, WS	EP	MC, CC
Sand preparation and handling	FF	WS, EP	MC, CC
Ventilation	FF		MC, FF, EP
Machining	MC, FF	WS	EP
Feed and flour milling	MC, FF		WS, EP, CC
Lumber mills	MC	FF	WS, EP
Wood working	MC, FF	WS	EP
PULP AND PAPER			
Black liquor recovery furnace	EP	WS	MC, FF
Lime kiln	MC, WS	EP, CC	FF
Chemical dissolver tank	WS	MC, FF, EP	
ELECTRIC POWER—TYPE OF FUEL			
Stoker fired coal	MC	EP, CC, WS	FF
Spreader stoker fired coal	MC	EP, CC, WS	FF
Puverized coal fired	EP, CC	WS	FF, MC
Oil fired	MC	EP	FF, WS, CC
Natural gas fired	none	none	
Lignite fired	MC, EP, CC	WS	FF
Wood and bark fired	MC	WS, EP	FF, CC
Bagasse fired	MC	WS	FF, EP, CC
Fluid coke	MC, EP	WS	FF, CC
WASTE DISPOSAL INCINERATORS			
Apartment house	WS	EP	MC, FF, CC
Industrial (thermal oxidizer)	EP	WS	MC, FF, CC
Municipal	EP, WS	MC, CC	FF
CHEMICAL AND OIL REFINING			
Refinery cat cracker—reactor	MC	none	
—regenerator	MC	none	
—CO boiler	EP	MC, WS	FF, CC
Sulphuric acid mist	EP, WS	MC	FF, CC
Phosphoric acid mist	WS		
Nitric acid mist		WS	
Carbon black	FF	MC, EP, WS	CC
Oil shale distillation	MC, CC	EP	FF, WS
Raw material preparation	MC	WS, EP, FF	CC

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*MC = mechanical collector, *FF* = fabric filter, WS = wet scrubber, *EP* = electric precipitator, CC = combined collector = MC + EP.

Table 25. Typical use of particulate collectors.

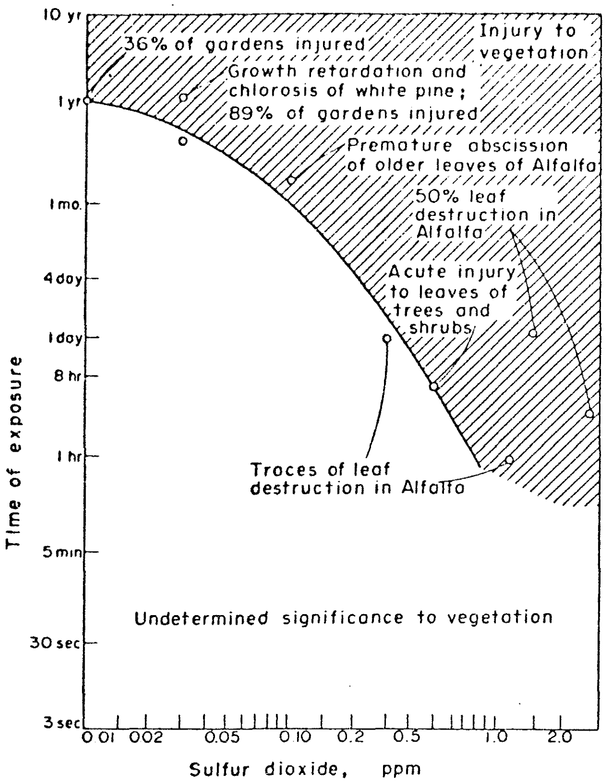


Figure 19. The effects of SO_2-bearing gases on vegetation.

The copper smelter is faced with two major problems:

(a) how to capture most of the SO_2 and fix the sulfur in a useful or stable form (e.g. elemental sulfur, liquid SO_2, or sulfuric acid);

(b) what to do with the product.

Hydrometallurgical techniques of copper extraction from sulfide minerals avoid the SO_2 emission problem. However, the sulfur usually enters leach solutions as sulfates (or other oxy-sulfur anions) and these must be removed to avoid water pollution. Hydrometallurgical processes which will produce elemental sulfur directly are being investigated, however, and these may prove to be useful in the future (Subramanian and Jennings, 1972).

Three basic techniques can be used to fix SO_2 (and other oxy-sulfur compounds):

(a) reduction to elemental sulfur

(b) manufacture of sulfuric acid (or liquid SO_2)

(c) direct manufacture of ammonium sulfate (fertilizer) from ammoniacal leach solutions.

All of these products are suitable for use in industry or agriculture but only solid elemental sulfur is suitable for long-term inexpensive storage, possibly in worked-out quarries or mines. It has been suggested that SO_2 gases or sulfate solutions might be treated with limestone or dolomite to form discardable $CaSO_4$ or $MgSO_4$, but these products are of limited usefulness and their long-term stability is open to question. This proposal seems to be unacceptable.

Process selection is determined by:

- economic conditions for sulfur by-product disposal
- variation in the nature of the offgases
    sulfur dioxide concentration
    impurities carried over from smelting operations
    fluctuations in gas flow rates
- geographic locations
- nearness of markets for sulfurous products
- availability of land for product disposal
- water pollution problems

Figure 20 is a generalized diagram showing some of the more popular alternatives in current and developing SO_2 control systems. While each system is unique in detail, many contain similar basic steps.

It is technically feasible to fix well over 95 percent of the sulfur entering a pyrometallurgical smelter. This is particularly true if the smelting furnace is of the electric, flash, or in the future, the continuous

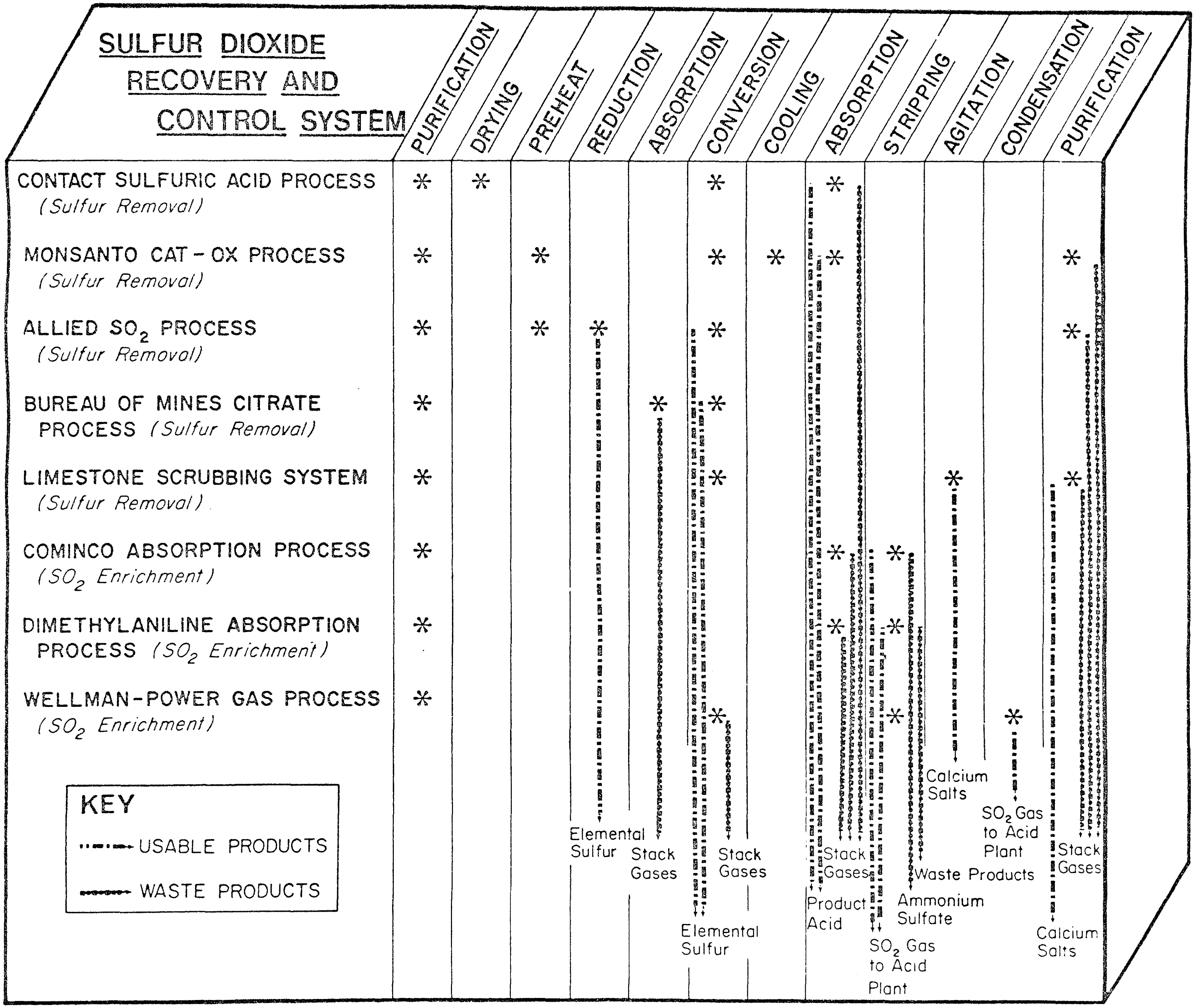


Figure 20. Major sulfur dioxide recovery and control systems.

copper-making type. The sealed Hoboken type of converter will also be advantageous for improving SO_2 collection. With extraordinary care it should be possible to prevent 99 percent of the sulfur entering the smelter from entering the atmosphere.

Sulfur dioxide is most easily fixed as H_2SO_4 and techniques are available to treat gases containing as low as 2 percent SO_2. The tail gases from even the best acid plants contain in the order of 0.1 percent SO_2 which can only be recovered by scrubbing with basic solutions. The products of these scrubber systems are small quantities of basic sulfates ($CaSO_4$, $MgSO_4$, Na_2SO_4) which are water soluble and hence not good for sulfur storage. They can, however, be recycled to the smelting furnace (after evaporation) to keep this part of the sulfur stream in a closed circuit.

Elemental sulfur is the best form for permanently storing sulfur. The production of elemental sulfur from gases containing 5 percent SO_2 is technically feasible but plants to date have not operated below 10 percent SO_2. The elemental sulfur plants have been able to fix only 90 percent of their input sulfur but existing Claus Plant technology could raise this to 95+ percent.

It is admitted that many of the sulfur treating processes are only in the testing stage and have not been proven in large scale situations. The most popular selection today is that of the contact sulfuric acid plant (a fully proven system) where sulfur dioxide gases are converted to sulfuric acid. This system might be considered in tandem with some sort of pyrometallurgical scheme should this type of metallurgy be utilized.

Refer to appendix C for a review of the flowsheets of the various process systems, and to the August, 1976 report for a more detailed discussion of each process.

SUMMARY

All of the primary steps in the metallurgical processing of nonferrous minerals emit pollution to the atmosphere either in a gaseous form or in a solid form. The absolute quantity emitted during a prescribed period of time is a direct function of the selection (including the type and the quantity) of auxiliary anti-pollution devices which are capable of minimizing emissions to the atmosphere. Depending upon the circumstances, reasonable levels of emissions, as prescribed by law, can be achieved and/or maintained successfully.

APPENDIX A^2

Production data of various industrial metallurgical processes (Biswas, 1976).

PRODUCTION DATA

	Lubumbashi, Zaire, (Claus and Guebels, 1967)	Shisakajima, Japan (Momoda *et al.*, 1970)	Shisakajima, Japan (Momoda *et al.*, 1970)	Copper-Nickel, Falconbridge (Falconbridge, 1963)
Furnace size				
W × l × h (inside) (m)	1.5 × 6.1 × 6	1.3 × 7.3 × 5.6	1.2 × 5.5 × 4.3	1.5 × 7.6 × 5.2
Shaft volume (m^3)	55	60	28	60
Hearth area (m^2)	9.2	9.5	6.6	11.4
Production details				
Type of charge	Sinter + solid conv. slag	Wet conc. (31% Cu) + solid conv. slag	Wet conc. (31% Cu) + solid conv. slag	Sinter 8% Ni + 4% Cu (plus ore and solid conv. slag)
Solid charge rate (excluding coke (tonnes/day)	1190	320	250	1300
Average % Cu in charge	27	20	20	6Ni, 3Cu
Matte (tonnes/day)	490	140	110	650
Matte grade % Cu	63	46	46	12Ni, 6Cu
Slag (tonnes/day)	700	160	120	600
% Cu in slag	1.0	0.4	0.4	0.16Ni, 0.15Cu
Productivity (tonnes of charge per day/m^2)	130	35	35	115
Fuel				
Coke (tonnes/day)	131	15	11	126
Oil in tuyeres (tonnes/day)	none	8	6	none
Total energy in fuel (kcal/tonne of charge)	8×10^5	6×10^5	6×10^5	7×10^5

Figure A-1. Production details of copper matte and copper-nickel matte blast furnaces.

	Mount Isa (Middlin *et al.*, 1970)	Luanshya (Verney, 1967)	Kennecott, Utah (Anderson, 1970)	Onahama (Niimura *et al.*, 1973)	Noranda wet charge (1974)	Noranda calcine charge (1974)
Furnace size						
W × l × h (m)	10 × 33 × 4	$9\frac{1}{2} \times 34 \times 4$	9 × 35 × 4	10 × 34 × 4	$10\frac{1}{2} \times 35 \times 4$	$10\frac{1}{2} \times 35 \times 4$
Hearth area (m^2)	330	320	315	340	360	360
Fuel	Pulverized coal	Pulverized coal	Natural gas	Bunker C oil	Bunker C oil	Bunker C oil
Rate (tonnes/day)	115	70	1.3×10^5 Nm^3/day	115 The air is enriched to 23% O_2	76 Natural gas 2.8×10^4 Nm^3 (plus 1.2×10^4 Nm^3 of nat. gas per day for air preheating)	80 (plus 10^4 Nm^3 of natural gas per day for air preheating)
Production details						
Type of charge	Calcine (21% Cu)	Wet concentrate (30% Cu)	Wet concentrate (29% Cu)	Wet concentrate (30% Cu)	Wet concentrate (25% Cu)	Calcine (19% Cu)
Solid charge rate (tonnes/day)[a]	(Total) 1300 (Calcine) 1100	(Total) 400 (Conc.) 350	(Total) 900 (Conc.) 800	(Total) 1150 (Conc.) 950	(Total) 720 (Conc.) 625	(Total) 1100 (Calcine) 1000
Average % Cu in charge	19%	26%	30%	25%	22%	18%
Converter slag (tonnes/day)	400	260	420	450	480	470
Matte (tonnes/day)	650	250	700	800	650	600
Matte grade (% Cu)	36	47	41	34	34	40
Discard slag (tonnes/day)	750	260	480	840	450	900
% Cu in slag	0.38	0.6	0.41	0.47	0.43	0.57
Productivity (tonnes of charge per day/m^2)	3.6	1.2	2.9	3.4	2	3
Energy requirement kcal/tonne of charge	8×10^5 (plus an additional 2×10^5 kcal in the roaster)	15×10^5	13×10^5	With O_2 enrichment, 13×10^5 Without 16×10^5	15×10^5 plus 1×10^5 for air preheating	8×10^5 plus 1×10^5 for combustion air heating plus 1×10^5 in roasters

[a] Excluding converter slag.

Figure A-2. Production details of industrial reverberatory furnaces. Charges and analyses are on a dry basis.

