

EP/0408-75-01

B



**ENVIRONMENTAL ASPECTS
OF THE ALUMINIUM INDUSTRY**

- an overview -

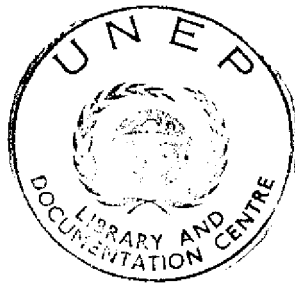


UNITED NATIONS ENVIRONMENT PROGRAMME

0408-75-01

**ENVIRONMENTAL ASPECTS OF THE
ALUMINIUM INDUSTRY**

an overview



UNEP, Industry Programme
Paris, May 1977

100
-100-

Design : EUROPUBLICA, 7, place Vendôme, 75001 Paris – France
Printed in France AUGUSTIN S.A., 75009 Paris – TÉL. 073.02.66

This publication is printed on recycled paper

CONTENTS

	<i>Page</i>
FOREWORD	
1. INTRODUCTION	7
2. THE ALUMINIUM INDUSTRY	8
2.1. Bauxite Mining	9
2.2. Production of Alumina from Bauxite	9
2.3. Reduction of Alumina	10
2.4. Remelting, Fabricating and Finishing	11
2.5. Recycling of Scrap	12
3. CURRENT ENVIRONMENTAL PROBLEMS, POLLUTION ABATE- MENT TECHNOLOGY AND COSTS	12
3.1. Land Use	12
3.2. Solid Wastes	13
3.3. Water Effluent	14
3.4. Air Emission	16
3.5. Biological Effects of Atmospheric Fluoride	21
4. NEW PRODUCTION PROCESSES IMPACT ON POLLUTION ABATE- MENT	25
4.1. Alternative Alumina Production Processes	25
4.2. Alternative Aluminium Production Processes	26
5. FLUORIDE LEGISLATIONS AND STANDARDS	27
6. CONCLUSIONS	31

FOREWORD

In its first session held in June 1973, the UNEP Governing Council recognized the importance of environmental issues associated with industrial development, and in its decision noted the intention of the Executive Director to initiate preliminary work on environmental problems of specific industries.

The aluminium industry is one of the major industrial sectors agreed for examination. Consultations have been undertaken with experts nominated by Governments, Industry and international governmental and non-governmental Organizations, culminating in a Seminar, held in Paris in October 1975, where the state of the art of existing pollution abatement techniques, outstanding problems and possible avenues of research and development to resolve these problems in relation to the environmental impact of the aluminium industry, were assessed.

This report is a synthesis of the evaluation that has taken place, and gives an overview of the decision and policy aspects that pertain to the environmental issues emanating from the aluminium industry.

The views expressed in this report do not necessarily represent the decisions or the stated policy of the United Nations Environment Programme, nor does mention of trade names or commercial processes constitute endorsement.

*

*

*

1. INTRODUCTION

Aluminium is the most abundant metal in the earth's crust and alumina is the principal raw material for aluminium metal production. All igneous rock contains silicates of aluminium and upon weathering the aluminium usually remains insoluble in the form of an impure aluminium silicate, a clay. Some of these clays may someday be used for production of aluminium metal but at the present time, only mineral bauxite is used. World reserves of bauxite are estimated at about 6000 million tonnes.

Aluminium is used in a wide range of applications because of its low density, high strength to weight ratio, resistance to corrosion, high electrical conductivity and ease of fabrication. The total annual world production of the primary metal in 1973 was in excess of 13 million tonnes. Output over the last ten years increased at an annual growth rate of about 8 percent, resulting in a doubling time of about 9 years. Consumption of aluminium metal is higher than the production of primary metal because of recycling through the secondary industry.

The production of aluminium is a two step operation consisting of :

- a) Refining of alumina-bearing raw materials to high-purity alumina or possibly aluminium-chloride and
- b) Conversion of high-purity alumina or aluminium chloride to molten aluminium by high-temperature molten salt electrolysis.

The two steps are often undertaken at two separate locations far apart. In the recent past, much research and development work was done on the so-called "direct reduction" of alumina-bearing raw materials to aluminium. Several alternative methods were considered, but none showed any real promise and thus all have been abandoned. It is, therefore, unlikely that this activity will be renewed.

Primary aluminium production, especially the reduction operation and auxiliary casting, consumes a large quantity of energy. It is difficult to generalise on energy requirements for aluminium production because there is wide variation between plants. In considering energy requirements per tonne of aluminium produced, a distinction between the electrical energy required (mainly for electrolysis) and the thermal energy required (for calcining, process steam, baking, reheating, etc.) should be made, to avoid erroneous conclusions. Typical energy requirements for the production of one metric tonne of aluminium is presently estimated (1) to be

(1) - Organization for Economic Cooperation and Development, OECD, (1976) "*Industrial Adaptation in the Primary Aluminium Industry*" OECD, Paris.

Operation	Electrical (kwh)	Thermal (10 ⁶ Kcal)
Mining, transportation	100	1.3
Alumina production	400	7.1
Reduction	17,400	5.5*
Casting	100	2.0
	<hr/>	<hr/>
	18,000	15.9

* Including carbon materials.

Improved production techniques have significantly reduced power consumption in the reduction process to an average of 17,400 Kwh/tonne, and in efficient plants, it can be as low as 14,300 Kwh/tonne. For the future, new processes now at pilot plant stage indicate that energy consumption may decrease to about 9,900 Kwh/tonne (1). Large capital investment, however, will be required.

Although alumina resources are plentiful and constitute about 7 percent of the earth's crust, the supply of high grade bauxite is limited and hence other sources of aluminium will have to be used. This will result in somewhat higher energy consumption when compared with using bauxite.

A most important aspect of resource conservation in aluminium production is recycling. Recycling of aluminium requires only a small percentage of the energy needed to produce the same metal from virgin sources and very large amounts of aluminium scrap are potentially available for recycling.

In the production of aluminium, using present processes and technology solid wastes (red mud), gaseous emissions (fluorides, sulphur oxides, carbon monoxide, hydrocarbons, particulates) and liquid effluents (spent alkaline solution containing sodium aluminate or calcium fluoride) are the main pollutants produced. The major environmental problems are associated with the discharge of fluorides and particulates and the disposal of red mud.

2. THE ALUMINIUM INDUSTRY

The important factors for the establishment of an aluminium plant are, large capital investment, abundant and reasonably priced power and a supply of basic raw materials. Capital costs for a totally intergrated facility – bauxite

(1) – Organization for Economic Cooperation and Development, OECD (1976) *Industrial Adaptation in the Primary Aluminium Industry* OECD, Paris.

processing, aluminium smelting and metal fabrication were estimated at US \$ 2500 per tonne at the end of 1974. Of this total, US \$ 350 was for bauxite processing, US \$ 1610 for aluminium reduction and US \$ 540 for metal fabrication. As of the end of the first quarter of 1975, the costs had increased by nearly 30 percent to US \$ 3250 per tonne. These costs are for facilities constructed in North America and will vary depending upon the location of the facility.

