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ALUMINA INDUSTRY

Case study No. 2

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ABSTRACT

As a consequence of the plant operating technological characteristics on the basis of the Bayer-process numerous effects detrimental to the environment can be seen.

The technology applied to extract the bauxite produces 0.3 to 2.0 t of red mud per tonne of alumina. Its discharge and storage cause serious environmental problems.

The energy requirement of the process is 10 to 18 GJ/t of alumina. produced mainly on the basis of fossil fuels and a proportional quantity of deleterious emissions (SO_2. CO_2. CO. NO_x. dust etc.) which are contaminating the atmosphere.

The case study deals with the actual situation related to the main environmental impact and technological trends to eliminate or reduce pollution in order to reach an environmentally sustainable industrial development.

The technical, economic, institutional and social barriers to the correctional measures are also discussed and conclusions are drawn to serve as guidelines for operating plants and future projects. The most important ways of reducing the negative environmental impact of the alumina industry are the following:

(a) Reduction of the amount of natural resources (firstly of energy) consumed per unit amount of alumina manufactured.
(b) Reduction of the residual discharges (effluents. dust. stack gases) per unit amount of alumina manufactured.
(d) Environmentally sustainable discharge and storage of digestion residue (dry stacking of red mud. recultivation of the filled-up storage areas).

The authors of the case study give detailed recommendations on the technical solution and economic viability of the latest environmental protection measures applied in the alumina production, pointing out at the same time the importance of well performed maintenance and house-keeping.

1. INTRODUCTION

1.1. PRODUCTION

The raw material of the worldwide used Hall-Heroult aluminium smelting process is alumina, which is a white, crystalline, dustlike material consisting mainly of aluminium oxide. During the last 17 years annual amounts varying between 30 and 37 million tonnes of this material were produced. (Prior to the oil price shock of 1973/74 the expansion was dynamic, with an annual rate of 7 to 10 per cent). Meanwhile the regional shift of the industry from North America and Europe to Australia and Latin America continued. Table 1 gives the location of aluminium plants worldwide in 1989 (by region) and their capacities. Thirty-two of these plants (nearly half of the total 69) are situated in developing countries. At the same time most of the bauxite resources are in developing countries (Guinea, Brazil, Surinam, Guyana, Jamaica, India, etc.) and only one of the developed countries has really any significant bauxite reserves (Australia) [1]. New alumina capacities and plant expansions are expected first of all in the above-mentioned countries.

Some 90 to 92 per cent of the total alumina produced worldwide is used for aluminium smelting, the rest is utilized mainly by the refractory, abrasive, ceramics, glass and chemical industries.

Some 95 to 96 per cent of the total alumina is produced from bauxite (only a few Soviet plants use non-bauxitic raw materials like nepheline and alunite) and some 98 per cent of this either by using the Bayer process (see figure I), or in Bayer sections of combined Bayer-sinter plants. (Non-Bayer and combined plants operate only in the USSR, China and Czechoslovakia).

1.2. EMPLOYMENT

Alumina plants have workforces of 500 to 5.000 employees per plant. Worldwide the alumina industry employs some 100 to 150 thousand people, and about 50 thousand people are employed in bauxite mining.

1.3. NATURAL RESOURCES USED

1.3.1. *Bauxite*

The main natural resource used by the alumina industry is bauxite. It takes 2 to 4 t bauxite to produce 1 t of alumina, depending on the chemical and mineralogical composition of the ore and on its moisture content. The average figure is about 2.5 t/t. This means that (depending on the annual alumina production) some 75 to 90 million tonnes of bauxite are mined for metallurgical purposes, i.e. for alumina manufacturing. (The other uses of bauxite, like refractories, abrasives, etc. are relatively small compared to the metallurgical use). The worldwide total of prospected, probable and possible bauxite reserves amounts to 20 to 40 billion t according to various sources. This is sufficient to supply the alumina industry with its raw material for 200 to 400 years at the present rate and consumption (the second highest figure among metals surpassed only by iron ore).

1.3.2. *Caustic soda*

The industry consumes almost 3 million tpa of caustic soda (sodium hydroxide, NaOH). Though this is a significant proportion of the total world production, its total demand is usually more or less balanced by the demands for chlorine and hydrochloric acid and they are manufactured from sodium chloride, which is in abundant supply. Only the energy required for its manufacture can be considered as a demand on natural resources.