				Cu-Ni matte smelters[a]		
	Boliden (Sweden) (Herneryd *et al.*, 1954)	Jinja (Uganda) (Treilhard, 1965)	Inspiration (Arizona) (Dayton, 1974) design data only	INCO (Thompson) (Boldt and Queneau, 1967) updated to 1975	Rustenburg (South Africa) (Mostert, 1973)	Copper smelting from dead roasted concentrates Brixlegg, Austria (Kettner *et al.* 1972)
Furnace size				2 Furnaces		
W × l × h (m)	6 × 24 × 3	6 × 14 × 3	10 × 35 × 5	8.5 × 30 × 5	7 × 26 × 4.5	5 m diameter
Hearth area (m^2)	144	84	350	260	181	20
kVA (kilovolt-amperes)	12,000	5500	50,000	30,000	19,500	2500
Power density (kW/m^2)	60	60	120 (max)	115	100	125 max
Electrodes						
Number	6	3	6	6	6	3
Diameter (m)	1.2	1.1	1.8	1.4	1.1	0.8
Current density (A/cm^2)	2–3	2–3		2.0	2.6 (max)	
Consumption (kg/tonne of charge)	1.6	2.5		2.1	2.7	2.5
Production details						
Type of charge	Hot calcine (700°C) and dry concentrate	Concentrate (7% H_2O)	Dry concentrate	Calcine	Dry concentrate pellets (2% H_2O)	Dead roasted calcine
Solid charge rate (tonnes/day)	500 (total)	250	1650 (total)	1500 per furnace (including 300 tonnes of flux)	565 (total)	75 (total) plus 6 (coke)
	450 (calcine plus concentrates)		1500 (concentrates plus precipitates)		435 (concentrates)	55 (calcine)
Average % Cu in charge	15	20		0.2 (5% Ni)	2 (4% Ni)	25
Converter slag (tonnes/day)	130	150		360	110	nil
Matte (tonnes/day)	200	150	1100	330	110	20 (metal)
Matte grade (% Cu)	36	30–40	40	22.5 (Cu + Ni)	27 (Cu + Ni)	92.5
Discard slag (tonnes/day)	400	160		1360	500	35
% Cu in slag	0.4	0.63		0.18 (Cu + Ni)	0.16 (Cu + Ni)	0.7
Productivity (tonnes of charge per day/m^2)	3.5	3.0	3.7	5.8	3.1	3.8
Energy requirement						
kWh/tonne of charge	400	420		430	690	520
or						
kcal/tonne of charge	3.5×10^5	3.6×10^5		3.7×10^5	5.9×10^5[b]	4.5×10^5 plus coke 5.5×10^5 oil 0.9×10^5 Total 10.9×10^5

[a] INCO also have three 18,000-kVA furnaces. Falconbridge are replacing their blast furnaces with electric furnaces.

[b] This anomalously high-energy requirement is probably due to (a) the moisture content and (b) a high temperature (1350°C) of furnace operation.

Figure A-3. Product details of industrial matte smelting electric furnaces.

PRODUCTION DATA - (contd.)

	INCO, Canada (Merla *et al.*, 1972, updated to 1975)	Tamano, Japan (Kitamura *et al.*, 1973)	Hitachi, Japan (Yasuda, 1974)	Toyo, Japan (Ogura, 1973, 1974)
Furnace size				
W × l × h (m)	6 × 23 × 5	7 × 20 × 3	7 × 19 × 3	7 × 20 × 3
Hearth area (m^2)	138	140	133	140
Burner tower	none			
Diameter × height from roof (m)		6 × 6	5.7 × 6	6 × 6
Concentrate burners	4	4	3	3
Inlet air temperature	20°C	450°C	930°C	450°C
Gas offtake				
Length × width (m)	6 × 3	2.5 diameter	7 × 3	7 × 3
Height (m)	6	7	6	6
Production details				
Type of charge	Dry concentrate (30% Cu)	Dry concentrate (30% Cu)	Dry concentrate (26% Cu)	Dry concentrate (28% Cu)
Solid charge rate (tonnes/day)	(Total) 1600	(Total) 1200	(Total) 1200	(Total) 1100
Average % Cu in charge	25	24	20	25
Converter slag (tonnes/day)	None	None	None	None
Matte (tonnes/day)	850	600	550	550
Matte grade (% Cu)	47	47	49	49
Flash furnace slag (tonnes/day)	550	(500)	450	300
% Cu in slag	0.7	0.55	≃1	≃1
% SiO_2 in slag	36	36	34	40
Auxiliary Cu recovery system	None	Electric furnace within flash furnace, 0.55% Cu	Electric furnace	Electric furnace
% Cu in final discard slag	0.7		0.5	0.45
Productivity (tonnes of charge per day/m^2)	11.6	8.6	9.0	7.9
Fuel (Bunker C oil, tonnes/day)				
Flash furnace combustion tower		37	11	32
Flash furnace hearth		7 plus 5.2×10^4 kWh/day	17	16
Air preheater		none	31	15 (est.)
Charge dryer	≃7	7	9	None (uses waste gases)
Total	≃7	51 $+0.5 \times 10^5$ kWh	68	63
Oxygen (tonnes/day)	300 (95–97% O_2)	None	40 (99.5% O_2)	None
Energy requirement, including O_2 manufacture (kcal/tonne of charge)	1.1×10^5	4.5×10^5	5.8×10^5	5.8×10^5
Energy in auxiliary Cu recovery system (kcal/tonne of flash-furnace charge)			$\simeq 0.3 \times 10^5$	0.3×10^5
Total energy requirement (kcal/tonne of charge)	1.1×10^5	4.5×10^5	6.1×10^5	6.1×10^5

Figure A-4. Production details of industrial flash smelting furnaces.

PRODUCTION DATA - (contd.)

	INCO flash furnace (Merla, 1972 updated)	Outokumpu type flash furnace (Table 8.1)
Productivity (tonnes of charge per day/m^2)	11.6	8.7
Dust loss in effluent gas (% of charge)	2	5–10
SO_2 concentration in gas (vol.%)	80	10–15
Volume of effluent gas (Nm^3 per tonne of charge)	175	1100
Copper concentration in slag (%)	0.7	≈1
Auxiliary facilities	Oxygen plant	Air preheater or heat exchanger Small electric furnace for recovering copper from slag
Fuel required per tonne of charge (kg)	8 (Oil in concentrate dryer)	55 (oil)
Oxygen required per tonne of charge (kg)	200 (95% O_2)	
Electrical energy in slag retreatment furnace per tonne of charge (kWh)		40 (Section 10.3)

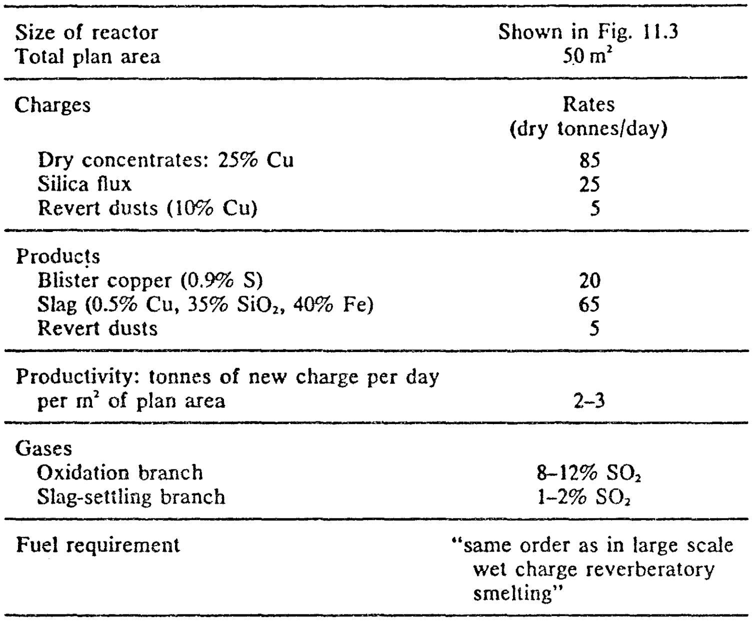
Figure A-5. Comparative operating data for INCO and Outokumpu flash smelting furnaces.

Size of reactor	21 m long, 5 m diameter	
Total plan area	≈100 m^2	
Operation (tuyere blast)	Air	Air enriched to 30.5% O_2
Charges	Tonnes per day (dry basis)	
Wet concentrate: 10% H_2O 25% Cu (dry basis)	730	1200
Slag concentrate from slag flotation plant, 55% Cu (dry basis)	165	250
Silica flux	150	250
Revert dusts (10% Cu)	30	60
Pure oxygen		200
Products	Tonnes per day	
Blister copper (98% Cu, 0.1% Fe, 1.5% S)	180	300
Slag (12% Cu, 36% Fe, 22% SiO_2) to slag flotation circuit	700	1150
Revert dusts	30	60
Productivity, tonnes of new charge smelted per day per m^2 of plan area	9	15
Fuel requirement (total) kcal per tonne of new charge (dry basis)	11×10^5	3×10^{5a}

[a] Excluding energy for oxygen manufacture (≈400 kWh/tonne of oxygen).

Figure A-6. Production data for the industrial Noranda process reactor.

PRODUCTION DATA - (contd.)



Size of reactor	Shown in Fig. 11.3
Total plan area	50 m^2
Charges	Rates (dry tonnes/day)
Dry concentrates: 25% Cu	85
Silica flux	25
Revert dusts (10% Cu)	5
Products	
Blister copper (0.9% S)	20
Slag (0.5% Cu, 35% SiO_2, 40% Fe)	65
Revert dusts	5
Productivity: tonnes of new charge per day per m^2 of plan area	2–3
Gases	
Oxidation branch	8–12% SO_2
Slag-settling branch	1–2% SO_2
Fuel requirement	"same order as in large scale wet charge reverberatory smelting"

Figure A-7. Production data for the WORCRA pilot reactor.

PRODUCTION DATA - (contd.)

Production details	Semi-commercial unit[a]	Commercial unit
Smelting furnace	Rates	(Dry tonnes per day)
Charges:		
Wet concentrate	120 (25% Cu)	500 (27% Cu)
Silica and lime fluxes	25	200
Revert dusts	5	15
Solid recycle slag from converting furnace (10–15% Cu)	50	55
Pure oxygen (30% O_2 in blast)	7	55
Products:		
Matte and slag to electric settling furnace		
Electric settling furnace		
Charge: pyrite reductant	NR	3 (or less)
Products:		
Matte to converting furnace	60 (60% Cu)	225 (65% Cu)
Discard slag (0.5% Cu, 30–40% Fe, 30–35% SiO_2 5–10% CaO, 2–6% Al_2O_3)	90	440
Converting furnace		
Charge: limestone ($CaCO_3$) flux	15	15
Pure oxygen (25% O_2 in blast)	1	0
Products:		
Blister copper (0.1–0.8% S, 99–99.5% Cu)	30	135
Recycle converting furnace slag (10–15% Cu, 65–70% Fe_3O_4, 10–20% CaO, little or no SiO_2) Recycle to smelting furnace	50	55
Productivity, tonnes of new charge smelted per day per m^2 of plan area (3 furnaces)	2–3	furnace dimensions not given
Fuel requirement	kcal/tonne of charge	kcal/tonne of charge
Smelting furnace	6×10^5	6×10^5
Electric settling furnace	0.4×10^5	0.3×10^5
Converting furnace	0.6×10^5	0
Total	7×10^5	6×10^5

[a] Smelting furnace: 7 m diameter, 2–4 lances. Electric settling furnace: 3½ m dia, 250 kVA. Converting furnace: 3 m diameter, 2–3 lances.

Figure A-8. Production data from semi-commercial and commercial Mitsubishi continuous smelting systems.

APPENDIX B[13]

Pictorial summary of particulate removal pollution equipment.

MECHANICAL COLLECTORS

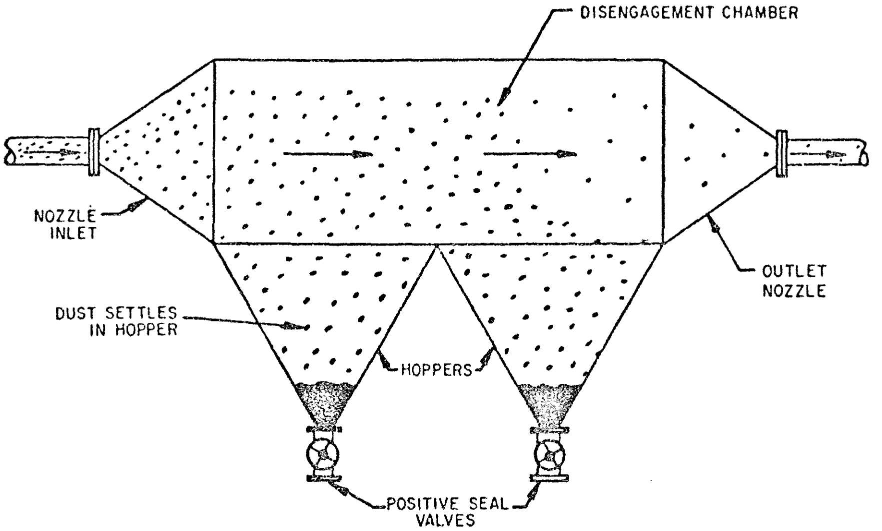


Figure B-1. Gravity settling chamber.

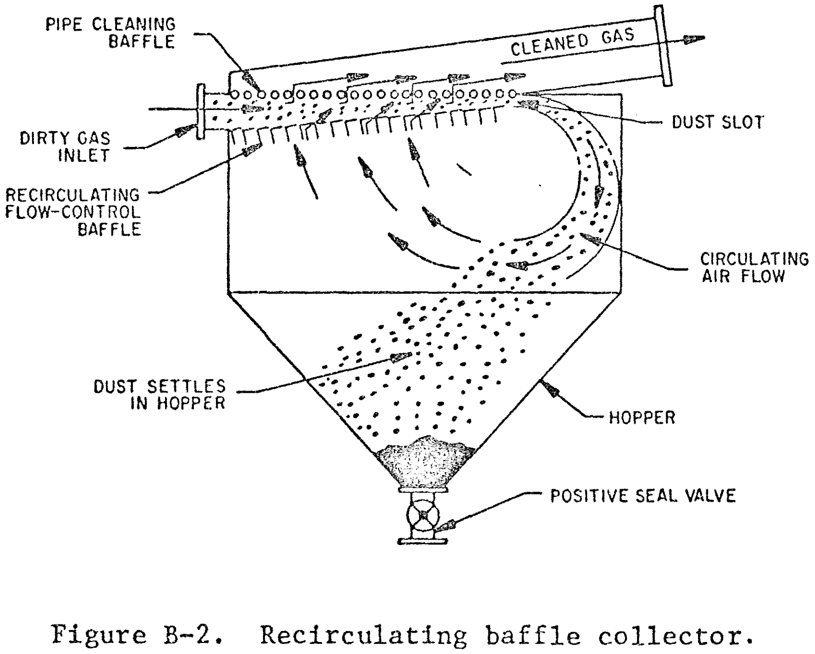


Figure B-2. Recirculating baffle collector.

MECHANICAL COLLECTORS - (contd.)