Optimal size for an aluminium reduction facility has been estimated at about 100,000 tonnes. However, smaller plants of about 70,000 tonnes have also been built. Economics of scale are not always significant enough to warrant construction of large size initial facilities. The preferred method in many cases has been to start with a small reduction facility and expand capacity over a period of years. Capacity of an alumina plant would have to be approximately twice that of the reduction facility. The bauxite mine capacity would again have to be twice as large for a producer to be completely integrated without having to purchase input materials.

The aluminium industry is presently comprised of two basic operations,

- a) The production of alumina from bauxite by the Bayer process, and
- b) The reduction of alumina to aluminium metal by the Hall-Heroult electrolytic reduction process.

2.1. Mining of Bauxite

Bauxite is generally extracted by strip mining, blasting or by the use of earth moving equipment. Some bauxites are crushed, washed to remove some of the clay and sand waste, and dried in kilns prior to shipment. Other bauxites are crushed and may be dried.

In relation to bauxite mining attention has to be paid to land use planning, so that after extraction of the mineral, the land is returned to its original or some other agreed use. Budgetary provisions should, therefore, be made for reclamation and restoration.

2.2. Production of Alumina from Bauxite

Alumina is extracted from bauxite by digestion at elevated temperatures (149°C to 204°C) and pressures (14 Kg/cm²). The digestion liquor contains sodium aluminate and free caustic soda. The alumina hydrate in the bauxite is dissolved by the free caustic soda as sodium aluminate. After the digestion step, the insoluble components of the bauxite, primarily the oxides of iron, silica and titanium, are removed by thickening and filtration, resulting in a residue termed "red mud". The filtrate, consisting of a weak liquor solution

is recycled after the excess water is evaporated. Silica is a particularly undesirable impurity in bauxite, especially in the form of clay, since it is readily dissolved in the caustic liquor. Although silica is rapidly rejected from solution as a complex sodium aluminium silicate, these silicates cause problems with equipment scaling and filtration which lead to proportionate amounts of alumina and sodium being carried away with the precipitate.

The quantity of red mud formed may, depending on the composition of the bauxite, represent between 0.5 to 1.0 tonne dry weight per tonne of aluminium oxide. The mud normally contains 20 to 30 percent of solids which by filtration may be increased to 40 to 60 percent.

2.3. Reduction of Alumina

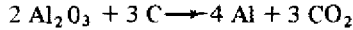
Primary aluminium is normally produced, from refined alumina, in reduction plants using the Hall-Heroult process. This is an electrolytic process during which alumina is continuously dissolved in molten cryolite.

Aluminium is liberated at the cathode and oxygen transported to the anode, releasing carbon dioxide. Electrolytic cells are large steel boxes lined with insulating refractory and carbon materials. Carbon blocks at the bottom of the cell serve as the cathode in the electric circuit. During electrolytic reduction, molten aluminium metal is deposited in liquid form at the bottom of the cell on the surface of the carbon cathode. Cathodes are more or less a permanent installation. Typically, a cathode cell lining lasts three to six years, about the same as the life of the cell itself, after which time the cell is taken out of service, rebuilt and refitted.

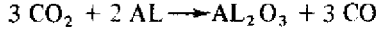
Anodes are also made of carbon suspended in the electrolyte from steel connector rods that connect to the anode bus. Cells are classified as, Söderberg (vertical or horizontal studs) or Prebake (open or closed), according to design of the anode. In both systems a combination of petroleum or coal tar pitch and petroleum coke is used to produce the anodes.

In the Söderberg system, so-called Söderberg paste is fed continuously into the top of the steel casing in which the heat from the cell and from the current flow bakes the paste and removes the volatiles. In the Prebake system, the volatiles are removed by making the anodes in a separate anode-forming prebaking operation. Each of these systems have their advantages and disadvantages. The Prebake system, the older of the two, requires significantly less energy than the Söderberg system, and, because the anodes are baked in separate facilities, it is easier to recover the volatiles released from the anode paste. The Söderberg system however, requires lower capital costs for small smelters, because it avoids the cost of separate anode-making and baking facilities. With this system, it is also easier to produce large cross sectional block anodes that are required in large cells.

The overall reaction for the Hall-Heroult process is as follows :



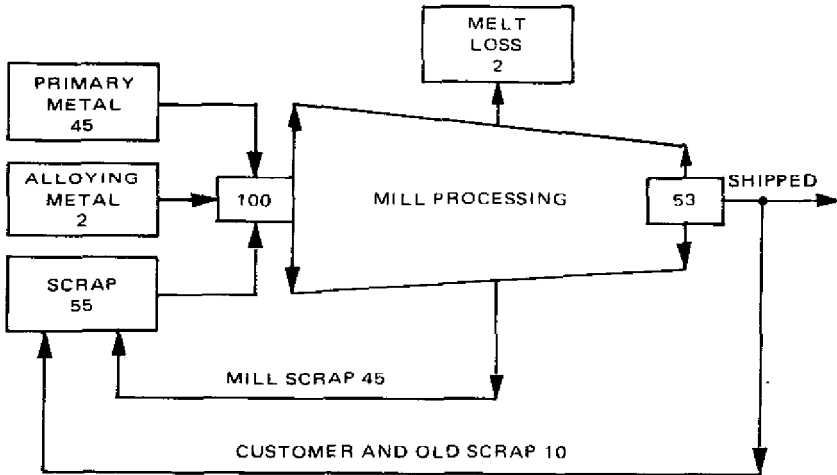
The anode gas will also contain some CO resulting from back reaction of the aluminium dissolved in the electrolyte reacting with CO_2 ,



The anode gas is a function of the electrolysis current efficiency and the composition is typically 70 to 90 percent CO_2 and 30 to 10 percent CO.

2.4. Remelting, Fabricating and Finishing

Remelting, fabricating and finishing comprise only a relatively small part of the energy cost (12 to 15 percent) of producing aluminium. When remelting or scrap recycling is carried out in primary aluminium smelters, it is usually done in oil or gas fired open hearth furnaces. Flow of metal through remelt and fabrication is shown below :



The two percent value for metal loss may appear small until it is put into perspective. The total loss in energy, including heat and metal which must be replaced is reported (1) to be 6.7 million Btu/tonne.

(1) - Flemings, M.C. (1975) "Resources and Energy in Aluminium Production". Paper prepared for and presented at a UNEP Industry Sector Seminar. Aluminium Meeting, Paris, October.

Aluminium fabrication and finishing plants can and have achieved significant energy reductions of the order of 10 to 25 percent by :

- replacement of direct fired furnaces by radiant tube furnaces,
- improved furnaces and insulation,
- improved scheduling,
- replacement of gasoline trucks by electric trucks,
- general plant maintenance and personnel education programmes,
- scrap reduction programmes.