1.3.3. *Burnt lime*

Some 0.5 to 1 million tpa of burnt lime is also consumed by the alumina industry, but the raw material (limestone) is also in abundant supply and only the fuel used for its burning is a demand on natural resources.

1.3.4. *Energy*

The second most important natural resource used by the alumina industry (after bauxite) is energy. The Bayer process of alumina manufacturing requires three main forms of energy:

- secondary heat (usually steam),
- primary heat (usually fuel oil or natural gas) and
- electric power.

The secondary heat energy is typically required at two different temperature levels:

(a) High temperature heat demand for the digestion of bauxite.

The temperature of this process is determined by the mineralogical composition of the bauxite. Gibbsitic (trihydratic) bauxites are usually digested at 140 to 150°C, in some cases at 105 to 110°C, boehmitic bauxites at 240 to 260°C in modern plants, at a slightly lower temperature in older plants and diasporic bauxites at more or less similar temperatures, though higher temperatures could offer even greater advantages. Consequently gibbsitic bauxites demand a 1 MPa steam supply with a temperature of 180 to 200°C and monohydratic bauxite a 5 to 8 MPa steam supply with temperature of 270 to 300°C. (About 50 per cent of the world's alumina production is manufactured by the low temperature process, and 50 per cent by the high temperature process. A few alumina plants use molten salt instead of steam to supply heat to the digestion).

(b) Low temperature heat demand for evaporation.

Usually 0.3 to 0.5 MPa steam is used at temperature of 140 to 160° C to concentrate the process liquor to maintain the water balance of the process and for minor heating purposes not covered by the main heat recuperation processes.

The high and low temperature heat demands are not independent of each other. The total secondary heat requirement is significantly influenced by the quality of the processed bauxite.

Primary heat is required for calcining the product at a temperature level of 1100 to 1200°C.

Electric power is required for operating the equipment (pumps, agitators, etc.) of the alumina plant.

The energy requirement of the Bayer process is:

Secondary heat:	high temperature	3.0-6.0 GJ/t
	low temperature	0.5-7.0 GJ/t
Total secondary heat:		4.0-11.0 GJ/t
Primary heat:		3.0-5.0 GJ/t
Electric power (10 MJ/kWh):		2.0-4.0 GJ/t
Total energy demand:		9.0-20.0 GJ/t

The lower figures are typical of western European and some Australian plants and of those built after the oil price shock, such as at Sao Luis, Interalumina and Damanjodi. The higher figures are typical of older plants in developing countries and the USSR.

The "energy content" of the raw and auxiliary materials (first of all caustic soda) may add another 2 to 5 GJ/t to the above figures showing how much energy is really required.

1.3.5. *Water*

The last main natural resource is water. The water consumption of alumina plants varies widely depending on availability. In arid climates alumina plants can survive on a 2 to 3 m^3/t water supply, whereas in places, where water is abundant, 10 to 20 m^3/t consumption is typical.

1.4. WASTES

1.4.1. *Digestion residue (red mud)*

The Bayer alumina manufacturing process has a digestion residue called red mud. The amount of this material varies between 0.3 and 2 t dry residue per tonne of alumina depending on the quality (chemical and mineralogical composition) of the processed bauxite. The annual amount of this waste produced worldwide varies between 30 and 40 million tonnes (calculated as dry material) and constitutes the main environmental hazard of the alumina industry.

The digestion residue is composed of bauxite minerals not dissolved during the digestion process and [illegible] solid, crystalline phases formed in the Bayer process. Table 2 and figure II contain the chemical composition of red muds formed from bauxites originating from seven characteristic deposits of the world. Table 3 and figure III show the mineralogical composition.

The chemical and mineralogical compositions, grain size distribution and morphological characteristics of the digestion residue vary according to the characteristics of the processed bauxite and the processing technology from bauxite deposit to bauxite deposit and from alumina plant to alumina plant.

After the digestion process some residues have to be classified into a coarse (sandlike) and a fine (mudlike) fraction to improve their handling. The coarse fraction can be easily washed and its impoundment causes less problems than that of the fine fraction which can be rightfully called red mud.