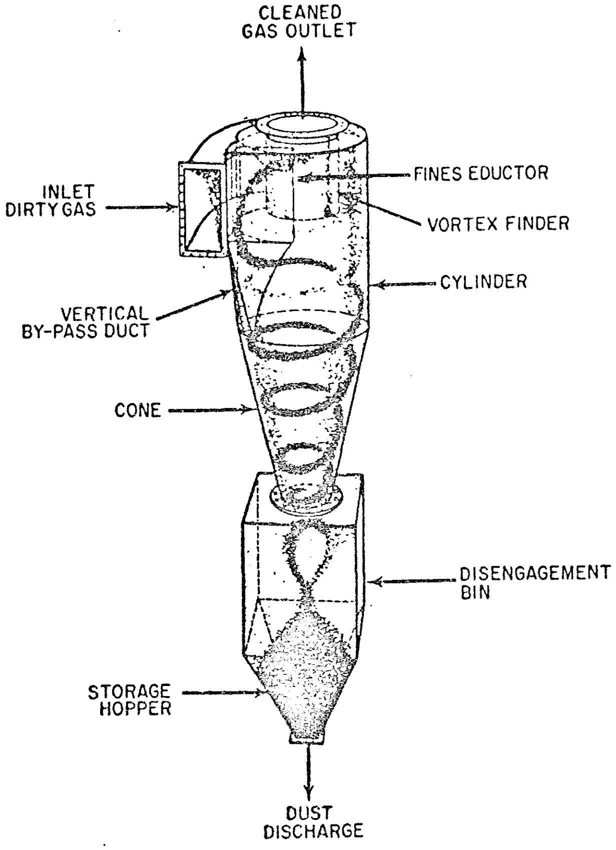


Figure B-3. Flow pattern in mechanical cyclone with vertical fines eductor.

MECHANICAL COLLECTORS - (contd.)

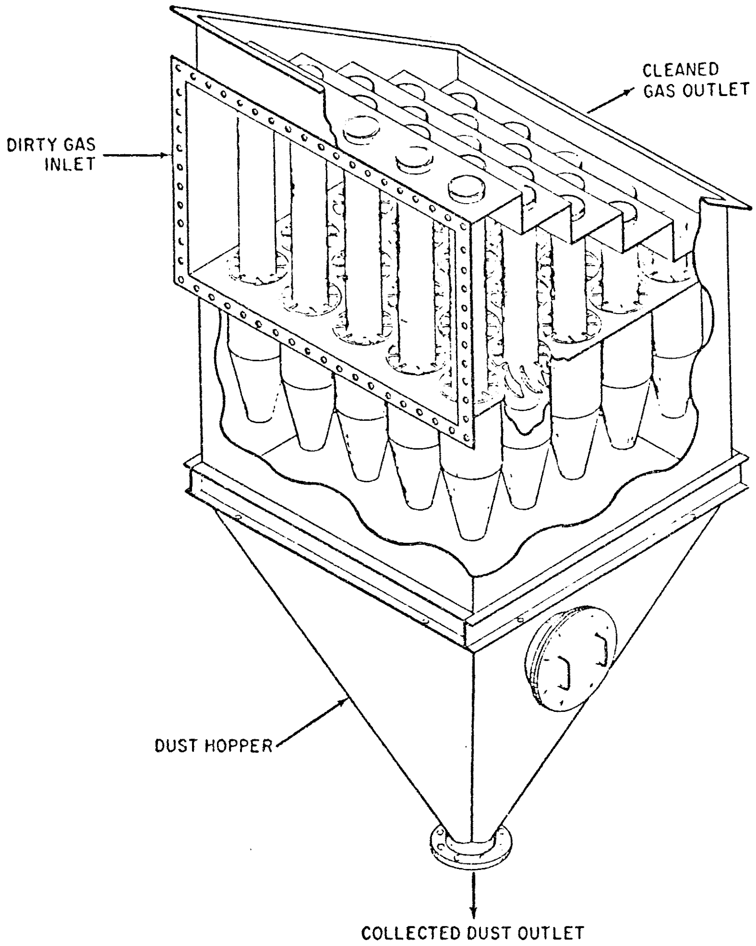


Figure B-4. Vane axial cyclone collector.

MECHANICAL COLLECTORS - (contd.)

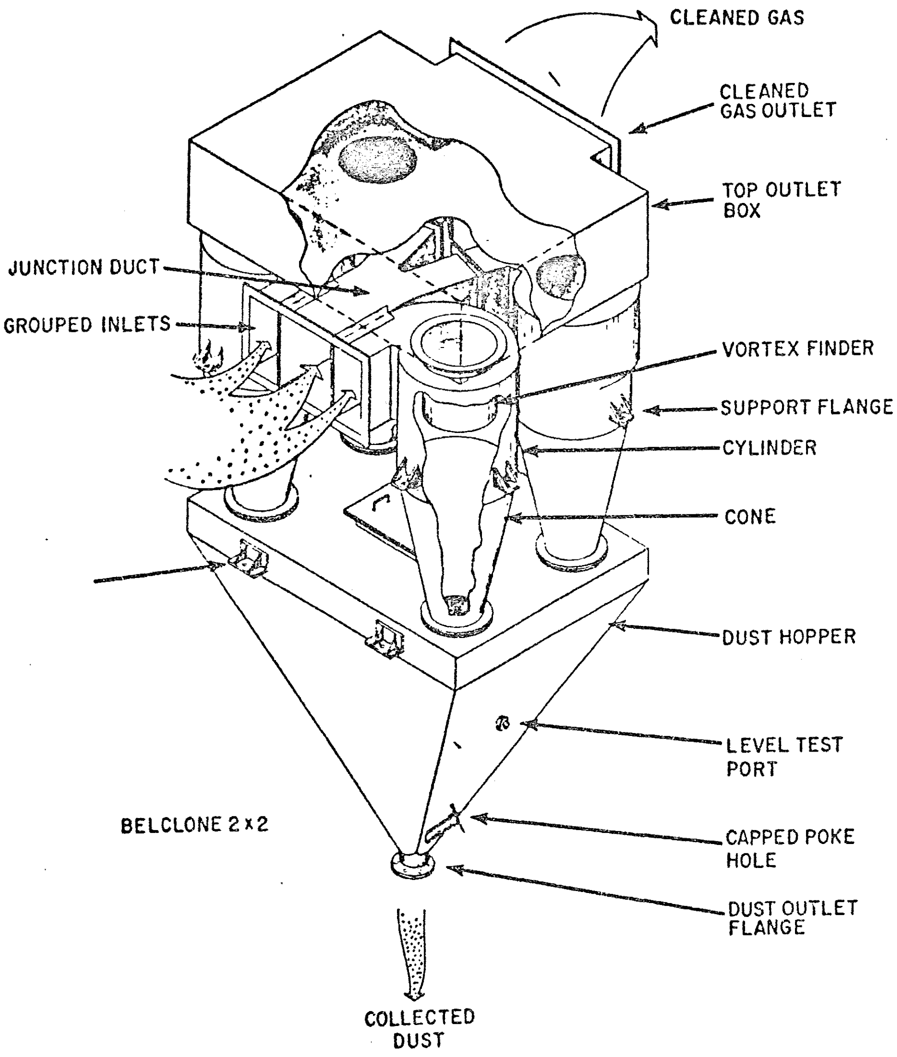


Figure B-5. Group of four involute cyclones.

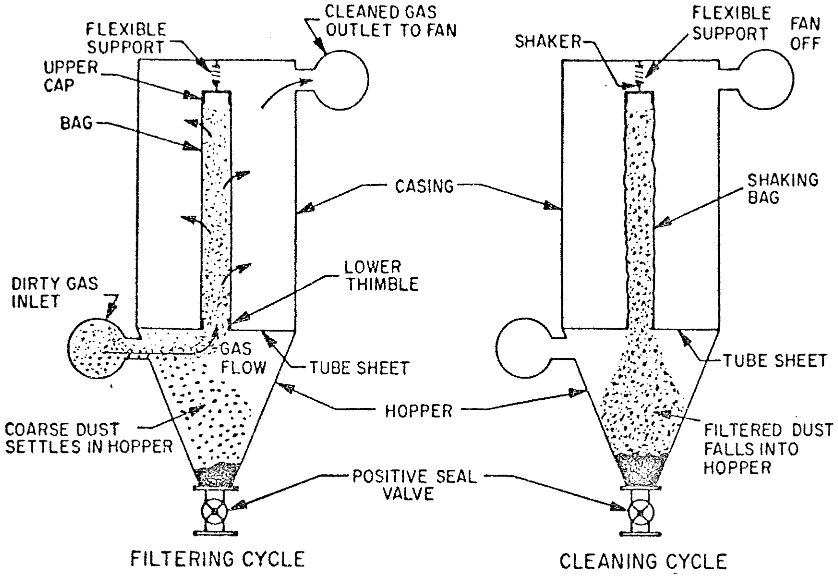


Figure B-6. Intermittent baghouse with manual or powered shaking.

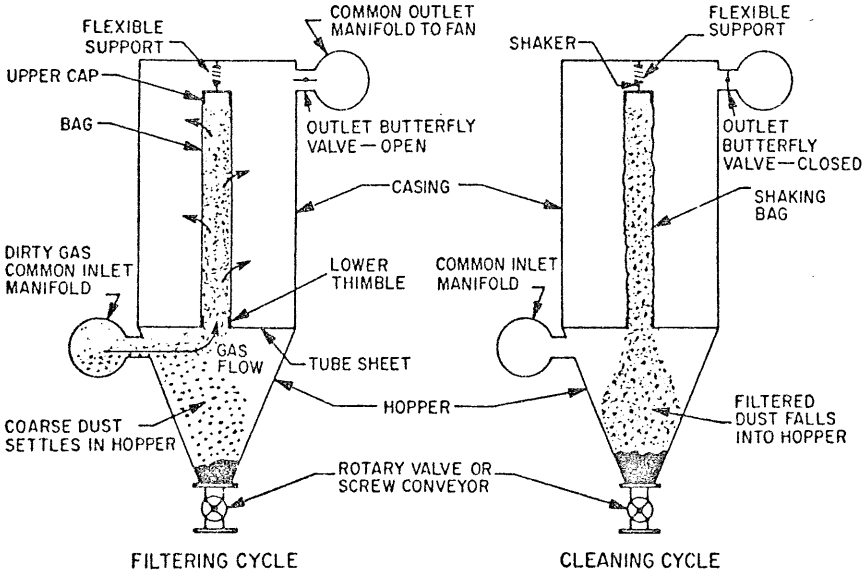
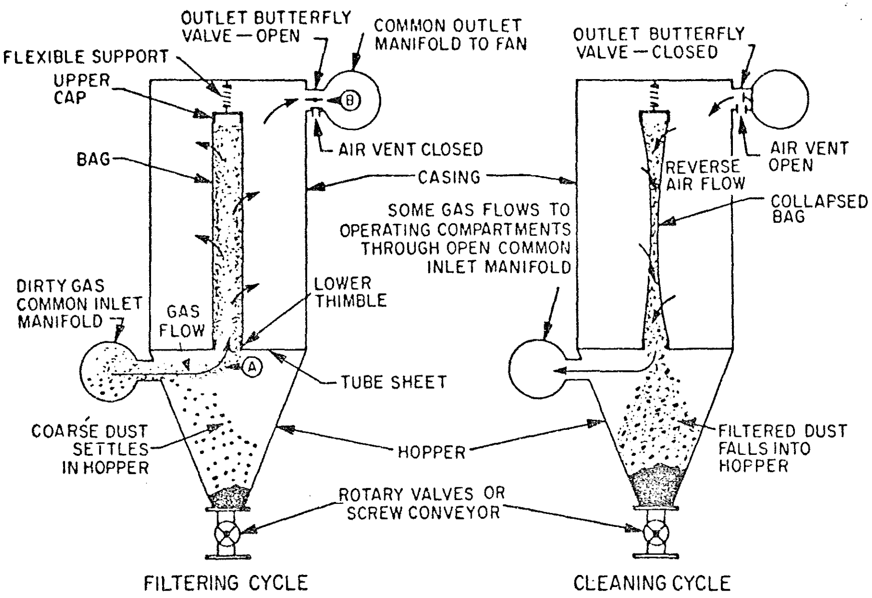


Figure B-7. Automatic conventional baghouse with mechanical shaking.

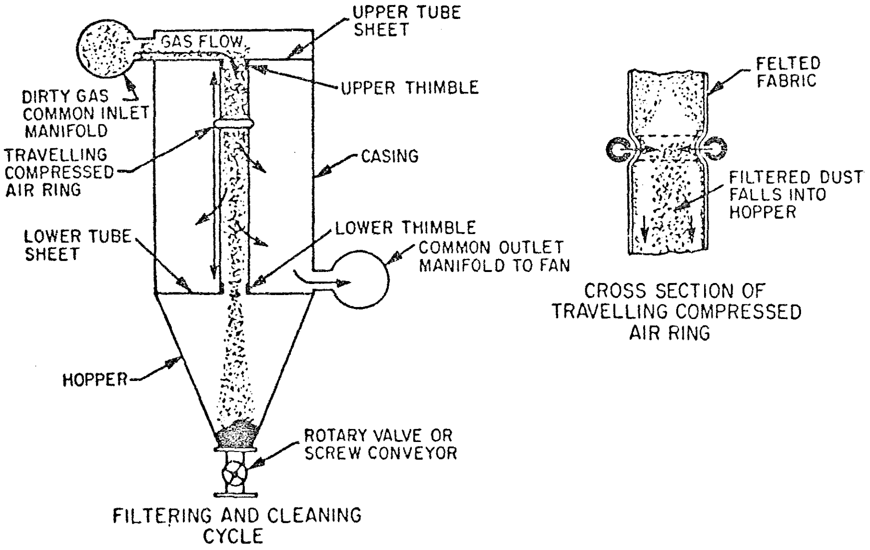
FABRIC FILTERS - (contd.)



FILTERING CYCLE

CLEANING CYCLE

Figure B-8. Automatic baghouse with reverse airflow cleaning.



FILTERING AND CLEANING CYCLE

CROSS SECTION OF TRAVELLING COMPRESSED AIR RING

Figure B-9. Automatic baghouse with reverse ring jet cleaning.

FABRIC FILTERS - (contd.)

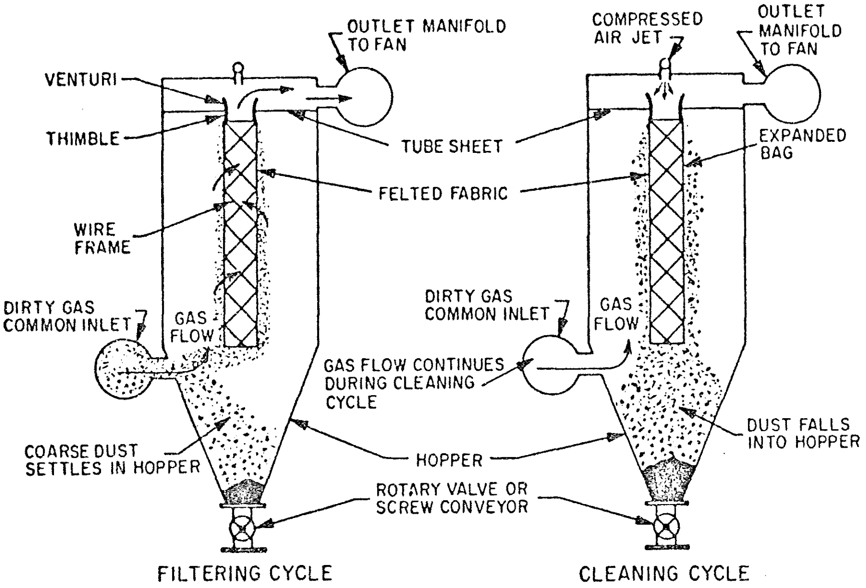


Figure B-10. Automatic baghouse with pulse jet cleaning.