2.5. Recycling of Scrap

Essentially all "new" aluminium scrap generated by primary producers, fabricators, and manufacturers of industrial or consumer products, is recycled and reprocessed by primary or secondary smelters. The theoretical energy required to melt a kilogram of aluminium is about 1100 Btu, but in practice about 7000 Btu are used. Thus improving melting efficiency is possible and desirable. Potential energy savings are possible with less oxidation losses. Technologies used to achieve this include, minimizing fires, melting with salt additions or in deep salt baths, and removing oil and coatings prior to melting. However, more efficient and thus less polluting processes are needed to reduce and recover oxidation losses.

Energy and materials savings can be greatly increased by recycling "old" scrap. Aluminium cans, motor vehicle bodies and home appliances are among the major products that are being recycled after special processing to remove dirt, paint and coatings. Shredding, redensifying and purification operations may also be carried out.

3. CURRENT ENVIRONMENTAL PROBLEMS, POLLUTION ABATEMENT TECHNOLOGY AND COSTS

3.1. Land Use :

An area that has been disturbed by mining seldom reaches the same ecological equilibrium that existed prior to the disturbance. This is especially true when major alterations of soil, topography, or living organisms are made during the disturbance. Rehabilitation can best be accomplished when planning prior to the actual mining includes the establishment of desirable and attainable objectives for the use of land after mining. Rehabilitation objectives are achieved through careful management, including monitoring of mining techniques, reshaping the spoils, prompt revegetation, control of erosion, and prevention of damage to hydrologic systems. The rehabilitation of a specific site will depend on the physical characteristics of the site and the post-mining land use objectives.

The selection of the mining technique is most commonly made on the basis of economics. When rehabilitation is considered part of the mining operation, extraction techniques may change to those which most economically combine the objectives of bauxite mining and rehabilitation of affected areas (e.g. to those techniques that make the most effective realignment of geologic materials for plant growth, erosion control, prevention of water pollution, attainment of aesthetic objectives, etc.). An environmental impact assessment should, therefore, be undertaken as part of the overall management tool, to ensure that bauxite extraction is compatible with land use objectives.

When rehabilitating a mined site, the proper application of rehabilitation techniques is essential. The natural ecosystem does not stop at the boundary of the mined area, but it is integrated with that of the surrounding area and indeed with the entire region in complex ways that are not well understood. Some of the operations of rehabilitation where skill and planning are imperative if results are to be successful include, handling of overburden, handling of topsoil, reshaping the physical environment, effects of shaping methods upon animals, hydrologic effects of shaping, proper revegetation of surface mined lands, etc.

3.2. Solid Wastes

For each tonne of alumina produced from bauxite, between one third to one tonne (dry weight) of solids are discharged in the fine "red mud" slurry, depending upon the quality of the ore being processed. The "red mud" is currently disposed of in ponds, by landfilling or by dumping into the sea. These methods can give rise to environmental concerns : the present trend is to prohibit dumping at sea and to impose stringent precaution measures at land filling sites in order to reduce land needs as well as to prevent leaching of pollutants. In tropical monsoon countries, care has to be taken to ensure an adequate barrier for disposal ponds. To minimize the aesthetic impact, these disposal ponds can be designed with suitable landscaping and a filled pond revegetated.

There exist a number of processes for disposal and utilization of red mud. One method for disposal is to use filtered mud for land filling, the site being arranged for recovering alkaline leachate to be returned to the process. The top of the fill is then covered with soil.

Red mud consists of a solid fraction composed of insoluble particles and a soluble fraction. A typical composition of these two fractions is :

Insoluble Fraction		Soluble Fraction	
SiO_2	↔ 5.5 Percent	Al_2O_3	↔ 2.5 g/kg liquid
Al_2O_3	↔ 12.0 "	NaOH	↔ 3.7 " "

Fe ₂ O ₃	←————→	49.5 Percent	Na ₂ CO ₃	←————→	1.6 g/kg liquid
P ₂ O ₅	←————→	2.0 "	Na ₂ SO ₄	←————→	0.4 " "
CaO	←————→	8.0 "	NaCl	←————→	0.7 " "
Na ₂ O	←————→	3.5 "	Na ₂ C ₂ O ₄	←————→	0.1 " "
TiO ₂	←————→	5.0 "	pH	←————→	12.5 " "
MnO ₂	←————→	1.0 "	BOD	←————→	6. ppm
Miscellaneous	←————→	1.5 "	COD	←————→	148 ppm
Loss on Ignition	←————→	11.0 "			

3.3. Water Effluent

The principal waste streams in the refining of bauxite are :

- Red-mud stream
- Spent liquor
- Condensates
- Barometric condenser cooling water
- Storm water run-off
- Miscellaneous cooling water and waste streams

Effluent treatment technologies are available to essentially meet "zero" pollutant discharge level, except where rainfall exceeds evaporation. The costs involved for achieving this level are largely the cost of red-mud pond construction, piping, neutralization and any other equipment necessary for the proper operation of a recycling system. The estimated disposal costs (1) in North America, for 1973, range from US \$ 0.27 to US \$ 0.60 per short ton of alumina or US \$ 0.14 to US \$ 1.09 per short ton of mud. To achieve "zero" pollutant discharge, the following treatment steps will have to be taken :

Waste stream	Parameters	Best Practicable Control Technology Currently Available
Red mud	TDS,* TSS** alkalinity	Impound & recycle aqueous phase ; concentrate if necessary
Spent cleaning acid	TDS, sulfates, pH	Impound in red mud lake
Salt slurry from salt- ing out evaporator	TDS, sulfates, alkali- nity	Impound in red mud lake or landfill
Barometric conden- ser cooling water	TDS, heat, alkalinity	Cool and recycle
Barometric condenser cooling water blowdown	TDS	Impound in red mud lake
"Hose-down" and cleanup streams	TSS, TDS, alkalinity	Recycle to process

* TDS, Total Dissolved Solids.

** TSS, Total Suspended Solids.

(1) - U.S. Environmental Protection Agency, EPA (1973). "Development Document for Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Bauxite Refining Subcategory of the Aluminium Segment of the Nonferrous Metals Manufacturing Point Source Category". EPA 440/1.73/019. October.

The potential sources of waste water from primary aluminium smelting include :

- wet scrubbers used on potline and potroom ventilation air
- wet scrubbers used on anode bake furnace flue gas
- wet scrubbers used on casthouse gases
- cooling water used in ingot casting, rectifiers and in fabrication
- boiler blowdown

These sources are very much interrelated to the type of air pollution control systems used for particulate and fluoride control. The waste water constituents that can be present in primary aluminium production effluents are :

suspended solids, dissolved solids, chemical oxygen demand, COD oil and grease,	fluoride, chloride, sulphate, free cyanide and trace metals (including Zn, Cu, Ni)
--	--

Waste water flow rates and quantities of pollutants present are highly dependent upon the specific type of air pollution control equipment used (wet versus dry). It is, therefore, not realistic to report raw wasteload values for the primary aluminium industry, as these values vary greatly from plant to plant. Generally however, plants with a once through treatment system will have an effluent flow rate of (16 to 160 m³/tonne) of aluminium. Typically, the concentration of fluorides in the untreated effluent varies between 20 to 50 ppm.