A relatively stable watery suspension of red mud containing 20 to 60 weight per cent solids and 5 to 15 g/dm^3 sodium salts and hydroxide (expressed as Na_2O) is transported to the disposal areas of the alumina plants which are mostly on land but in some cases at sea). Unfortunately, no economic use for it has yet been found. In subsequent parts of this paper it will be shown that methods for mud disposal and storage have greatly improved in the last while (see figure IV) [1] and the most modern methods (usually realized in developed countries) correspond to the generic norms of Ecologically Sustainable Industrial Development (ESID). Some alumina plants such as the older ones in developing countries still use unacceptable disposal procedures.

1.4.2. *Stack gases*

When converting the secondary heat requirement of a typical alumina plant (see section 1.3.4.) into a primary one the typical plant would use a total of about 14 GJ of primary energy per tonne of alumina. This corresponds to 0.335 toe (tonne oil equivalent) or 0.558 tce (tonne coal equivalent). The typical emissions relating to 1 tce are given for various fuels as follows [2]:

Fuel	Specific emissions (kg/tce)				
	SO_2	NO_x	CO	C_xH_y	Dust
Hard coal	26	7	0.1	0.5	3.5
Lignite	23	8.5	0.1	0.1	4.5
Fuel oil	23	7	0.2	0.1	1
Natural gas	-	5	-	-	-

For a total annual world output of 36 million tonnes of alumina an energy consumption of 20 million tce (12 million toe) can be estimated (25 per cent more, if the energy content of the raw and auxiliary materials are also included) i.e. about 0.17 (0.21) per cent of the total fossil energy burnt in the world. An equal split among the above four fuels would mean a total annual emission of about 360,000 (450,000) t of SO_2, 140,000 (175,000) t of NO_x, 2,000 (2,500) t of CO, 3,500 (4,400) t of hydrocarbons and 45,000 (56,000) t of dust (excluding the alumina dust leaving the calciners, which can be another 3,000 to 6,000 t). Even more menacing from the point of view of long-term global climatic change (greenhouse effect) is the thought that the alumina industry is responsible for an annual emission of about 40 to 50 (50 to 60) million tonnes of CO_2, i.e. some 0.17 (0.21) per cent of the world total of about 27 billion tonnes [3].

1.4.3. *Bauxite, alumina and lime dusts*

Typical dust losses are 0.1 to 0.2 per cent for bauxite and 0.05 to 0.1 per cent for alumina. Some 100 to 150 thousand tonnes of bauxite dust and 15 to 30 thousand tonnes of alumina dust is lost in the environment. Fortunately neither has any negative health effect, however, only the colour of bauxite dust turning red the alumina plant surroundings over the years and the abrasiveness of alumina dust can be considered a nuisance. Lime dust has a strong caustic effect on the eyes, lungs and the skin, but fortunately it tends to settle within a short distance and contaminates only the immediate surroundings of the lime handling facilities.

1.4.4. *Effluents*

Though most of the systems of alumina plants are closed, some caustic liquor may find its way out through leaking. Most of this is caught and washed back into the process, however, some of it will "disappear". Typically some 2 kg of caustic soda (NaOH) per tonne of alumina cannot be accounted for which gives an annual world total output of some 70.000 t. Most of this gets into the soil or into rivers and the sea. Seawater easily neutralizes these effluents, so problems arise only in the surrounding of in-land alumina plants. Here they can lead to a chemical imbalance of the soil in the vicinity of the alumina plant and a slight alkalinity of nearby small rivers.

1.5. BAUXITE MINING

Most of the processed bauxite is mined in open-pit mines with 3 to 10 m thick bauxite horizons. With an average density of 2 t/m^3 and an average thickness of 5 m some 10 million tonnes of bauxite can be mined in 1 km^2. This means that an annual average of 8 to 10 km^2 of vegetation (usually some kind of tropical or subtropical forest) has to be removed and some 5 to 10 million m^3 of soil to be scraped away. A few decades ago the mined-out areas were usually abandoned and left to recover naturally. Nowadays many bauxite mining companies have extensive reforestation programmes and carry them out as an integral part of their mining operations. This problem in theory appears to be technically solved. Reference [4] gives a very good summary of the environmental problems connected with bauxite mining and their solutions.