WET SCRUBBERS

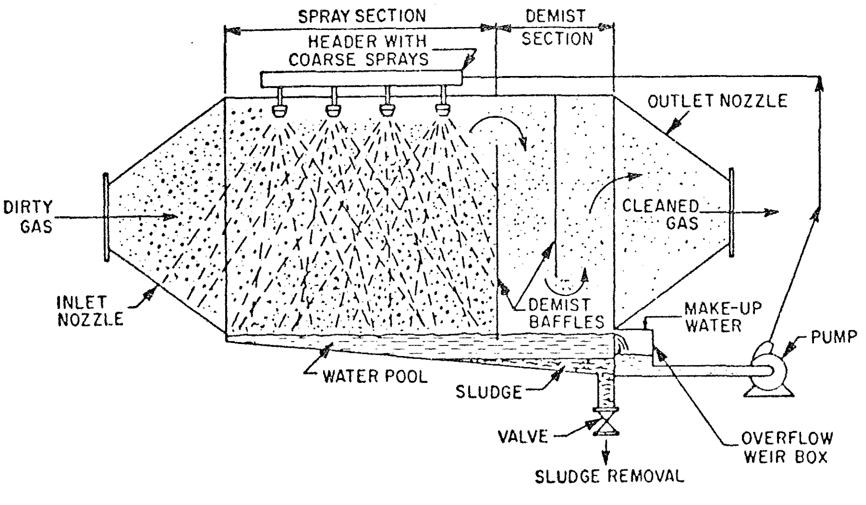


Figure B-11. Gravity settling chamber scrubber.

WET SCRUBBERS - (contd.)

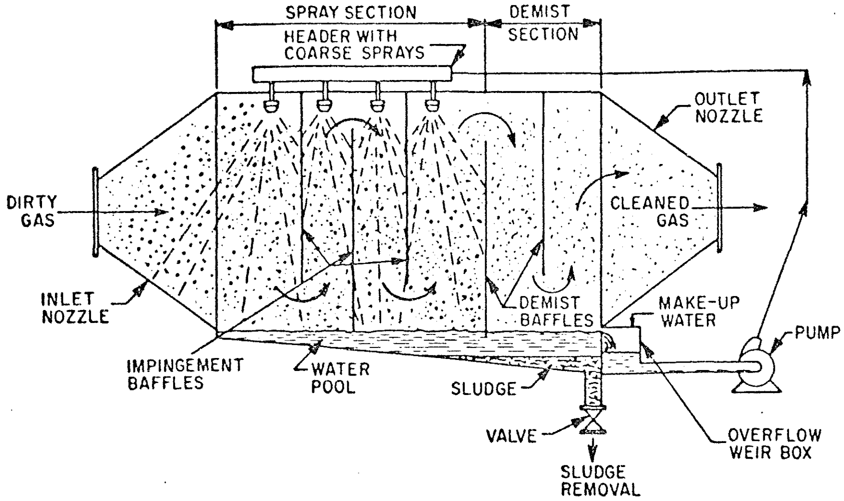


Figure B-12. Wetted impingement baffle scrubber.

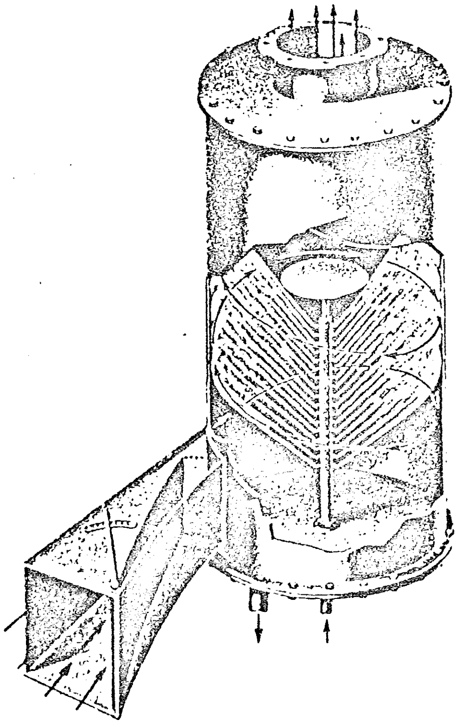


Figure B-13. Cyclone scrubber.

WET SCRUBBERS - (contd.)

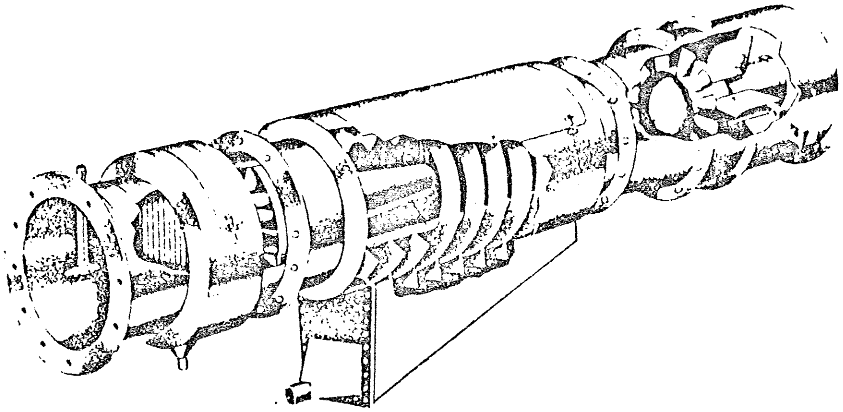


Figure B-14. Multiple-action scrubber.

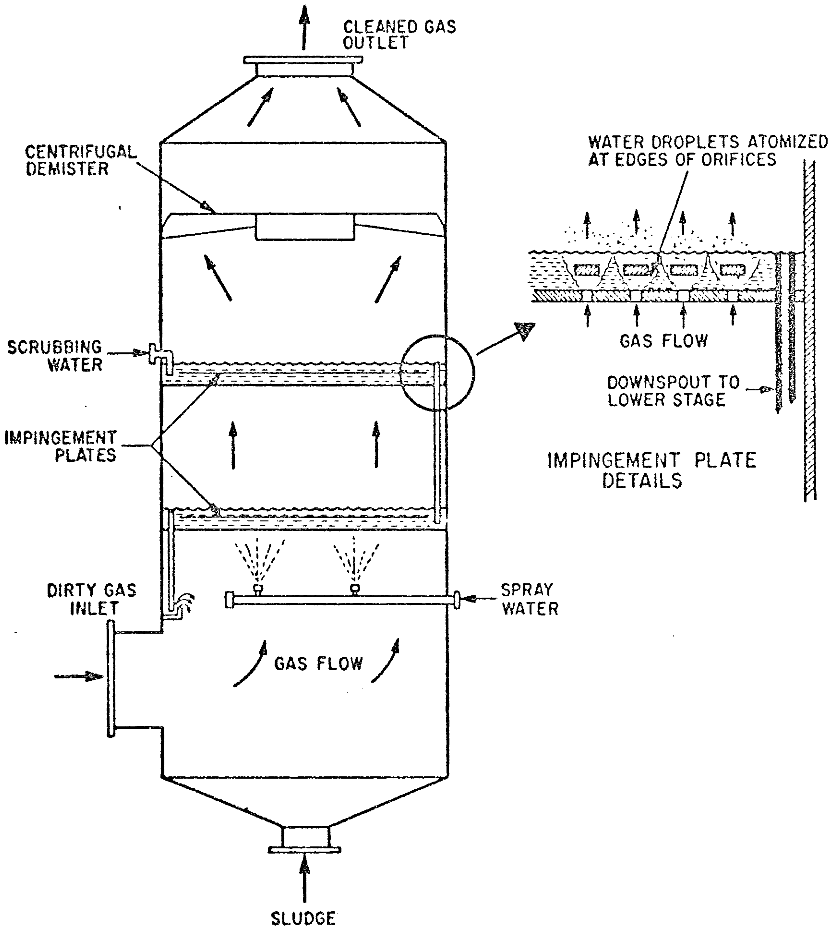


Figure B-15. Impingement plate scrubber.

WET SCRUBBERS - (contd.)

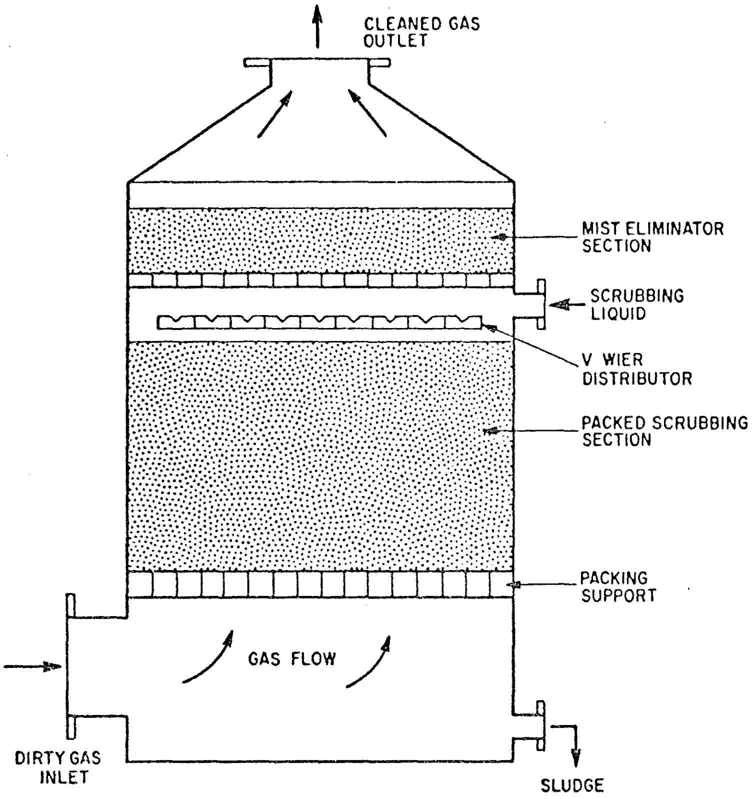


Figure B-16. Countercurrent flow scrubber.

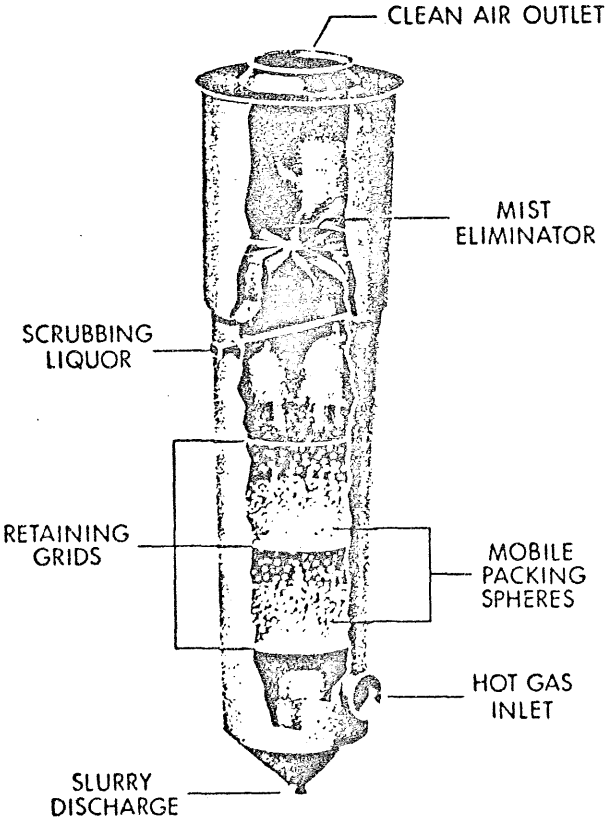


Figure B-17. Fluidized bed scrubber.

WET SCRUBBERS - (contd.)

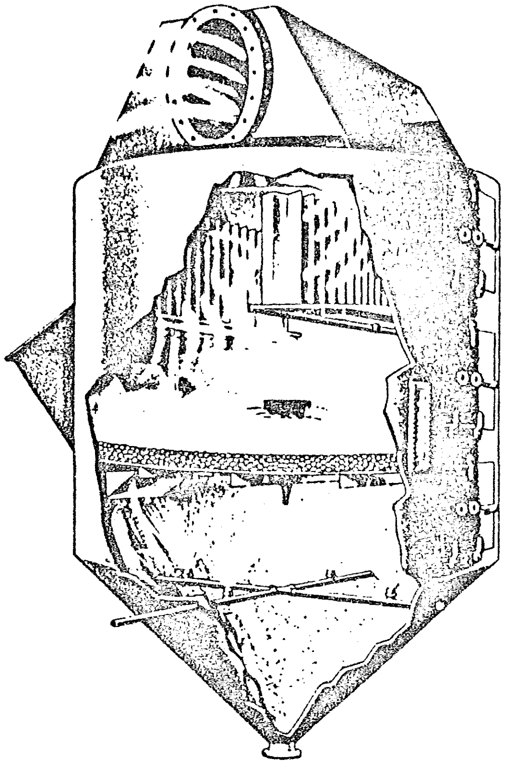


Figure B-18. Flooded bed scrubber.

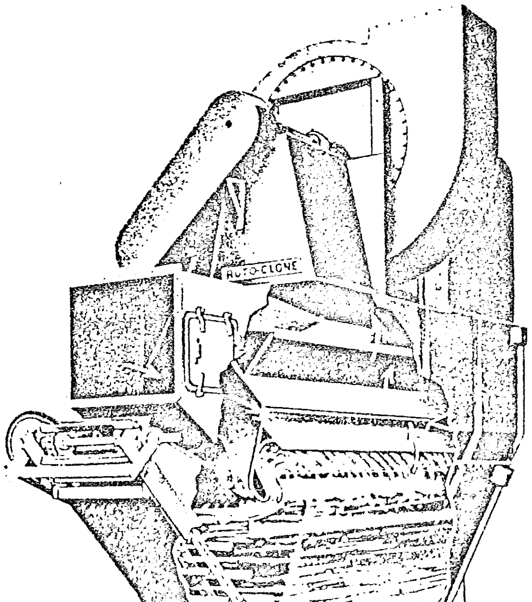


Figure B-19. Submerged-orifice scrubber.

WET SCRUBBERS - (contd.)

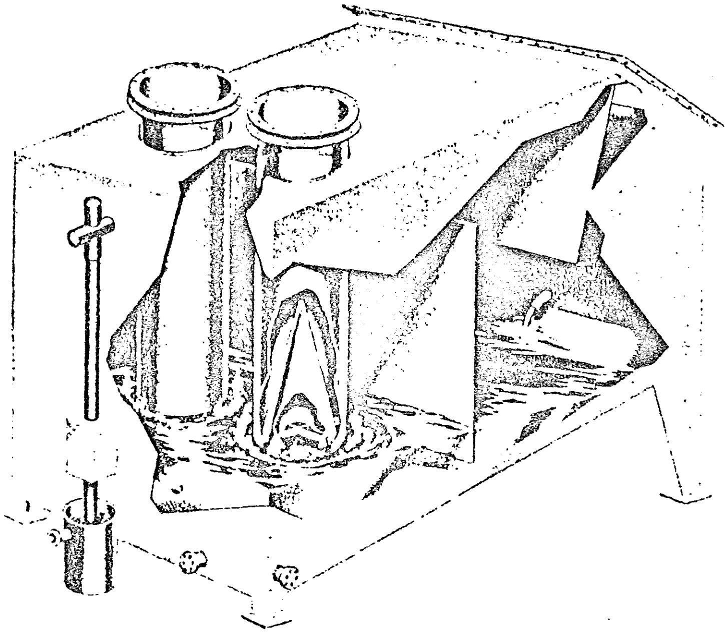


Figure B-20. Multiple submerged-orifice scrubber.

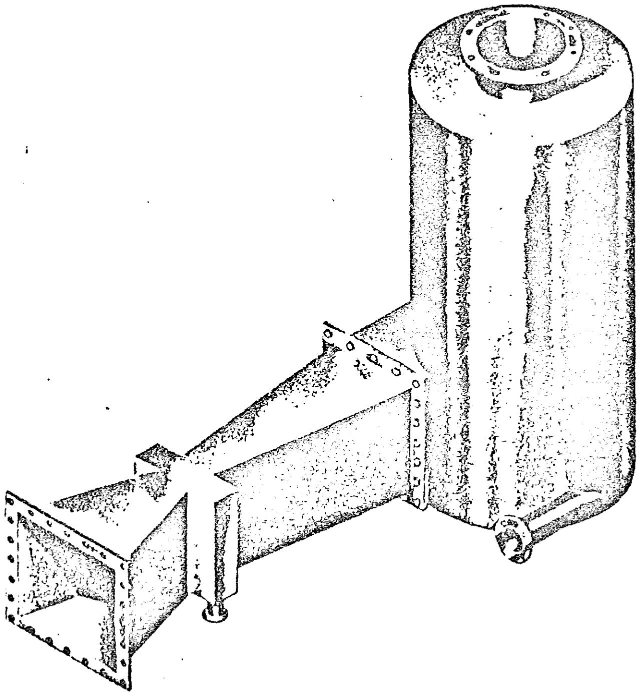


Figure B-21. Rectangular, horizontal gas flow venturi scrubber.