The costs for removing fluorides from effluents by various treatment alternatives have been estimated (1) for a plant producing 250 tonnes/day of aluminium, with 20,000 m³/day effluent flow containing 35 ppm of fluoride.

Process Alternative	Discharge Fluoride lb/1000 lb	Capital cost* US\$/annual ton	Total operating cost US \$/ton
Dry scrubbing	0	48.6	19.8
Wet scrubbing - once-through	5	9.0	4.5
Wet scrubbing - recycle	1	12.2	7.5
Recycle with bleed and filtrate treatment	0.05	14.0	8.4
Once-through and alum treatment	1	22.2	16.7
Once-through and activated alumina treatment	0.25	11.3	9.4
Once-through and hydroxylapatite treatment	0.25	26.6	24.0
Once-through and reverse osmosis treatment	0.8	-	29.7

* Dollars/annual ton = total capital cost divided by annual production rate.

NOTES - 1. Capital costs have been adjusted to 1975 Dollars

(1) - U.S. Environmental Protection Agency, EPA (1973). *Op. Cit.*

Cont'd

2. Operating cost includes :
 - a. Depreciation @ 7.1 % of capital investment
 - b. Return on investment @ 20 % of capital investment
 - c. Admin. overhead @ 4 % of operating and maintenance
 - d. Taxes and insurance @ 2.0 % of capital
 - e. All energy and chemicals associated with the treatment plant

The once through process alternatives have not been tested on a pilot or prototype scale. The cost and efficiency data were based on laboratory studies.

3.4. Air Emissions

Sources :

The major source of emissions when bauxite is ground and digested to produce sodium aluminate, is the ore grinder. At the rotary kiln for calcining alumina trihydrate, the kiln is usually fitted with a particulate collection device to recover the alumina dust. However, further additional cleaning of the exhaust gas from the primary control device, may still be needed to meet emission standards for particulate matter. At the aluminium reduction plant, particulates, sulphur oxides, hydrocarbons as well as fluorides are emitted. The amount of emissions depends upon the type of cell used. With Prebake cells, the gaseous emissions consist of carbon monoxide, carbon dioxide, sulphur dioxide, hydrogen fluoride and traces of other gases. Particulate emissions include alumina, fluoride salts and carbon. With Söderberg cells, hydrocarbons (pitch volatiles) are emitted in addition to the emissions listed for Prebake cells. In horizontal stud Söderberg cells the hood does not fit close to the pot and, therefore, large volumes of air are entrained with the exhaust from the cell hood. This has the effect of quenching combustion of hydrocarbons, thereby creating a large tar fouling problem as the heavy hydrocarbons condense on ducts and control equipment. On the other hand, vertical stud Söderberg cells have close-fitting skirts which enable the anode gases to be collected with little dilution and burnt in a special burner. These gases are, therefore, converted to CO₂ and a carbon dust which does not cause fouling.

Rate of Emissions :

Fluorides can be emitted as a gas (HF) or as solid (CaF₂, NaF₂, etc). Typical emission of fluorides from a cell is estimated to be 23 kg/tonne Al (1), however emissions from different types of cells with different collection efficiencies are reported to be (2) :

- (1) - Singmaster and Breyer (1973) "Air Pollution Control in the Primary Aluminium Industry" New York.
- (2) - Nastaas. I. (1975) "A Survey of Pollution Problems in the Aluminium Industry". Paper prepared for and presented at a UNEP Industry Sector Seminar, Aluminium Meeting. Paris. October.

Type of Cell	Cell Gas Cleaning	Ventilation Air Scrubbing	Emission of Fluorides Compounds kg/tonne Al (Emission of HF, kg/tonne Al)			
			Collection Efficiency for cell gas, percent			
			0	75	90	95
Söderberg Vertical Stud	None	None	20 (18)	20 (18)		
	Dry electrostatic precipitator + spray tower	"	20 (18)	5.2 (4.6)		
	"	Spray screen	2.4 (1.3)	0.8 (0.5)		
	Alumina + bag filter	"	2.4 (1.3)	0.9 (0.6)		
Söderberg Horizontal Stud	None	None	20 (16)		20 (16)	
	Floating ball scrubber	"	20 (16)		4.0 (2.3)	
Prebake closed	None	None	16 (8)			16 (8)
	Floating ball scrubber	"	16 (8)			3.8 (0.7)
	Alumina + bag filter	"	16 (8)			1.3 (0.6)
	" "	Spray screen	4.8 (0.4)			0.7 (0.2)
Prebake open	None	None	16 (8)			
	"	Spray screen	4.8 (0.4)			

The quantity of sulphur oxides emitted depends upon the sulphur content of the pitch and coke used to manufacture the anodes of the Prebake cells or the anode paste of the Söderberg cells. Typical emissions of oxides of sulphur and other pollutants for different kinds of cells are : (1)

Cell type	Solid F	kg / tonne Al				
		HF	SO _x	Co	Particles	Hydrocarbon
Prebake Vertical Stud	8	8	15	200	30-100	negligible
Söderberg	2	18	15	0 50	20-40	1-3 2-6
Horizontal Stud Söderberg	4	16	15	200	20-40	6- traces

Emissions Abatement Technology :

Effective abatement of pollutants from an aluminium smelter can be achieved by improving operating conditions in the electrolytic cells, and installing emission control equipment.

(1) - Nestaas, I. (1975) - *Op. Cit*

Cells operating conditions can be improved by suppression of anode effect ; reducing bath temperature ; careful attention to the design, construction, maintenance and operation of hoods; efficient operation of ancillary equipment, as well as proper training of plant personnel.

Emission control techniques consist of two steps. The first one consists of collecting the gaseous compounds when emitted. This is then followed by the second step, that is removing the undesirable components from the gas stream, before it is exhausted.

Collection :

Air borne pollutants in cell rooms are collected by roof monitors and cells emissions are by hoods or skirts. Generally in aluminium smelters the primary collection efficiencies for hooded Prebake and horizontal stud Söderberg cells range from 75 to 95 percent, averaging above 90 percent for the Prebake cells and somewhat lower for the Söderberg cells.

Removal :

Emission abatement problems are primarily caused by the removal of particulates and of gaseous hydrogen fluoride from the stream.

Particulates :

These include solid particles of bath material, alumina and carbon, inorganic fumes and hydrocarbon tar fogs. Their removal from gas streams can be accomplished by segregation and attraction through electrostatic forces (electrostatic precipitators), collection in a solid and or liquid phase (scrubbers), interception on a porous medium (filters) and by inertial segregation (cyclones). The separation and collection efficiencies of these mechanisms depend to a large extent on the size of the particulates in the gas stream. Normally, particles larger than 3 microns can be separated from gas streams by gravitational or centrifugally induced forces. However, a substantial percentage of the solid fluoride is in the form of sub-micron particulates, which are difficult to remove efficiently. In ore refining plants using the Bayer process, particulates from the ore grinder after collecting in a hood, are removed by an electrostatic precipitator, venturi scrubber or bag filter. Wet collection devices have also been applied, but have not been found to be as effective. In the calcining operation, particulates are usually removed by a combination of multi-cyclone and electrostatic precipitator or bag filter. The collected dust is primarily alumina which is recycled.