1.6. ANTICIPATED DEVELOPMENTS

A long term annual expansion rate of 2 to 3 per cent is expected for primary aluminium production, and a similar one for alumina. This is more or less the same rate as that achieved by minor improvements to alumina manufacturing processes and equipment. The main vehicle is the increase of liquor productivity. This is the amount of alumina hydrate precipitated from 1 m^3 of pregnant liquor expressed as Al_2O_3. Today's average is about 60 kg, this could be increased to 75 kg and may be as high as 90 kg. Therefore, few new alumina plants will be built over the next 20 years.

The shift of the production capacities towards the countries with large bauxite reserves will continue. Practically no expansion can be expected in North America, Europe or Japan and some of their present plants may even be closed or converted to produce non-metallurgical alumina. The regions best suited for large expansion and even new plants are in South America (especially Brazil and Venezuela), India and Australia, where large bauxite deposits are accompanied by abundant sources of energy (hydropower in South America, coal in India, coal and natural gas in Australia required for smelting the alumina to primary aluminium). Capacities to be expanded will, to a great extent, depend on the economic situation and the government policies of these countries.

As far as the development of the processing technology is concerned the greatest savings can be expected (not least as a result of increased liquor productivities) in the field of energy consumption. Though annual capacity will increase, energy consumption will remain the same which indicates a much improved energy efficiency. The other main trend expected will be improved environmental management of all alumina plants [5].

2. ENVIRONMENTAL REQUIREMENTS FOR ACHIEVING ECOLOGICALLY SOUND INDUSTRIAL DEVELOPMENT

2.1. EFFICIENT RESOURCE UTILIZATION

2.1.1. *Bauxite*

The available Al_2O_3 content of the processed bauxites is 98 to 99 per cent and of this 95 to 96 per cent is obtained as product. (Available Al_2O_3 is the alumina content of the bauxite present in the form of hydrates: gibbsite, boehmite and diaspore). There is very little scope to further improve these high yields. The only possibility is to digest the boehmite and diaspore or diaspore contents of those bauxites, of which presently only gibbsite or gibbsite and boehmite are extracted. (Boehmite can be extracted by increasing the digestion temperature; diaspore by further increasing it and adding some catalyst like burnt lime or hydrogarnet). However, mixed type bauxites are anyway digested according to the mineral(s) requiring the most severe conditions and only boehmite and/or diaspore contents not exceeding 10 per cent (relative) of the total available alumina are sometimes left undigested. Such an improvement of only 1 or 2 per cent might be expected, and even less, if the slow deterioration of the quality of the processed bauxites is also taken into consideration.

Some techniques profess to extract most of the alumina content of the bauxites that would otherwise be considered not available using the Bayer process (i.e. the alumina content bound to silica in kaolinite, chamosite, etc.). These usually require very large amounts of energy, most often fossil fuels.

2.1.2. *Caustic soda, burnt lime*

Most of the caustic soda used by the alumina plants will be bound to the silica content of the bauxite and left in the digestion residue. This part cannot be saved by conventional methods. Improved maintenance (better packing, immediate repair of leaking equipment, frequent washing of the floor, etc.) can save 1 or 2 per cent of the caustic soda consumption. A little more can be saved by better mud and hydrate washing, however, this requires either higher capital spending (more washing stages) or more energy (more water used for washing, and more evaporation to maintain the water balance of the process cycle). These washing processes optimized from the economic point of view do not offer much scope for improvement. Widespread use of deep thickeners developed recently could shift the optimum towards better washing of the red mud.

The amount of NaOH bound into sodium-aluminium-silicates will take a relatively long time to increase in the future because of the slow deterioration of the quality of the processed bauxites (i.e. the slow increase of their silica content). This trend can only be reversed by an increased use of burnt lime. However, it takes about 3 to 4 kg of CaO and some 10 kg of steam to save or recover 1 kg of NaOH. The extent of NaOH saving will depend on the relative price of caustic soda, burnt lime and process steam.