WET SCRUBBERS - (contd.)

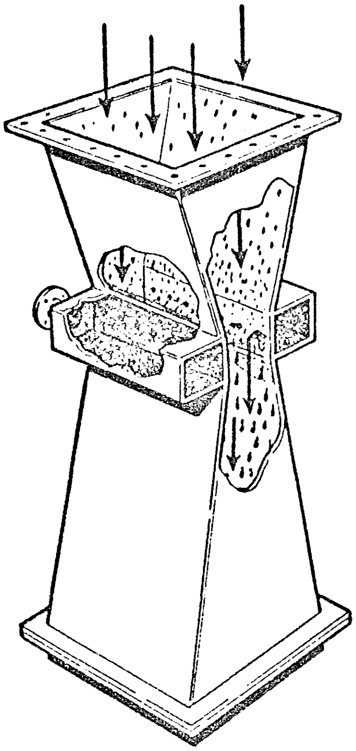


Figure B-22. Vertical downward gas flow venturi scrubber.

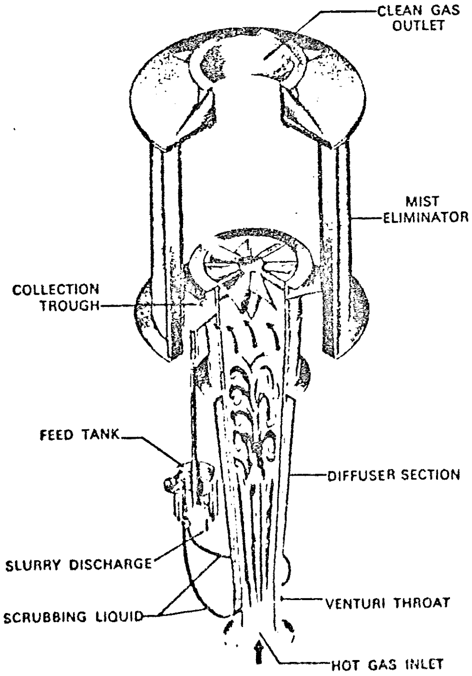


Figure B-23. Vertical upward gas flow venturi scrubber.

WET SCRUBBERS - (contd.)

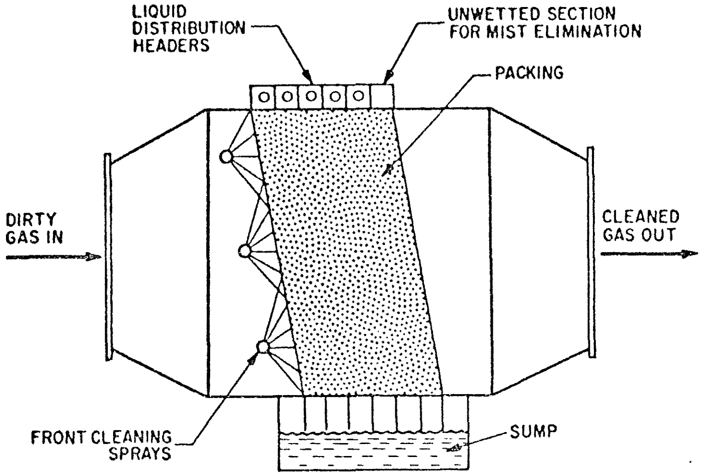


Figure B-24. Cross-flow packed scrubber.

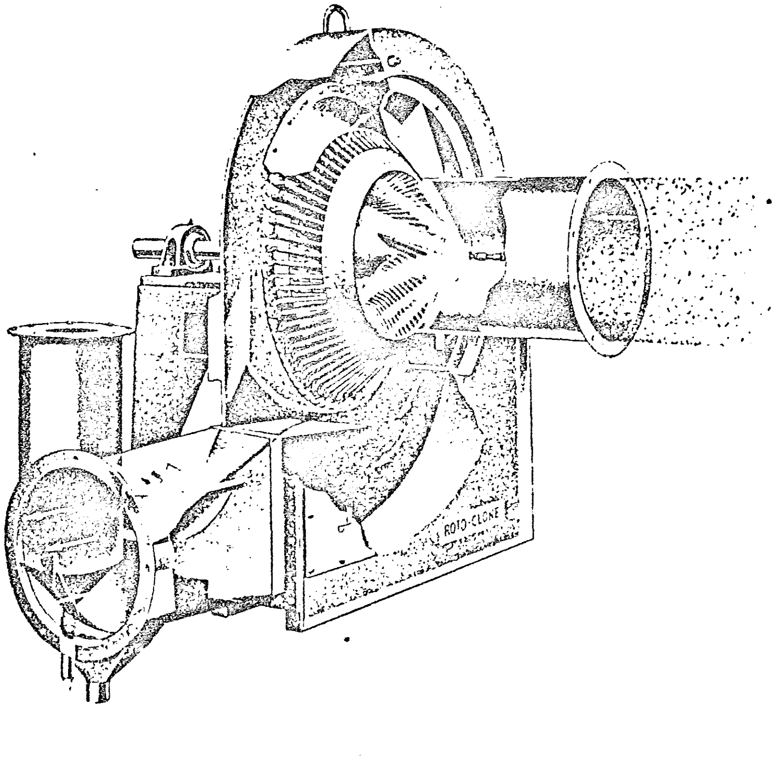


Figure B-25. Centrifugal fan-type wet scrubber.

WET SCRUBBERS - (contd.)

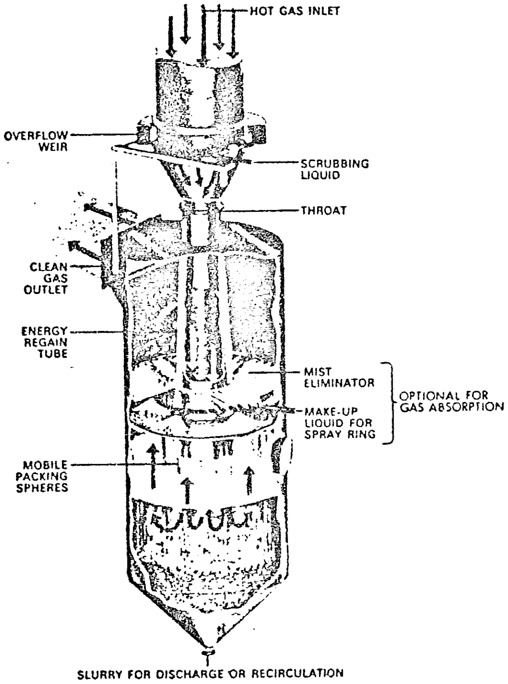
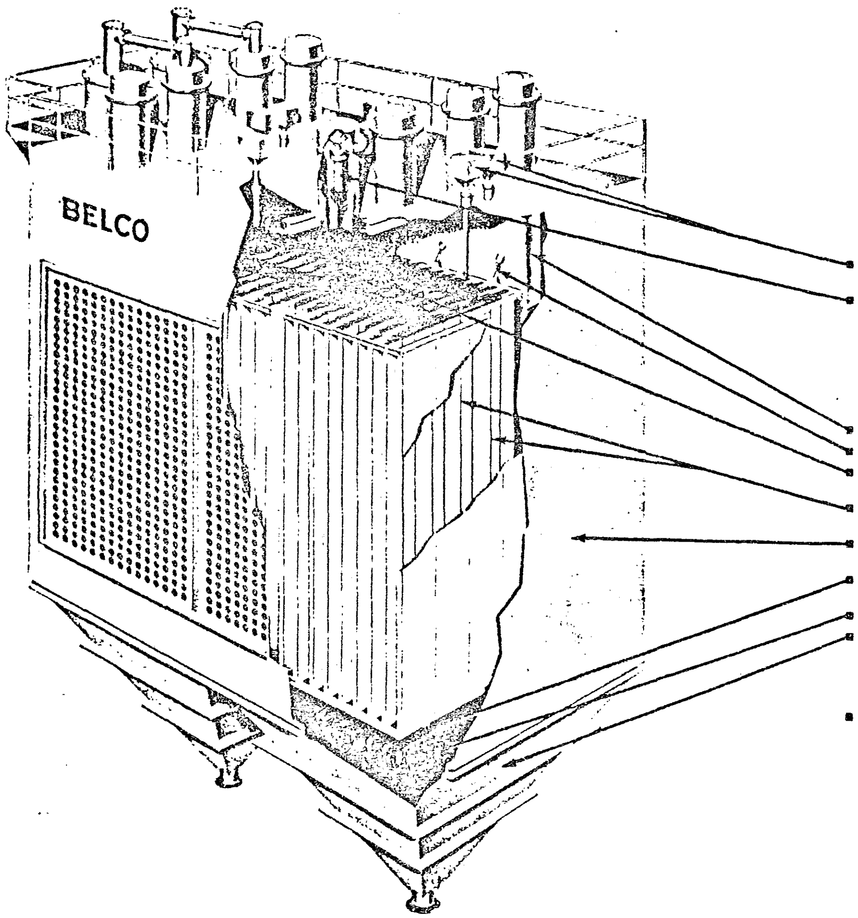


Figure B-26. Combination wet scrubber.

ELECTRIC PRECIPITATORS



- All Vibrators and Rapping Devices are Roof Mounted for Easy Checking and Adjustment.
- Each High Voltage Support Insulator is Mounted in an Individual, Roof-Mounted, Insulator Housing providing many operational advantages:
  - a — Insulators Far Removed from Gas Stream.
  - b — Insulators can be Inspected, Cleaned, and Even Replaced from Roof without Entering Casing.
  - c — Insulators Protected from Dust by Grounded Shroud.
  - d — For Unusual Services Insulators can be Protected by Dried, Heated Air.
- Casing Roof of Shop-Fabricated, Integral-Beam Steel Construction.
- Collectrode Modules Suspended from Shop-Fabricated, Shock-Isolated Grids.
- Discharge Electrode Fields Suspended from Shop-Fabricated Grids, Are Held in Precise Position by Four High Voltage Support Insulators.
- Discharge Electrode Wires are Specially Fitted on Both Ends to Insure Good Electrical Contact, to Eliminate Burning, and to Extend Life.
- Casing Roof, Walls, and Hoppers Have Clean Exterior Design to Facilitate Application of Thermal Insulation.
- A Broken Wire can be Located, Removed, and Replaced Within Minutes of Entering Casing.
- Weights Cannot Fall Into Hoppers to Block or Break Hopper Valves.
- Pyramidal Hoppers are Equipped with Flush Access Doors, Poke Holes, Steep Valley Angles, and Large, Flanged Outlets. Where Service Requirements Warrant, Hoppers can be Equipped with Heating Coils, Vibrators, Hammers, and Level Indicators. Other Hopper Construction: Scraper Bottom, Trough Type, and Wet Bottom.
- Safety-Key-Interlocked, Quick-Opening, Doors Provide Easy Access Through Roof and Sides of Casing.

Figure B-27. Modern dry-plate-type electric precipitator.

APPENDIX C[9]

Various flowsheets of the current and developing process systems for SO_2 recovery and control.

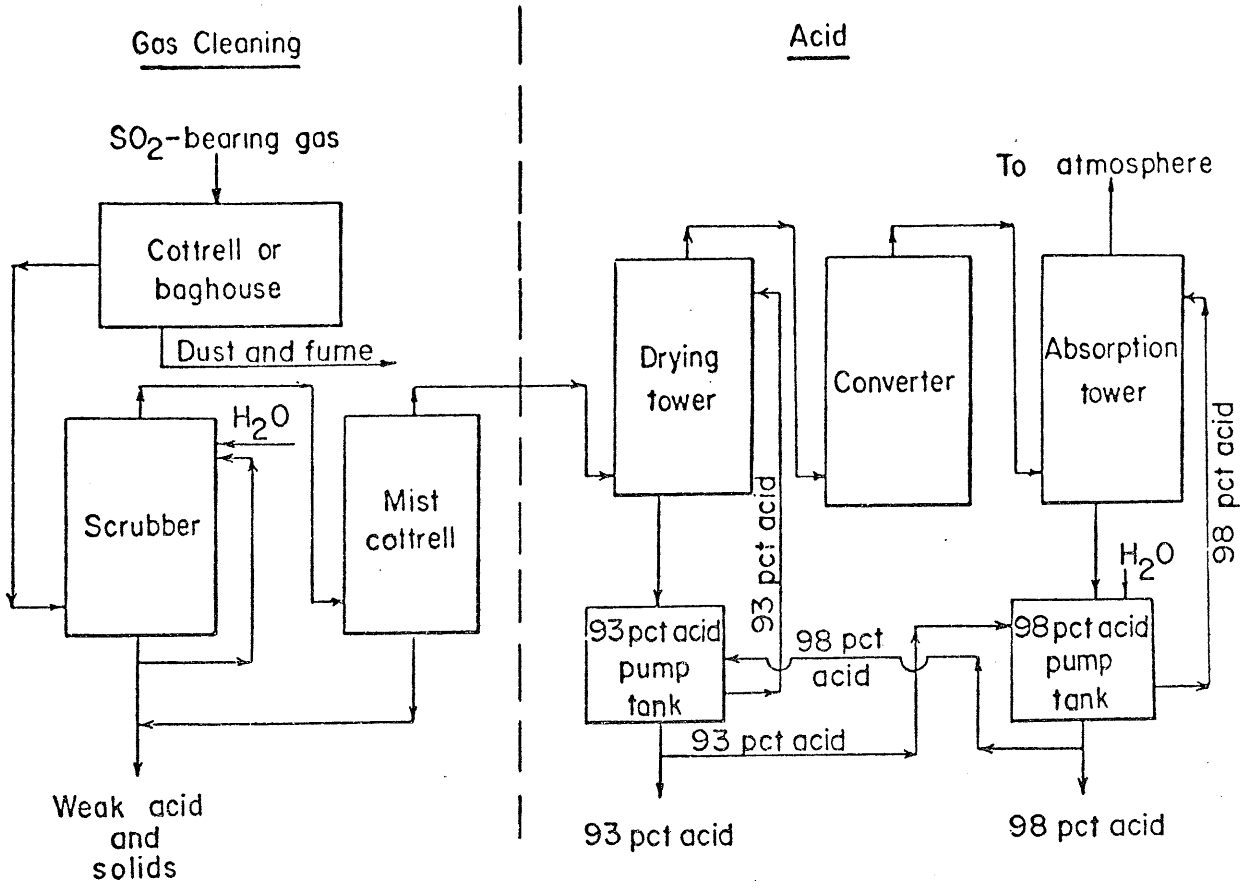


Figure C-1. Contact sulfuric acid process.

Comments

The contact sulfuric acid process is the only well established chemical process for removing sulfur dioxide for smelter gases.

Strong gas is a primary consideration for acid production (matter of economics).

The normal economic minimum concentration of sulfur dioxide in acid plant feed gas is 3.5-4.0 percent.

The major factor limiting production of sulfuric acid from smelter gases is the marketability of acid.

Disposal of neutralized acid poses serious problems for some smelters.