In the electrolytic reduction process, the control technology depends upon the type of electrolytic cell being used. Control systems include scrubbers using lime neutralized recycled water to remove particulates as well as gaseous hydrofluoric acid. "Dry" processes using alumina are also being used. These remove both gaseous and particulate fluorides and have the advantage that the fluorine values can be returned directly to the electrolysis step. The

disadvantage with these processes is that SO_2 is not removed and must be controlled, if required, by a final wet scrubbing operation.

Gaseous compounds :

These are primarily gaseous fluorides, hydrocarbons and sulphur oxides. Hydrocarbons are normally controlled by combustion in special burner equipment, converting the hydrocarbons to carbon dioxide and water vapour. With fluorides and sulphur gases the mechanism for removal is absorption in a selected liquid solvent or adsorption on the surface of a selected solid. Caustic or floating bed scrubbers are used for this purpose.

Air pollution characteristics and control technology adapted from a report (1) are summarized as follows :

Cell Type	Particulates and Fluorides	Gaseous Fluorides	Hydrocarbons	Sulfur Oxides	Controls
Prebake cells	Yes	Yes	Carbon dust and volatiles	Yes	Caustic scrubber
Anode Furnace	Yes	Yes	Volatiles	Yes*	Hot precipitator Incineration Dry scrubbing
Vertical Stud Söderberg Cells	Yes	Yes	Carbon dust	Yes*	Caustic scrubber
Horizontal Stud Söderberg Cells	Yes	Yes	Tars	Yes*	Floating bed scrubber

* present as SO_2 or H_2S

With the Prebake anode baking furnace, a high proportion of the sulphur in the raw material is retained and is evolved as SO_2 in the electrolytic cell.

Costs :

The cost of controlling Fluoride emissions in typical new plants, utilizing Prebake and Söderberg cells and with different modes of pollution abatement are reported (2) to be as follows :

-
- (1) - U.S. Environmental Protection Agency, EPA (1976) "Environmental Considerations of Selected Energy Conserving Manufacturing Process Options". Alumina/Aluminium Industry Report. EPA 600/7-76-034h, December.
 - (2) - International Primary Aluminium Institute, IPAI (1975) "Fluoride Emissions Control : Costs for New Aluminium Reduction Plants". IPAI, London, April.

Cell Type	Control System Family	Cell operation		Fluoride			Plant size 1000 metric ton/yr	Cost data	
		Centre break	Side break	Evolution kg F/metric ton Al	Total emission kg F/metric ton Al	Recovery credit US \$/ton Al		Operating US \$/metric ton Al	Equipment US \$/metric ton Al
Prebake	dry primary wet primary ³ + wet secondary tall stack	X		17-20	0.6-1.68	11.00-12.46	50-57	6.17-20.50	70-132
			X	15-20	0.97-1.1	9.28-12.50	50	6.50-27.00	77-156
		X		12-18	0.6-2.3	6.51-10.84	50	19.00-31.30	70-142
			X ¹	16.7	4.46	8.10	50	32.34	159
Söderberg HSS	dry primary wet primary		X	16-20	0.75-1.1	9.42-11.84	50	16.75-52.75	108-213
			X	16	4.8	1.72	50	27.37	110
			X	15	12.35		50	10.17	50
Söderberg VSS	dry primary wet primary + wet secondary		X	18.8	1.20	11.65	40	31.56	177.50
			X	17.0	1.33-3.20	9.12-10.35	40	36.87-37.55	167.50-185.0
			X ²	20	4.3	10.37	45	0.15	44.44
		X ²	19	1.11	9.49	45	43.11	185-11	

1 Special system – Each cell totally enclosed

2 Skirts on VS Söderberg

3 Primary system can be wet or dry

The above costs were determined using the following assumptions :

- Power -- US \$ 0.012 per kilowatt hour
- Operating labour -- US \$ 8.00 per hour (excludes fringe benefits)
- Maintenance labour -- US \$ 9.00 per hour (excludes fringe benefits)
- Supervisory labour -- US \$ 10.00 per hour (excludes fringe benefits)
- Credit for fluoride recovery (dry weight) -- US \$ 600 per short ton
- Credit for dry particulate material -- US \$ 40 per short ton
- Chemical for water treatment -- A flat US \$ 60,000 per year.

A Capital-Recovery Factor of 0.17698, for 12 percent interest for ten years, was used to determine the cost of capital and, in addition, maintenance parts were calculated on total capitalization.

3.5. Biological Effects of Atmospheric Fluorides

The major pollutant of environmental concern emitted by the aluminium industry is fluoride. Although fluorides are used in the artificial fluoridation of water to aid in preventing dental caries, the potential hazard of exposure of large population groups to an increased intake of fluoride has caused a continuing controversy. Airborne fluoride from dusts and gases have been an obvious health risk in many localities since the time of the earliest known volcanic eruptions. This air pollutant is emitted from natural sources, from fluoride containing materials and from industrial processes.

Other industrial sectors also emit fluoride. Amongst these are the manufacture of normal superphosphate fertilizer, steel, bricks and tiles as well as the combustion of coal.

The biological effects of atmospheric fluoride have been vigorously studied and widely reported (1), (2).

Effects on health :

Severe effects such as crippling fluorosis have so far only been observed from longterm occupational exposures. The increasing intensity of acute effects with increasing concentrations of gaseous fluorides are quoted (3) to be :

-
- (1) -- U.S. National Academy of Sciences (1971) "*Biological Effects of Atmospheric Pollutants : Fluorides*" -- National Academy of Sciences, Washington, D.C.
 - (2) -- World Health Organization, WHO (1970) "*Fluorides and Human Health*" -- WHO Monograph Series N° 59.
 - (3) -- Hodge, H.C. and F.A. Smith (1977) "*Occupational Fluoride Exposure*" -- Special Issue on Understanding Occupational Exposure to Fluoride, J. of Occupational Medicine, Vol. 19 N° 1, January.

- 3 ppm – no local immediate systematic effects are noted
 10 ppm – many persons experience discomfort
 30 ppm – all persons complain and object seriously to staying in the environment
 60 ppm – brief exposures – definite irritation of conjunctiva, nasal passages, tickling and discomfort of pharynx, trachea
 120 ppm – highest concentration tolerated less than 1 min. by two male subjects.

It has been estimated (1) that the exposure limits for hydrogen fluoride and inorganic fluoride, recommended by the U.S. National Institute for Occupational Safety and Health, are :

- 2.5 mg of F per cubic meter of workplace air,
 4.0 mg of F per liter of urine collected per shift, and
 7.0 mg of F per liter potshift,

are a valid protection of a working environment.