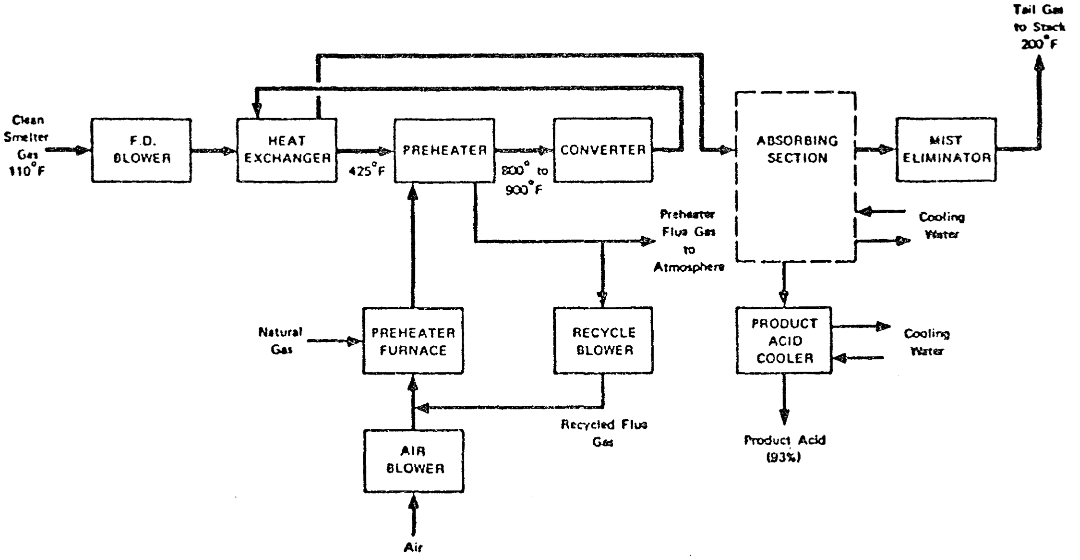


Figure C-2. Cat-ox system for smelter gases.

Comments

The Monsanto Cat-Ox system is essentially an adaptation of the contact sulfuric acid process.

Feed gas entering the system must be at a temperature high enough for conversion, otherwise additional heat must be supplied to the system.

The system operates on wet gas.

The heat of the exit gas is used to concentrate the sulfuric acid formed in this final absorption step.

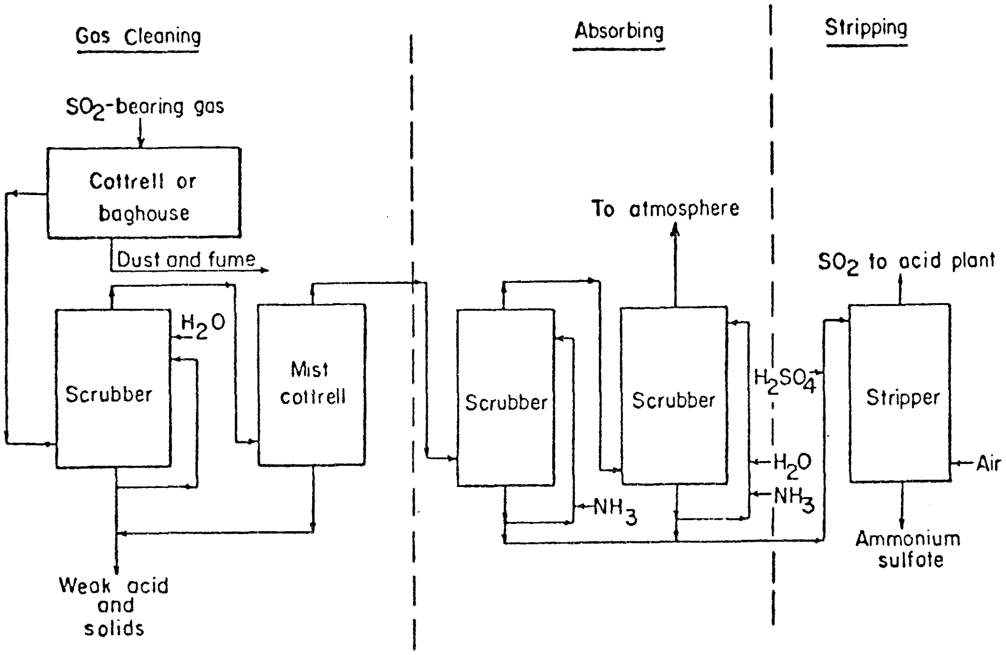


Figure C-3. Cominco absorption process.

Comments

Developed by the Consolodated Mining and Smelting Company of Canada, Ltd., it has seen only limited application.

The process will recover 90 percent of the sulfur dioxide from dilute flue gases.

A serious disadvantage of process is the high cost of ammonia.

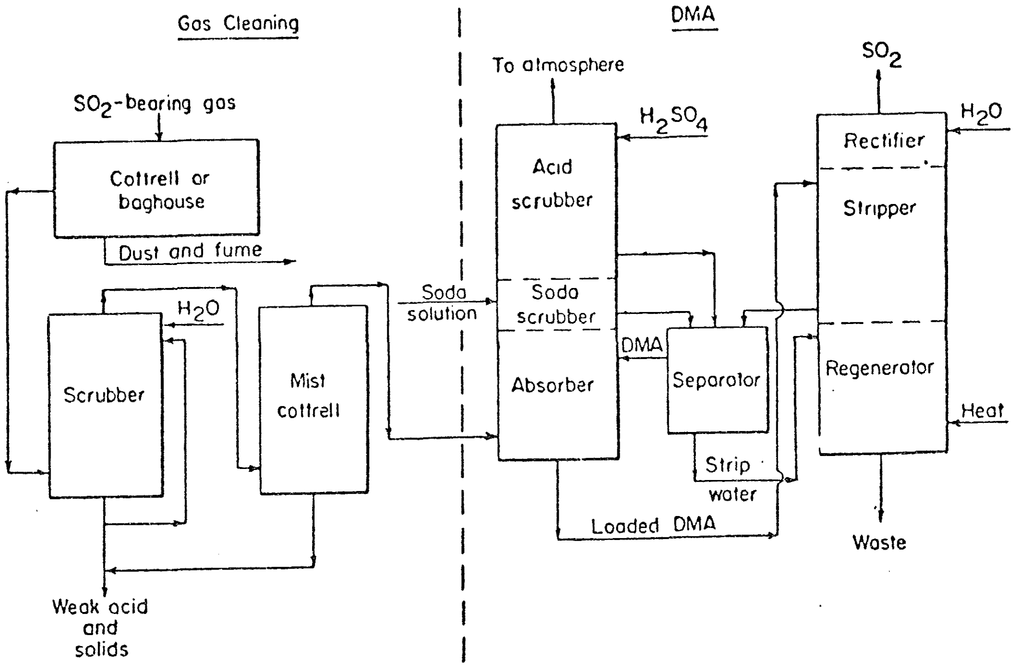


Figure C-4. DMA process.

Comments

Developed by the American Smelting and Refining Company, the process has seen limited use.

The process can recover 90-95 percent of the sulfur dioxide from weak gases and 95-98 percent of the sulfur dioxide from strong gases.

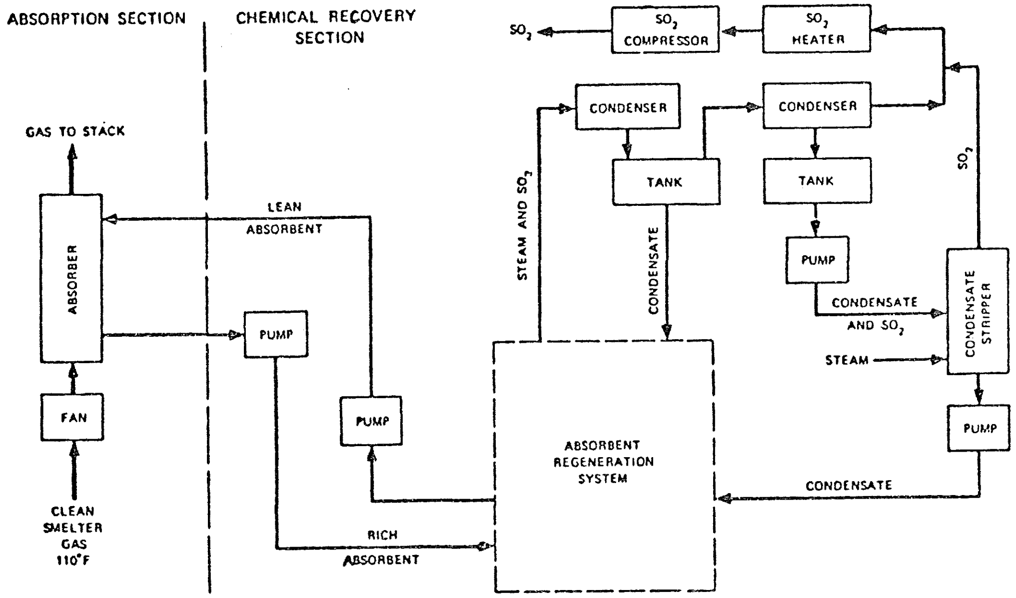


Figure C-5. Wellman-Lord SO_2 recovery system for smelter gases.

Comments

Application of the Wellman-Lord process to smelter gas is only speculative and cost estimates recently published are discouraging.

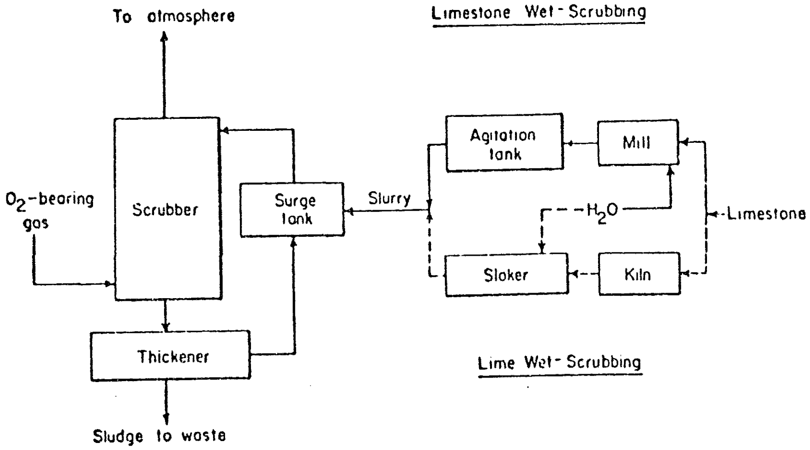


Figure C-6. Lime or limestone wet-scrubbing process.

Comments

In the Limestone Wet-Scrubbing process, a good grade of Limestone is required, hence, substantial costs in mining, hauling, grinding, and calcining will be realized.

Disposal of the final product will involve problems similar to those encountered in acid neutralization.

Is flexible and applicable to variable gas flows and sulfur dioxide concentrations.

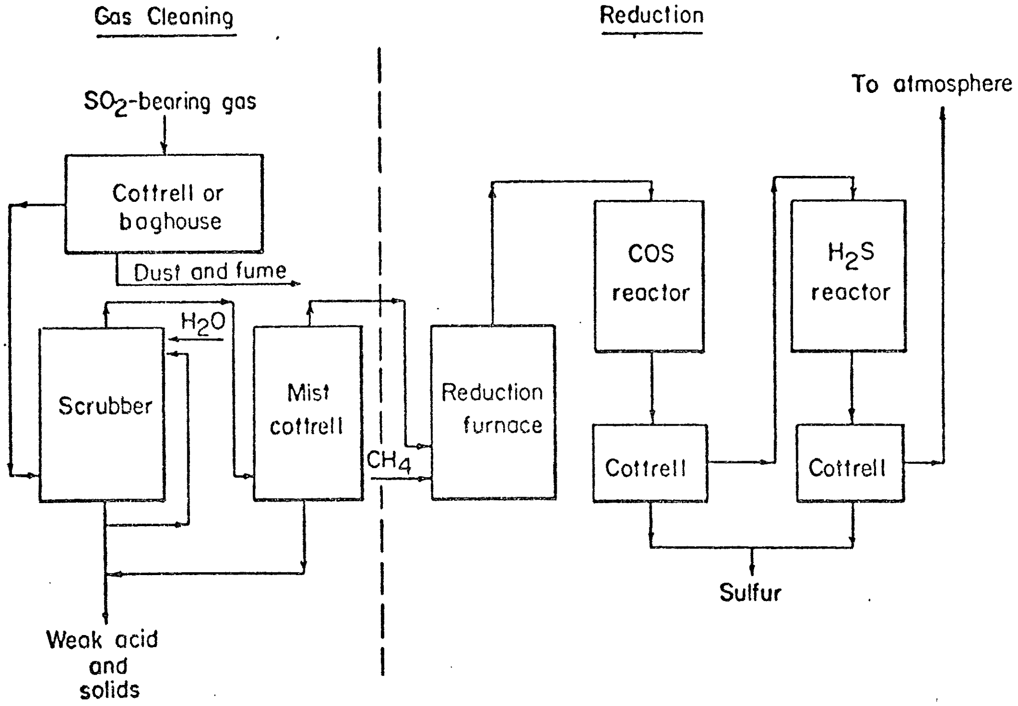


Figure C-7. Asarco process for reduction to sulfur.

PRELIMINARY
SUBJECT TO REVIEW

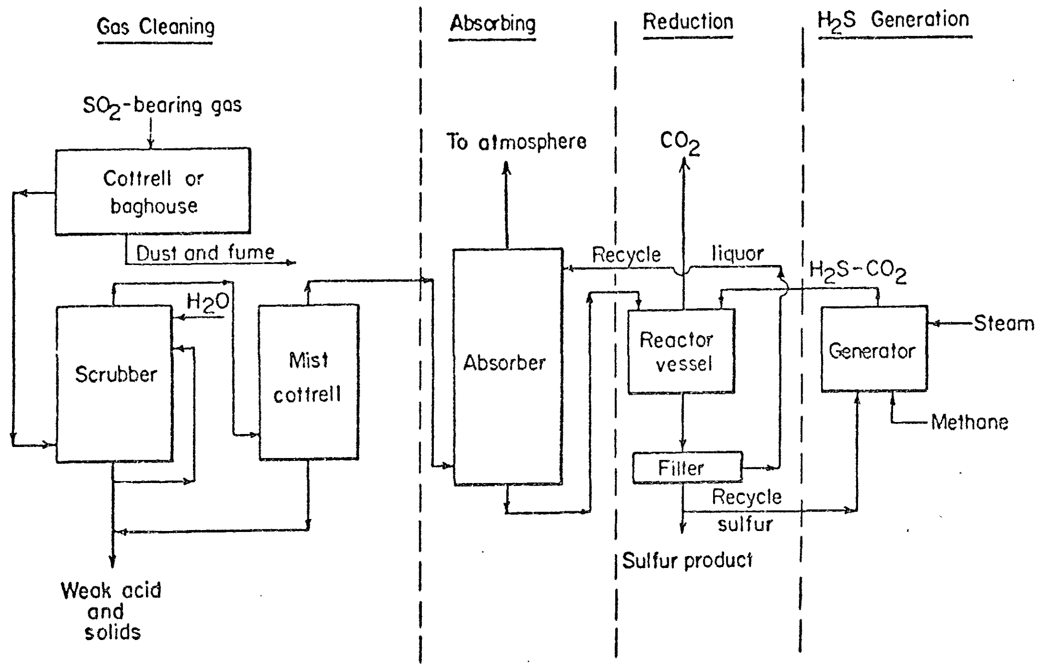


Figure C-8. Citrate process.

APPENDIX D[1,10,14]

Rules and Regulations of the MPCA for Air and Water Quality Control in Minnesota.

Control of air and water pollution is of tremendous importance when considering the development of mining systems. So important are these variables that environmental safeguards have been established to control excessive contamination of air and water. The following rules and regulations apply to the air and waters of Minnesota.