Effects on livestock (2) :

Small quantities of fluorides are normally ingested by animals in their rations with no harmful effects, but excessive ingestion can be damaging. The relationship between fluorine content of the diet and the development of various symptoms in cattle has been summarized as being :

Symptom	Total Fluorine in Diet (ppm)			
	20-30	30-40	40-50	50
Discernable dental mottling *	Yes	Yes	Yes	Yes
Enamel hypoplasia (score number :4)*	No	No	Yes	Yes
Slight gross periosteal hyperostosis	No	Yes	Yes	Yes
Moderate gross periosteal hyperostosis	No	No	Yes	Yes
Significant incidence of lamenesses	No	No	No	Yes
Decreased milk production	No	No	No	Yes
Skeletal F equivalent to 5000 ppm at 5 yr ♀	No	No	No	Yes
Urine F of 25 ppm ‡	No	No	Yes	Yes

* Only if fluoride is present during formative period of the tooth

♀ Metacarpal or metatarsal bone, dry, fat-free basis

‡ Based on values taken after 2-3 years of exposure ; specific gravity = 1.04

- (1) – Hodge H.C. and F.A. Smith (1977) - *Op. Cit.*
 (2) – Suttie, J.W. (1977) "Effects of Fluoride on Livestock" an expanded and updated paper presented at a UNEP Industry Sector Seminar. Aluminium Meeting, Paris, October 1975. J. of Occupational Medicine, Special Issue, Vol. 19 N°1, January.

The tolerable levels of fluorides such as NaF, that domestic animals could ingest without clinical interference and with normal performance, are :

Animal	Performance (ppm F)
Beef or dairy heifers	40
Mature beef or dairy cattle	50
Finishing cattle	100
Feeder lambs	150
Breeding ewes	60
Horses	60
Finishing pigs	150
Breeding sows	150
Growing or broilers chickens	300
Laying or breeding hens	400
Turkeys	400
Growing dogs	100

Effects on vegetation (1) :

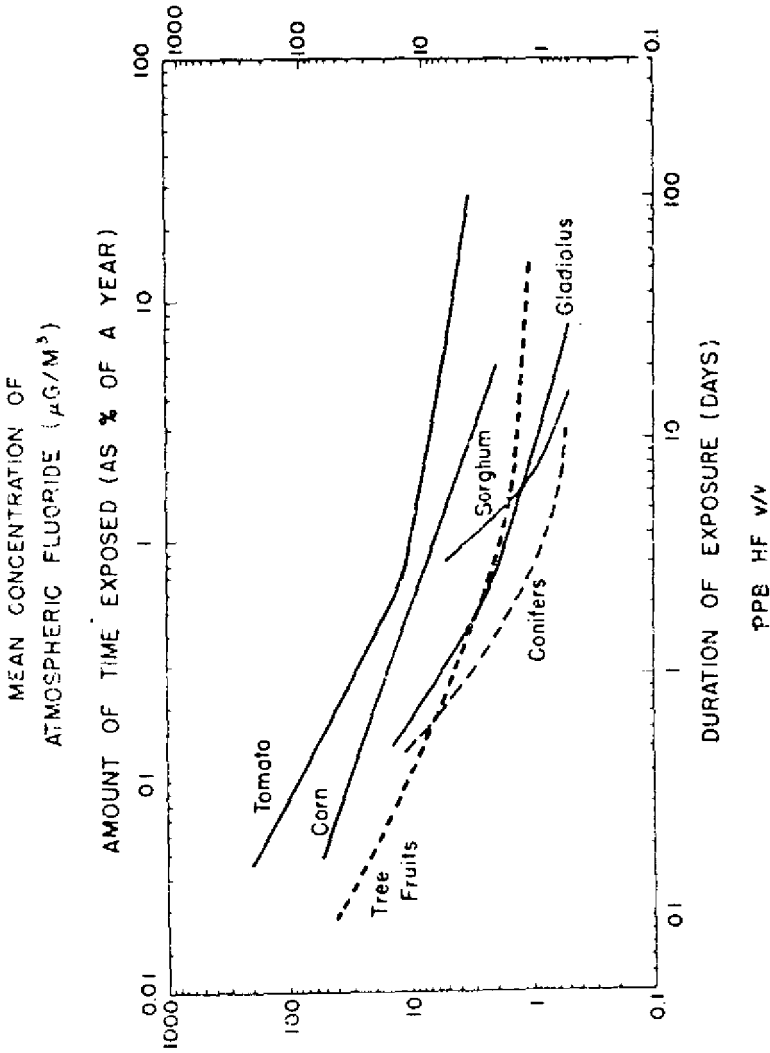
Among the common air pollutants, fluoride is ranked fifth in importance with respect to the amount of plant damage caused in the U.S. However, fluoride is the most phytotoxic pollutant, and it may cause injury to susceptible plant species at atmospheric concentrations 10 to 1000 times lower than other pollutants (less than 1 ppb or $0.8 \mu\text{g F}/\text{m}^3$). Fluoride has also one other important characteristic - it accumulates in the plant.

A scheme serving as a guide to the kinds of effects of fluoride on plants that might occur by relating cellular effects to higher levels of biological organization, is :

Cell	Level of biological organization		
	Tissue or organ	Organism	Ecosystem
?	Increased yield	Increased growth	?
(Altered cell milieu ?)	?	?	?
Effects on enzymes and metabolites	Decreased assimilation		Increased F in ecosystem
	Altered respiration		
Modification of cell organelles and metabolism	Decreased growth and development	Modified growth	Increase in F burden of animals
Pathway disruption	Chlorotic lesions	Reduced reproduction	Fluorosis in animals
Cellular modification			
Disruption and death of cell	Necrotic lesions	Decreased fitness for environment	Change in plant community
	Death or abscission of leaf	Death of plant	Desolation

- (1) - Weinstein. L.H. (1977) "Fluoride and Plant Life" an expanded and updated paper presented at a UNEP Industry Sector Seminar. Aluminium Meeting, Paris, October 1975. J. of Occupational Medicine. Special Issue, Vol. 19, N° 1, January.

The reported dose-response relationships for foliar injury for different plant species are shown below :



4. NEW PRODUCTION PROCESSES IMPACT ON POLLUTION ABATEMENT

4.1. Alternative Alumina Production Processes

There is a growing interest from industry for the possible production of alumina from alumina bearing raw materials, such as alunite, kaolin, and anorthosite clays as well as dawsonite, a sodium aluminium carbonate mineral found in oil shale. There are a number of processes under development to produce alumina from clay, as alternatives to the Bayer process. The processes that have received attention (1) and show potential for commercial development are :

- nitric acid leaching
- hydrochloric acid leach and
- clay chlorination

Clay Leaching by Nitric Acid and Hydrochloric Acid :

The application of either of these two processes would produce liquid wastes containing soluble nitrates or chlorides. The solid wastes are generated by the separation of insoluble materials in thickeners during the leaching step. In addition, both processes include a crystalline step which removes impurities as nitrates and chlorides. These are finally treated by decomposition to recover the nitrate or hydrogen chloride. Nitrates of alkali earth metals are difficult to decompose completely, while the chlorides would not be decomposed at all.

Thus, most likely there will be soluble nitrates or chlorides in the solid discharge from these decomposition steps. It is also likely that there will be gaseous emissions of unrecovered oxides of nitrogen and hydrogen chloride from the acid recovery systems. These gases may then have to be removed from the off-gases in small scrubbers using alkali solutions. Pollution control costs per net tonne of alumina is estimated to be US \$ 19.0 and US \$ 5.0 for the nitric and hydrochloric acids processes, respectively.

Clay Chlorination :

Alumina can be recovered through a dry process, by chlorination of the in clay in the presence of carbon. The aluminium chloride is volatilized overhead, along with other chlorides of iron, silicon, titanium, sodium, etc... present in the clay. The chlorides are separated by a combination of fractional condensation and distillation to produce separated fractions, all of which are oxidized to recover chlorine and the respective oxides, primarily alumina oxides and titanium dioxide, for sale.

(1) - U.S. Environmental Protection Agency, EPA (1976) - *Op. Cit.*

There are several solid wastes generated by these operations. The primary stream is the discharge of unreacted materials from the chlorination step, which would be primarily silica but also some soluble chloride. This would normally be a dry material but could also be made into a slurry for disposal. Other sources are the separation of aluminium chloride from the chlorides of iron and sodium, as well as the process oxidizing the separated silicon tetrachloride to silica. This silica could be sold, but as a waste would contain soluble chlorides and fine particulates that settle slowly.

The possible major source of gaseous emissions is the off-gas from chlorination after final low temperature condensation of the silicon and titanium tetrachlorides. The final tail gas would contain carbon monoxide and dioxide, some hydrogen chloride, and possibly some uncondensed silicon tetrachloride which would hydrolyze.

These undesirable gaseous emissions could be removed by caustic or lime water scrubbing which would result in carbonates and soluble chloride salts. With this process the pollution control costs per net tonne of alumina is estimated to be US \$ 10.8. Total energy requirements by the acid leaching and chlorination processes are reported to be two to three times higher than the conventional Bayer process (39 to 27 million Btu per net tonne Alumina versus about 14.5 million Btu).

4.2. Alternative Aluminium Production Process :

Alcoa Process :

The new Alcoa System is different from the present Hall-Heroult process for which crust breaking is required and fluoride emissions occur. The new Alcoa cells are more like magnesium cells in which no crust-breaking is required and where chlorine is removed at the anode. Carbon cathodes are also used, but are inert, which means that less carbon oxide gases are released at the anode.

The major air pollution sources would be from the cooker and chlorinator. Cracked hydrocarbon gases, hydrogen sulphide, sulphur oxides, carbon oxides and hydrogen chloride are released.

The main air pollution cost would be incurred in the abatement of hydrogen sulphide or SO₂ from the cooker and hydrogen chloride from the chlorinator off-gas. Emission abatement of the latter would result in a liquid waste stream containing sodium chloride. In addition, there would also be salts and sludges removed from the cells periodically.

The cost of pollution control has been estimated (1) to amount to

(1) - U.S. Environmental Protection Agency, EPA (1976) - *Op. Cit.*

US \$ 12.44 / tonne of aluminium produced. If the sodium chloride stream had to be totally impounded in a tailing pond lined with an impervious barrier, the costs would range from US \$ 0.50 to US \$ 1.00 / tonne. The energy requirement for the Alcoa process has been estimated to be about 135 million Btu per net tonne of aluminium, on a total fossil fuel basis and for the Hall-Heroult smelters, about 190 million Btu per net tonne of aluminium.

5. FLUORIDE LEGISLATIONS AND STANDARDS

One of the follow-up activities resulting from the UNEP Industry Sector Seminar on the aluminium industry, in 1975, was a comprehensive survey and updating of Fluoride Legislations and Standards. The International Primary Aluminium Institute, IPAI, undertook this task (1) and the findings of the survey are summarized below.

5.1. Emission of Fluoride

Standards for the control of gaseous and particulate (dust) emissions via stacks and roof vents may be directed at one or more of the following parameters :

- Standards are frequently set specifying the total emission either of gaseous (Fg), particulates (Fs) or total F from stacks and/or roof expressed as Kg F/hr. or day.
- An alternative procedure is to specify the allowable emission as a function of the weight of metal produced, for example, Kg F/tonne Al.

In this case, the total emission permitted from a site is proportional to the rate of metal production.

Some standards limit the concentration of fluorides or dust in stack or roof gases or both. The volumes of air involved are such that the convenient concentration units adopted are usually mg F/m³.

(1) - International Primary Aluminium Institute, IPAI (1976) "*Survey of Legislation - Fluoride and other Emissions*". IPAI, London.

Regulations for the control of fluoride emissions include the following :

	Kg F/tAl		
	Fg	Ft	
US (Oregon)		0.5	new plants : yearly average
		0.65	new plants : monthly average
US (Federal)			Existing plants to conform by 1.1.84
		1.0	VSS and HSS
Norway		0.95	PB plus 0.05 Anodes Furnace
Germany (Federal Republic)	1.0 0.8	1.0	implied max. for new plants cell gases ventilation gases

In Japan the national standards for stack and roof emissions are $3.0 \text{ mgF}_g/\text{Nm}^3$ and $1.0 \text{ mgF}_g/\text{Nm}^3$ respectively.

5.2. Ambient Air Quality

Ambient air quality is normally assessed by measurements of the groundlevel concentrations (glc) of gaseous and particulate fluorides at locations on or beyond the boundaries of the plant site. The units usually adopted are :

$$\mu\text{g F}/\text{m}^3 \text{ or ppb (by volume)}$$

The environmental effects of fluoride emissions can be monitored in various ways .

- a) The accumulation of fluoride (as F) in vegetation and the incidence of characteristic leaf damage. The uptake of fluoride is usually reported in ppm (by weight) on the dried material. Some authorities impose an upper limit to the F content, for example of pine needles.
- b) The ingestion of fluoride by farm animals leading to higher than normal bone F contents. This results from the uptake of fluoride by grass, hay and related crops and regulations are frequently imposed specifying their maximum F content.

A number of countries and states have regulations specifying the maximum fluoride content of ambient air

e.g. US (Washington)

F_g $0.84 \mu\text{g}/\text{m}^3$ (1 ppb) monthly basis

F_g $2.9 \mu\text{g}/\text{m}^3$ (3.5 ppb) daily basis

F_g $0.5 \mu\text{g}/\text{m}^3$ (0.6 ppb) average from 1 March to 31 October in any year.