APC 1 Ambient Air Quality Standards[1]

(a) The "primary" air quality standards are levels of air pollutants above which, on the basis of present knowledge, health hazards or impairment may be produced. Health hazards include not only production, aggravation or possible production of disease, but also interference with function. Health impairment includes sensory irritation and impairment of well being by such phenomena as odor. The "secondary" air quality standards are levels which are desirable to protect the public welfare from any known or anticipated adverse effects, such as injury to agricultural crops and livestock, damage to or deterioration of property, annoyance and nuisance of person, sensory impairment and obstruction, or hazards to air and ground transportation.

(b) No person shall emit any pollutant in such an amount or in such a manner as to exceed any ambient air quality standard herein beyond such person's property line, without respect to whether emission regulations stated in other air pollution control regulations of the Agency are also being violated.

(c) State Ambient Air Quality Standards (a)(b)(c).

Pollutant/Air Contaminant	Concentration	Remarks
(1) Hydrogen Sulfide(d) (primary standards)	0.05 ppm by volume (70.0 micrograms per cubic meter)	½ hr. average not to be exceeded over 2 times per yr.
	0.03 ppm by volume (42.0 micrograms per cubic meter)	½ hr. average not to be exceeded over 2 times in any 5 consecutive days

Pollutant/Air Contaminant	Concentration	Remarks
(2) Photochemical[e] Oxidants (primary and secondary standards)	0.07 ppm by volume (130 micrograms per cubic meter)	maximum 1 hr. concentration not to be exceeded more than once per yr.
(3) Carbon Monoxide[f] (primary and secondary standards)	9 ppm by volume (10 milligrams per cubic meter)	maximum 8 hr. concentration not to be exceeded more than once per yr.
	30 ppm by volume (35 milligrams per cubic meter)	maximum 1 hr. concentration not to be exceeded more than once per yr.
(4) Hydrocarbons[g] (primary and secondary standards)	0.24 ppm by volume (160 micrograms per cubic meter)	maximum 3 hr. concentration (6 to 9 AM) not to be exceeded more than once per yr., corrected for methane
(5) Sulfur Oxides[h] (primary and secondary standards)	0.02 ppm by volume (60 micrograms per cubic meter)	maximum annual arithmetic mean
	0.1 ppm by volume (260 micrograms per cubic meter)	maximum 24 hr. concentration not to be exceeded more than once per yr.
	0.25 ppm by volume (655 micrograms per cubic meter)	maximum 3 hr. concentration not to be exceeded more than once per yr.
(6) Particulate[i] Matter (primary standard)	75 micrograms per cubic meter	maximum annual geometric mean
	260 micrograms per cubic meter	maximum 24 hr. concentration not to be exceeded more than once per yr.
Particulate Matter (secondary standard)	60 micrograms per cubic meter	maximum annual geometric mean

Pollutant/Air Contaminant	Concentration	Remarks
(6) Particulate Matter (contd.)	150 micrograms per cubic meter	maximum 24 hr. concentration not to be exceeded more than once per yr.
(7) Nitrogen Oxides(j) (primary and secondary standards)	0.05 ppm (100 micrograms per cubic meter	maximum annual arithmetic mean

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Footnotes:

(a) All standards apply throughout the State of Minnesota.
(b) All measurements of ambient air quality are corrected to a reference temperature of 25°C and a reference pressure of 760 mm of mercury.
(c) All measurements and tests shall be conducted by the methodology referenced herein, or other methodology as the Director shall hereafter approve.
(d) By methylene blue, or other method approved by the Director.
(e) Neutral-buffered one percent potassium iodide colorimetric detection technique corrected for SO_2 and NO_2 interference, gas phase chemiluminesence, or other method approved by the Director.
(f) Nondispersive infrared spectrometry (N.D.I.R.), or other method approved by the Director.
(g) Flame ionization, or other method approved by the Director.
(h) By pararosaniline, coulometric, or other method approved by the Director.
(i) High volume method, or other method approved by the Director.
(j) Jacobs-Hochheiser, or other method approved by the Director.

[July 7, 1969; amended June 3, 1970; amended February 18, 1971; amended April 13, 1972]

Standards of Performance for Industrial Process Equipment

(a) Definitions. As used in this regulation, the following words shall have the meanings defined herein:

(1) "Collection efficiency" means the percent of the total amount of particulate matter entering the control equipment which is removed from the exhaust stream by the control equipment and is calculated by the following equation:

$$\text{collection efficiency} = \frac{100(A - B)}{A}$$

Where

A = the amount (grams or pounds) or the concentration (gr/SCF) of particulate matter entering the collection equipment

B = the amount (grams or pounds) or the concentration (gr/SCF) of particulate matter leaving the control equipment

(2) "Industrial process equipment" means any equipment, apparatus, or device embracing chemical, industrial, or manufacturing facilities such as ovens, mixing kettles, heating and reheating furnaces, kilns, stills, dryers, roasters, and equipment used in connection therewith, and all other methods or forms of manufacturing or processing that may emit any air contaminant such as smoke, odor, particulate matter, or gaseous matter. Industrial process equipment is an "affected facility." An emission facility may consist of more than one unit of industrial process equipment.

(3) "Process weight" means the total weight in a given time period of all materials introduced into any industrial process equipment that may cause any emission of particulate matter. Solid fuels charged are considered as part of the process weight, but liquid and gaseous fuels and combustion air are not. For a cyclical or batch operation, the process weight per hour is derived by dividing the total process weight by the number of hours in one complete operation from the beginning of any given process to the completion thereof, excluding any time during which the equipment is idle. For a continuous operation, the process weight per hour is derived by dividing the process weight for a typical period of time.

(b) Applicability. This regulation shall apply to industrial process equipment for which a standard of performance has not been promulgated in a specific regulation.

(c) Standards of Performance for Post 1969 Industrial Process Equipment.

(1) No owner or operator of any industrial process equipment which was not in operation before July 9, 1969, shall cause to be discharged into the atmosphere from the industrial process equipment any gases which:

(aa) In any one hour contain particulate matter in excess of the amount permitted in Table 1 for the allocated process weight; provided that the owner or operator shall not be required to reduce the particulate matter emission below the concentration permitted in Table 2 for the appropriate source gas volume; provided that regardless of the mass emission permitted by Table 1, the owner or operator shall not be permitted to emit particulate matter in a concentration in excess of 0.30 grains per standard cubic foot of exhaust gas; or
(bb) Exhibit greater than 20 percent opacity.

(2) The owner or operator of any industrial process equipment which was not in operation before July 9, 1969, which has control equipment with a collection efficiency of not less than 99.7 percent by weight shall be considered in compliance with the requirements of subsection (d)(1)(aa) of this regulation.

(3) The owner or operator of any industrial process equipment which was in operation after July 9, 1969, which is located outside the Minneapolis-St. Paul Air Quality Control Region and the City of Duluth, which is located not less than one-fourth mile from any residence or public roadway, and which has control equipment with a collection efficiency of not less than 85 percent by weight, and the operation of the entire emission facility does not cause a violation of the ambient air quality standards, shall be considered in compliance with the requirements of subsection (d)(1)(aa) of this regulation.

Process Weight Rate (lbs./hr.)	Emission Rate (lbs./hr.)
50	0.08
100	0.55
500	1.53
1,000	2.25
5,000	6.34
10,000	9.73
20,000	14.99
60,000	29.60
80,000	31.19
120,000	33.28
160,000	34.85
200,000	36.11
400,000	40.35
1,000,000	46.72

Interpolation of the data in Table 1 for the process weight rates up to 60,000 lbs./hr. shall be accomplished by the use of the equation:

$$E = 3.59P^{0.62}$$

$$P \leq 30 \text{ tons/hr.}$$

and interpolation and extrapolation of the data for process weight rates in excess of 60,000 lbs/hr shall be accomplished by use of the equation:

$$E = 17.31P^{0.16}$$

$$P > 30 \text{ tons/hr.}$$

Where E = Emissions in pounds per hour
P = Process weight rate in tons per hour

Table 1

(8)

Source Gas Volume, SCFM[a]	Concentration GR/SCF[b]	Source Gas Volume, SCFM[a]	Concentration GR/SCF[b]
7,000 or less	0.100	140,000	0.038
8,000	0.096	160,000	0.036
9,000	0.092	180,000	0.035
10,000	0.089	200,000	0.034
20,000	0.071	300,000	0.030
30,000	0.062	400,000	0.027
40,000	0.057	500,000	0.025
50,000	0.053	600,000	0.024
60,000	0.050	800,000	0.021
80,000	0.045	1,000,000 or more	0.020
100,000	0.042		
120,000	0.040		

[a] Standard cubic feet per minute

[b] Grains per standard cubic foot.

[July 7, 1969; amended June 4, 1976]

Table 2

Emission of Certain Settleable Acids and Alkaline Substances Restricted

(a) General Provisions. This regulation shall apply to all emissions from any sources or premises.

(b) Emissions Restricted. No person shall cause or permit the emission from any source or premises of substances having acidic or alkaline properties in such amounts that the down-wind fallout rate of acidic or alkaline substances at any place where an adverse effect could occur, exceeds the up-wind fallout rate by five or more spots per hour, measured in the manner prescribed in Section (b) of this regulation.

[July 7, 1969]

Standards of Performance for Sulfuric Acid Plants

(a) Definitions. As used in this regulation the following words shall have the meanings defined herein:

(1) "Sulfuric acid production unit:" Means any emission facility producing sulfuric acid by the contact process by burning elemental sulfur, alkylation acid, hydrogen sulfide, organic sulfides and mercaptans, or acid sludge, but does not include facilities where conversion to sulfuric acid is utilized primarily as a means of preventing emissions to the atmosphere of sulfur dioxide or other sulfur compounds.

Water Quality Standards[14]

Natural Intrastate Water Quality: The intrastate waters may, in a state of nature, have some characteristics or properties approaching or exceeding the limits specified in the standards. The standards shall be construed as limiting the addition of pollutants of human origin to those of natural origin, where such be present, so that in total the specified limiting concentrations will not be exceeded in the intrastate waters by reason of such controllable additions; except that where the background level of natural origin is reasonably definable and normally is higher than the specified standard the natural level may be used as the standard for controlling the addition of pollutants of human origin which are comparable in nature and significance with those of natural origin, but where the natural background level is lower than the specified standard and where reasonable justification exists for preserving the quality of the intrastate waters as nearly as possible to that found in a state of nature, the natural level may be used instead of the specified standard as the maximum limit on the addition of pollutants. In the adoption of standards for individual intrastate waters the Commission will be guided by the standards set forth herein but may make reasonable modifications of the same on the basis of evidence brought forth at a public hearing if it is shown to be desirable and in the public interest to do so in order to encourage the best use of the intrastate waters or the lands bordering such intrastate waters.

Industrial Consumption. (To include all intrastate waters which are or may be used as a source of supply for industrial process or cooling water, or any other industrial or commercial purposes, and for which quality control is or may be necessary to protect the public health, safety or welfare.)

General Standards Applicable to All Intrastate Waters of the State

(1) No untreated sewage shall be discharged into any intrastate waters of the state. No treated sewage, or industrial waste, or other wastes containing viable pathogenic organisms, shall be discharged into intrastate waters of the state without effective disinfection. Effective disinfection of any discharges, including combined flows of sewage and storm water, may be required where necessary to protect the specified uses of the intrastate waters.

(2) No raw or treated sewage, industrial waste or other wastes shall

be discharged into any intrastate waters of the state so as to cause any nuisance conditions, such as the presence of significant amounts of floating solids, scum, oil slicks, excessive suspended solids, material discoloration, obnoxious odors, gas ebullition, deleterious sludge deposits, undesirable slimes or fungus growths, or other offensive or harmful effects. In order to avoid possible development of nuisance conditions in surface intrastate waters for which no dissolved oxygen levels are given in the specific standards, the maintenance of at least a trace of dissolved oxygen shall be required in all such intrastate waters under all circumstances.

(3) Existing discharges of inadequately treated sewage, industrial waste or other wastes shall be abated, treated or controlled so as to comply with the applicable standards. Separation of sanitary sewage from natural runoff may be required when necessary to ensure continuous effective treatment of sewage.

(4) The highest possible levels of water quality, including dissolved oxygen, which are attainable in the intrastate waters by continuous operation at their maximum capability of all units of treatment works discharging effluent into the intrastate waters shall be maintained in the intrastate waters in order to enhance conditions for the specified uses.

(5) Means for expediting mixing and dispersion of sewage, industrial waste, or other waste effluent in the receiving intrastate waters shall be provided so far as practicable when deemed necessary by the Commission to maintain the quality of the receiving intrastate waters in accordance with applicable standards.

(6) It is herein established as a minimum requirement applicable to all persons and all intrastate waters of the state that primary treatment shall be provided for all existing or new sewage, and industrial or other wastes containing floating or suspended matter or viable pathogenic organisms, which may be discharged to intrastate waters of the state, unless such discharge is exempted under the terms of a special permit from the Commission. Primary treatment facilities are defined as works which will provide effective sedimentation and disinfection, or the equivalent, including effluents conforming to the following:

Item	Limits
Total coliform group organisms	5000 MPN/100 ml
Floating solids or liquids	None visible
Total suspended solids	100 milligrams per liter

(7) Allowance shall not be made in the design of treatment works for low stream flow augmentation unless such flow augmentation or minimum flow is dependable under applicable laws or regulations.

(8) In any instance where it is evident that natural mixing or dispersion of an effluent is not effective in preventing pollution,

or that it may not be feasible to provide by other means for effective mixing or dispersion of an effluent, or if at the applicable stream flows mentioned in the sections on specific standards of intrastate water quality and purity it is evident that the specified stream flow may be less than the effluent flow, the specific standards may be interpreted as effluent standards for control purposes, where applicable. Where stream flow records are not available, the flows may be estimated on the basis of available information on the watershed characteristics, precipitation, run-off and other pertinent data. In addition, the following effluent standards may be applied without any allowance for dilution where stream flow or other factors are such as to prevent adequate dilution or where it is otherwise necessary to protect the intrastate waters for the stated uses:

Item	Limits
5-day biochemical oxygen demand	20 milligrams per liter
Total coliform organisms	1000 MPN/100 ml
Total phosphorus	1 milligram per liter
Total suspended solids	20 milligrams per liter
Turbidity value	25

(9) In any proceeding where specific standards have been adopted which are directly or indirectly applicable to named intrastate waters of the state, it shall be incumbent upon all persons responsible for existing or new sources of sewage, industrial wastes or other wastes which are or will be discharged to such intrastate waters to treat or control their wastes so as to produce effluents having a common level or concentration of pollutants of comparable nature or effect as may be necessary to meet the specified standards or better, and in no case shall the concentration of polluting substances in any individual effluent be permitted to exceed the common concentration or level required of the other sources of comparable nature or effect discharging to the same classified and named intrastate waters, regardless of differences in the amount of pollutional substances discharged, or degree of treatment involved.

(10) Liquid substances which are not commonly considered to be sewage or industrial wastes but which could constitute a pollution hazard shall be stored in accordance with Regulation WPC 4, and any revisions or amendment thereto. Other wastes as defined by law or other substances which could constitute a pollution hazard shall not be deposited in any manner such that the same may be likely to gain entry into any intrastate waters of the state in excess of or contrary to any of the standards herein adopted, or cause pollution as defined by law.

(11) No sewage, industrial waste or other wastes shall be discharged into the intrastate waters of the state in such quantity or in such manner alone or in combination with other substances as to cause pollution thereof as defined by law. In any case where the intrastate waters of the state into which sewage, industrial wastes or other waste other waste effluents discharge are assigned different standards than the waters into which such receiving intrastate waters flow, the

standards applicable to the intrastate waters into which such sewage, industrial waste or other wastes discharge shall be supplemented by the following:

The quality of any waters of the state receiving sewage, industrial waste or other waste effluents shall be such that no violation of the standards of any other waters of the state in any other class shall occur by reason of the discharge of such sewage, industrial waste or other waste effluents.