In Europe, the Federal Republic of Germany imposes the following :

	Until 1978	After 1978
Long time average	$3 \mu\text{g}/\text{m}^3$	$2 \mu\text{g}/\text{m}^3$
Short time average	$6 \mu\text{g}/\text{m}^3$	$4 \mu\text{g}/\text{m}^3$

and in Italy, a maximum limit of $20 \mu\text{g}/\text{m}^3$ on a daily basis is also imposed. In Japan (Nigata Prefecture) the ambient air regulation, effective since 1974, is :

- 1.3 $\mu\text{g F}^*/\text{Nm}^3$ (average in 10 days)
- $\text{F}^* = \text{F}_g + 0.1 \text{F}_s$ (water soluble)
- 2.5 $\mu\text{g F}_g/\text{Nm}^3$ (average of hourly values in a day)
- 5.1 $\mu\text{g F}_g/\text{Nm}^3$ (average in two consecutive days)

The so-called Washington (Suttie) Standards which are widely accepted for fluorine in grass (dry weight basis) grazed by farm animals and sampled monthly are as follows :

- F not to exceed
- 40 ppm average for any 12 consecutive months
- 60 ppm each month for more than 2 consecutive months
- 80 ppm more than once in any 2 consecutive months

The World Health Organisation recommendation for a maximum tolerable level is 50 ppm for exposures of 6 months or more.

5.3. Working Environment

Most countries with regulations have adopted uniform standards either for specific observance or for reference. These standards are the Threshold Limit Values (TLV) recommended by the American Conference of Governmental Industrial Hygienists (ACGIH).

The concentration units for TLV data are .

$\text{mg F}/\text{m}^3$ or ppm (by volume)

The present values (published 1974) are :

	ppm (by volume)	mg/m ³ (a)
Fluoride (as F)	-	2.5
Hydrogen Fluoride	3	2
Sulphur dioxide	5	13
Carbon dioxide	5000	9000
Carbon monoxide	50	55
Coal tar pitch volatiles (benzene soluble fraction)	-	0.2

(a) approximate equivalents only

The USSR and Czechoslovakia recommendations are as follows :

	Fluoride (as F)	Hydrogen Fluoride
USSR (1966)	1.0 mg/m ³	0.7 mg/m ³
Czechoslovakia (1969)	1.0 mg/m ³	1.2 mg/m ³

5.4. Liquid Effluent Standards

Maximum fluoride (F) contents of effluents are specified in some countries and these are :

	mg F/litre	
Australia (NSW)	1.5	non-tidal waters
Australia (Tasmania)	10	bays and estuarine waters
Spain	1.5	river discharge
Canada (BC)	2.5	new plants, marine or fresh water discharge
Italy	10	all discharges except sea
	20	sea discharges
Switzerland	10	all discharges

US Federal interim regulations relate the total F discharge to primary aluminium produced as follows :

	Kg F/Al	
	by 1977	by 1983
Existing sources	1.0	0.05
New sources	0.025	

6. CONCLUSIONS

Considerable amounts of electrical and thermal energy, between the range of about 13,200 kwh/tonne and 17,200 kwh/tonne, are required in the production of primary aluminium, a consumption range comparable with other metals on a per unit volume basis. Recycling of aluminium, however, requires only a small fraction, (less than five per cent) of the energy used in production of the primary molten metal. Although much progress has been made in recent years by the aluminium industry to reduce energy consumption, energy remains the largest single component in production costs for aluminium. A major opportunity, therefore, exists for reducing energy consumption in melting, casting and fabricating operations.

Two dichotomous trends related to resources are observable in respect of siting of new plants. One is to site them near the supply of raw materials and hydroelectric energy. The other is to site them in the industrialized regions of the world with the infrastructure, as well as near skilled labour and markets. The former frequently means in remote areas as well as in developing countries. The latter approach has the possible advantage of integrating aluminium production with fabrication, avoiding the need for energy for remelting, as it is usually more expensive to transport fabricated goods than the metal. In both cases, and even where stringent emission limits have been imposed, careful site choice, good engineering practice and proper incorporation of pollution control equipment, will enable freedom in choosing a site, whilst meeting the required environmental protection standards. The International Primary Aluminium Institute is in the process of developing comprehensive environmental recommendations for siting and operation of : new primary aluminium reduction plants, new plants for refining bauxite to alumina and environmental recommendations for bauxite mining.

In relation to mining of bauxite, land use planning is important, so that after extraction of the mineral, the land is returned to its original or some other agreed use. Budgetary provisions should, therefore, be provided for reclamation and restoration. With regard to the disposal of bauxite residues, adequate technologies are available for impoundment on land without loss of material or discharge of alkaline effluent. It is essential, however, to take into account the physical characteristics of the bauxite as well as the local meteorological conditions in designing new disposal ponds and the usual criteria in choosing the site of the ponds. The estimated disposal costs for bauxite refining waste streams in 1973, range from US \$ 0.27 to US \$ 0.60 per short ton of alumina or US \$ 0.14 to US \$ 1.09 per short ton of mud.

In the primary aluminium industry, exposure to atmospheric fluorides and coal tar pitch volatiles, particularly in the cell room of Söderberg plants are conceivably the major potential health risks. In addition, working conditions are influenced by other air pollutants, sulphur dioxide, carbon monoxide, particulates, noise, heat risk of accidents and other factors.

The major potential environmental hazards outside aluminium reduction installations is gaseous hydrogen fluoride. The pollutant is much more toxic to certain species of plants than other pollutants, such as sulphur dioxide and ozone, and can injure agricultural crops and other vegetation, giving rise to economic losses. Particulate fluorides are generally considered to be far less toxic than gaseous fluorides, but may result in increased fluoride accumulation in or on plants.

Animals are exposed to fluorides through the ingestion of contaminated forage, and adverse effects may be observed in cattle continuously exposed to forage containing in excess of 40 ppm fluoride as annual average. Other grazing animals may suffer adverse effects at relatively higher concentrations depending on species sensitivity.

With regard to human health, concentrations which are of concern rarely occur outside the workroom atmosphere. At concentrations of 10 ppm many of the persons exposed will experience discomfort and at 30 ppm all persons complain and object seriously to staying in the environment. The Threshold Limit Values adopted by many countries are, an approximate equivalent of 2.5 mg/m³ of Fluoride (as F) and 3 ppm or 2 mg/m³ of hydrogen fluoride. The aluminium industry is not the only major source of fluoride emissions. Many other industries such as, iron and steel, fertilizers and bricks and ceramics also emit this pollutant.

The cost of fluoride emission control equipment for new plants has been estimated to range between two per cent and eleven per cent additional investment, averaging around 6.6 per cent. This is equivalent to a low of US \$ 6.17 / tonne of aluminium for a dry primary system to a high of US \$ 52.75 / tonne for a wet primary plus a wet secondary system including a multi-purpose cryolite recovery plant, for Prebake cells. Average operating costs for retrofitted equipment appear to range from about US \$ 20 to US \$ 40 / tonne of aluminium.

Waste water flow rates and the quantities of pollutants present are highly dependent upon the specific type of air pollution control equipment used. The technology is available to remove fluorides from effluents by a variety of treatment processes. Dry scrubbing, giving zero fluoride discharge and once-through and reverse osmosis treatment are some of the treatment alternatives.

There are a number of new processes for the production of alumina from resources other than bauxite. These processes, however, consume significantly more energy. With new alternate aluminium reduction processes, however, energy consumption is not only less when compared with the conventional smelting method, but also minimizes fluoride emissions. Shortage of capital may well prove a greater constraint on development of the aluminium industry and on advances in materials recovery than technology.