Industrial Consumption

Class A. The quality of this class of the intrastate waters of the state shall be such as to permit their use without chemical treatment, except softening for ground water, for most industrial purposes, except food processing and related uses, for which a high quality of water is required. The quality shall be generally comparable to Class B waters for domestic consumption, except for the following:

Substance or Characteristic	Permissible Limit or Range
Chlorides (Cl)	50 milligrams per liter
Hardness	50 milligrams per liter (surface); 250 milligrams per liter (ground)
pH value	6.5-8.5
Temperature	75°F (surface); 55°F (ground)
Total coliform organisms	5000 most probable number per 100 milliliters

Class B. The quality of this class of the intrastate waters of the state shall be such as to permit their use for general industrial purposes, except food processing, with only a moderate degree of treatment. The quality shall be generally comparable to Class D intrastate waters used for domestic consumption, except for the following:

Substance or Characteristic	Permissible Limit or Range
Chlorides (Cl)	100 milligrams per liter
Hardness	250 milligrams per liter (surface); 350 milligrams per liter (ground)
pH value	6.0-9.0
Temperature	85°F (surface); 65°F (ground)
Total coliform organisms	5000 most probable number per 100 milliliters

Class C. The quality of this class of the intrastate waters of the state shall be such as to permit their use for industrial cooling and materials transport without a high degree of treatment being necessary to avoid severe fouling, corrosion, scaling, or other unsatisfactory conditions. The following shall not be exceeded in the intrastate waters:

Substance or Characteristic	Limit or Range
Chlorides (Cl)	250 milligrams per liter
Hardness	500 milligrams per liter
pH value	6.0-9.5
Temperature	90°F (surface); 65°F (ground)
Total coliform organisms	5000 most probable number per 100 milliliters

Additional selective limits may be imposed for any specific intrastate waters as needed.

Natural Interstate Water Quality

The interstate waters may, in a state of nature, have some characteristics or properties approaching or exceeding the limits specified in the standards. The standards shall be construed as limiting the addition of pollutants of human origin to those of natural origin, where such be present, so that in total the specified limiting concentrations will not be exceeded in the interstate waters by reason of such controllable additions; except that where the background level of the natural origin is reasonably definable and normally is higher than the specified standard the natural level may be used as the standard for controlling the addition of pollutants of human origin which are comparable in nature and significance with those of natural origin, but where the natural background level is lower than the specified standard and where reasonable justification exists for preserving the quality of the interstate waters as nearly as possible to that found in a state of nature, the natural level may be used instead of the specified standard as the maximum limit on the addition of pollutants. In the adoption of standards for individual interstate waters, the Agency will be guided by the standards set forth herein but may make reasonable modification of the same on the basis of evidence brought forth at a public hearing if it is shown to be desirable and in the public interest to do so in order to encourage the best use of the interstate waters or the lands bordering such interstate waters.

Waters which are of quality better than the established standards will be maintained at high quality unless a determination is made by the State that a change is justifiable as a result of necessary economic or social development and will not preclude appropriate beneficial present and future uses of the waters. Any project or development which would constitute a source of pollution to high quality waters will be required to provide the highest and best practicable treatment to maintain high water quality and keep water pollution at a minimum. In implementing this policy, the Secretary of the Interior will be provided with such information as he requires to discharge his responsibilities under the Federal Water Quality Act, as amended.

Variance From Standards

In any case where, upon application of the responsible person or persons, the Agency finds that by reason of exceptional circumstances the strict enforcement of any provision of these standards would cause undue hardship; that disposal of the sewage, industrial waste or other waste is necessary for the public health, safety or welfare; and that strict conformity with the standards would be unreasonable, impractical or not feasible under the circumstances; the Agency in its discretion may permit a variance therefrom upon such conditions as it may prescribe for prevention, control or abatement of pollution in harmony with the general purposes of these classifications and standards and the intent of the applicable state and national laws. The Federal Water Pollution Control Administration will be advised of any permits which may be issued under this clause together with information as to the need therefor.

Industrial Consumption

(To include all interstate waters which are or may be used as a source of supply for industrial process or cooling water, or any other industrial or commercial purposes, and for which quality control is or may be necessary to protect the public health, safety or welfare.)

General Standards Applicable to All Interstate Waters of the State

(1) No untreated sewage shall be discharged into any interstate waters of the state. No treated sewage, or industrial waste or other wastes containing viable pathogenic organisms, shall be discharged into interstate waters of the state without effective disinfection. Effective disinfection of any discharges, including combined flows of sewage and storm water, will be required where necessary to protect the specified uses of the interstate waters.

(2) No raw or treated sewage, industrial waste or other wastes shall be discharged into any interstate waters of the state so as to cause any nuisance conditions, such as the presence of significant amounts of floating solids, scum, oil slicks, excessive suspended solids, material discoloration, obnoxious odors, gas ebullition, deleterious sludge deposits, undesirable slimes or fungus growths, or other offensive or harmful effects.

(3) Existing discharges of inadequately treated sewage, industrial waste or other wastes shall be abated, treated or controlled so as to comply with the applicable standards, separation of sanitary sewage from natural run-off may be required where necessary to ensure continuous effective treatment of sewage.

(4) The highest possible levels of water quality, including dissolved oxygen, which are attainable in the interstate waters by continuous

operation at their maximum capability of all units of treatment works discharging effluents into the interstate waters shall be maintained in the interstate waters in order to enhance conditions for the specified uses.

(5) Means for expediting mixing and dispersion of sewage, industrial waste, or other waste effluents in the receiving interstate waters shall be provided so far as practicable when deemed necessary by the Agency to maintain the quality of the receiving interstate waters in accordance with applicable standards.

(6) It is herein established that the Agency will require secondary treatment or the equivalent as a minimum for all municipal sewage and biodegradable, industrial or other wastes to meet the adopted water quality standards and a comparable high degree of treatment or its equivalent also will be required of all non-biodegradable industrial or other wastes unless the discharger can demonstrate to the Agency that a lesser degree of treatment or control will provide for water quality enhancement commensurate with present and proposed future water uses and a variance is granted under the provisions of the variance clause. Secondary treatment facilities are defined as works which will provide effective sedimentation, biochemical oxidation, and disinfection, or the equivalent, including effluents conforming to the following:

Substance or Characteristic	Limiting Concentration or Range
5-Day biochemical oxygen demand	25 milligrams per liter
Total coliform group organisms	1000 MPN/100 ml
Total suspended solids	30 milligrams per liter
Oil	Essentially free of visible oil
Turbidity	25
pH range	6.5-8.5

(7) Allowance shall not be made in the design of treatment works for low stream flow augmentation unless such flow augmentation of minimum flow is dependable under applicable laws or regulations.

(8) In any instance where it is evident that natural mixing or dispersion of an effluent is not effective in preventing pollution, or that it may not be feasible to provide by other means for effective mixing or dispersion of an effluent, or if at the applicable stream flows mentioned in the sections on specific standards of interstate water quality and purity it is evident that the specified stream flow may be less than the effluent flow, the specific standards may be interpreted as effluent standards for control purposes, where applicable. The period of record for determining the specific flow for the stated recurrence interval, where records are available, will include at least the most recent 10 years of record, including flow records obtained after establishment of flow regulation devices, if any. Such calculations will not be applied to lakes and their embayments which have no comparable flow recurrence interval. Where

stream flow records are not available, the flows may be estimated on the basis of available information on the watershed characteristics, precipitation, run-off and other pertinent data. In addition, the following effluent standards may be applied without any allowance for dilution where stream flow or other factors are such as to prevent adequate dilution, or where it is otherwise necessary to protect the interstate waters for the stated uses:

Item	Limits
5-day biochemical oxygen demand	20 milligrams per liter
Total phosphorus	1 milligram per liter
Total suspended solids	20 milligrams per liter

It is the intention of the Agency to require removal of nutrients from all sources to the fullest practicable extent wherever sources of nutrients are considered to be actually or potentially inimical to preservation or enhancement of the designated water uses.

(9) In any case where, after a public hearing, the Agency finds it necessary for conservation of the interstate waters of the state, or protection of the public health, or in furtherance of the development of the economic welfare of the state, it may prohibit or further limit the discharge to any designated interstate waters of any sewage, industrial waste, or other waste effluents, or any component thereof, whether such effluents are treated or untreated, or existing or new, notwithstanding any other provisions of classifications or specific standards stated herein which may be applicable to such designated interstate waters.

(10) In any proceeding where specific standards have been adopted which are directly or indirectly applicable to named interstate waters of the state, it shall be incumbent upon all persons responsible for existing or new sources of sewage, industrial wastes or other wastes which are or will be discharged to such interstate waters, to treat or control their wastes so as to produce effluents having a common level or concentration of pollutants of comparable nature and effect as may be necessary to meet the specified standards or better, and in no case shall the concentration of polluting substances in any individual effluent be permitted to exceed the common concentration or level required of the other sources of comparable nature and effect discharging to the same classified and named interstate waters, regardless of differences in the amount of pollutional substances discharged, or degree of treatment involved.

(11) Liquid substances which are not commonly considered to be sewage or industrial wastes but which could constitute a pollution hazard shall be stored in accordance with Regulation WPC-4, and any revisions or amendments thereto. Other wastes as defined by law or other substances which could constitute a pollution hazard shall not be deposited in any manner such that the same may be likely to gain entry into any interstate waters of the state in excess of or contrary to any of the standards herein adopted, or cause pollution as defined by law.

(12) No sewage, industrial waste or other wastes shall be discharged into the interstate waters of the state in such quantity or in such manner alone or in combination with other substances as to cause pollution thereof as defined by law. In any case where the interstate waters of the state into which sewage, industrial wastes or other waste effluents discharge are assigned different standards than the interstate waters into which such receiving interstate waters flow, the standards applicable to the interstate waters into which such sewage, industrial waste or other wastes discharged shall be supplemented by the following:

The quality of any waters of the state receiving sewage, industrial waste or other waste effluents shall be such that no violation of the standards of any interstate waters of the state in any other class shall occur by reason of the discharge of such sewage, industrial waste or other waste effluents.

(13) Questions concerning the permissible levels, or changes in the same, of a substance, or combination of substances, of undefined toxicity to fish or other biota shall be resolved in accordance with the methods specified by the National Technical Advisory Committee of the Federal Water Pollution Control Administration, U.S. Department of the Interior. The Committee's recommendations also will be used as official guidelines in other aspects where the recommendations may be applicable.

(14) All persons operating or responsible for sewage, industrial waste or other waste disposal systems which are adjacent to or which discharge effluents to these waters or to tributaries which affect the same, shall submit regularly every month a report to the Agency on the operation of the disposal system, the effluent flow, and the characteristics of the effluents and receiving waters. Sufficient data on measurements, observations, sampling and analyses, and other pertinent information shall be furnished as may be required by the Agency to in its judgment adequately reflect the condition of the disposal system, the effluent, and the waters receiving or affected by the effluent.

Industrial Consumption

Class A. The quality of this class of the interstate waters of the state shall be such as to permit their use without chemical treatment, except softening for ground water, for most industrial purposes, except food processing and related uses, for which a high quality of water is required. The quality shall be generally comparable to Class B waters for domestic consumption, except for the following:

Substance or Characteristic	Permissible Limit or Range
Chlorides (Cl)	50 milligrams per liter
Hardness	50 milligrams per liter
pH value	6.5-8.5

Substance or Characteristic	Permissible Limit or Range
Temperature	75°F in July and August,
	70°F in June and September,
	60°F in May and October, (Surface)
	50°F in April and November,
	40°F in March and December,
	and
	35°F in January and February.
	55°F (Ground)
Total coliform organisms	5000 most probable number per 100 milliliters

Class B. The quality of this class of the interstate waters of the state shall be such as to permit their use for general industrial purposes, except food processing, with only a moderate degree of treatment. The quality shall be generally comparable to Class D interstate waters used for domestic consumption, except for the following:

Substance or Characteristic	Permissible Limit or Range
Chlorides (Cl)	100 milligrams per liter
Hardness	250 milligrams per liter (Surface) 350 milligrams per liter (Ground)
pH value	6.0-9.0
Temperature	65°F (ground) 86°F (surface)
Total coliform organisms	5000 most probable number per 100 milliliters

Class C. The quality of this class of the interstate waters of the state shall be such as to permit their use for industrial cooling and materials transport without a high degree of treatment being necessary to avoid severe fouling, corrosion, scaling, or other unsatisfactory conditions. The following shall not be exceeded in the interstate waters:

Substance or Characteristic	Limit or Range
Chlorides (Cl)	250 milligrams per liter
Hardness	500 milligrams per liter
pH value	6.0-9.5
Temperature	65°F (ground) 90°F (surface)
Total coliform organisms	5000 most probable number per 100 milliliters

Additional selective limits may be imposed for any specific interstate waters as needed.

BIBLIOGRAPHY

1. __________. Air Pollution Control Rules, Regulations, and Air Quality Standards, Minnesota Pollution Control Agency, Documents Section, Department of Administration, 1976 Edition.

2. Biswas, A.K. 1976. Extractive Metallurgy of Copper, Pergamon Press, Oxford.

3. Butts, Allison. 1932. A Textbook of Metallurgical Problems, McGraw-Hill Book Company, Inc., New York.

4. Butts, Allison. 1954. Copper-The Metal Its Alloys and Compounds, Reinhold Publishing Corporation, New York.

5. Dennis, W.H. 1961. Metallurgy of the Non-Ferrous Metals, Sir Isaac Pitman & Sons Ltd., London.

6. Diaz, Carlos. 1973. The Future of Copper Pyrometallurgy, The Chilean Institute of Mining Engineers, Santiago, Chile.

7. Hayward, Carle R. 1952. An Outline of Metallurgical Practice, Third Edition, D. Van Nostrand Company, Inc., New York.

8. Jones, H.R. 1972. Fine Dust and Particulates Removal, Pollution Control Review No. 11, Noyes Data Corporation, Park Ridge.

9. Jones, H.R. 1972. Pollution Control in the Nonferrous Metals Industry, Pollution Control Review No. 11, Noyes Data Corporation, Park Ridge.

10. __________. Laws Relating to the Minnesota Pollution Control Agency, Documents Section, St. Paul, Minnesota.

11. Lawver, J.E. 1975. Mineral Beneficiation Studies and An Economic Evaluation of Minnesota Copper-Nickel Deposit From the Duluth Gabbro, USBM Grant No. 60144109, University of Minnesota.

12. Robinson, E. 1968. Sources, Abundance, and Fate of Gaseous Atmospheric Pollutants, Stanford Research Institute, Menlo Park.

13. Ross, R.D. 1972. Air Pollution and Industry, Van Nostrand Reinhold Company, New York.

14. __________. Rules, Regulations, Classifications and Water Standards, Minnesota Pollution Control Agency, Documents Section, Department of Administration, 1972 Edition.

15. __________. The Shorter Oxford Economic Atlas of the World, The Economist Intelligence Unit and the Catographic Department of the Clarendon Press, Third Edition, Oxford University Press, 1966.

16. Yannopoulos, J.C. 1976. Extractive Metallurgy of Copper-Pyrometallurgy and Electrolytic Refining, The Metallurgical Society of AIME, Port City Press, Baltimore.

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Data in tables 13 and 14 have been derived using the material balances found in the report titled "Mineral Beneficiation Studies and an Economic Evaluation of Minnesota Copper-Nickel Deposit from the Duluth Gabbro," USBM Grant No. G0144109, December 1, 1975.