Burnt lime itself can be better utilized, if it is of a better quality (it takes nearly the same amount of fuel to make a burnt lime with an active CaO content of 70 per cent as one with 90 or 95 per cent) and if its active CaO content is leached more efficiently. The most modern plants usually produce their own burnt lime (this is also an advantage from the environmental point of view, because the lime can be handled in a more or less completely closed system and follows their own high specifications). Some of the older plants (especially in some developing countries) buy their lime from outside suppliers (sometimes from a number of minor producers). It may be of a substandard quality.

2.1.3. *Water*

As has already been shown in section 1.3.5., alumina plants are flexible as far as water consumption is concerned. If necessary they can operate with 2 to 3 m^3 of water per tonne of alumina. (The actual minimum depends on the quality of the processed bauxite, first of all on the relative amount of its digestion residue). Of course, such low consumption figures can only be attained at the cost of a relatively high capital investment (closed water circuits, etc.) and increased maintenance and worker awareness.

2.1.4. *Energy*

The secondary heat requirements of alumina plants are usually covered by

- high or medium pressure (1 to 8 MPa) and
- low pressure (0.3 to 0.5 MPa) steam

generated either in boilers or power plants within plant limits or in adjacent commercial power plants. Their primary heat requirements are provided by fuel oil or natural gas burned in their calciners. Power demand comes from a reliable public power system (national or local grid) or from their own condensation power plant in an insular operating mode. Such a system is shown in figure V, representing the energy supply system of an alumina plant operating on a 100 per cent fossil fuel basis, in which all the power is generated in the local co-operating power system. Steam supplying secondary heat is generated in the boiler plant established in the alumina refinery. The high pressure steam is directly fed to the consumer (the digestion unit), whereas the low temperature consumers are supplied through a reducer or a back-pressure turbine. The calciner is directly fired by fuel oil or natural gas.

Line 1 of figure V shows the energy demand of the process, line 2 the energy demand of the alumina plant before conversion and line 3 the total primary energy demand. For a typical case these are as follows:

"1" (process):	E	Electric power	280 kW.h/t
	DH	High pressure steam	1.9 t/t
	DL	Low pressure steam	1.25 t/t
	FC	Calciner fuel	4.20 GJ/t
"2" (alumina plant):	EP	Electric power	1.06 GJ/t
	DH+DL	Boiler fuel	6.80 GJ/t
	FC	Calciner fuel	4.20 GJ/t
	FA	Primary energy	11.00 GJ/t
"3" (total primary energy):	EP	Electric power	3.00 GJ/t
	FA	Primary energy	11.00 GJ/t
	F	Total primary energy	14.00 GJ/t

The possibilities for reducing the harmful environmental emissions resulting from the energy supply can be found in two main areas:

(a) the alumina manufacturing process and
(b) the energy supply system serving the above process
In (a) above the secondary heat demand is a result of

- dissolution and reaction heats.
- incompleteness and irreversibility of the recuperative heat exchanges,
- condensor losses (at evaporation) and
- heat losses radiated to the environment.

The dissolution and reaction heats cannot be reduced. The recuperative heat exchanges can be optimized. The most important is that of digestion. The method used is flash recuperation. The limits are boiling point elevation of the digested slurry and the temperature steps due to finite heater surfaces and flash stages, and the capital costs of the recuperation system.

Condenser losses occur at the evaporation unit and can be reduced by bringing the liquor concentrations in the digestion and precipitation units closer to each other. Evaporation reduces the liquor concentration at the digestion, increases liquor flow and high temperature heat demand. This increased efficiency is, however, much less than the saving attained at the evaporation. Many alumina plants try to reduce the amount of water to be evaporated. These efforts are limited by the minimum amount of water required for mud washing.

An even more efficient way of reducing the condenser losses is to increase the concentration at the precipitation. This is the increasing of liquor productivity mentioned in section 1.6. Previously this course of action was followed only in some European alumina plants, which were not so concerned about the granulometry of the product. However, recently ways have been found to overcome this problem by precipitating coarse hydrate from liquors with higher caustic concentrations.

The heat radiated towards the environment is a result of incomplete insulation, leakages and other operational and maintenance problems. Reference[6] reports the results of an investigation carried out in an alumina plant consuming 8.5 GJ/t of secondary heat, where the total of radiation losses amounted to 4.5 GJ/t, i.e. 53 per cent of the total heat demand. It is estimated that some 70 to 80 per cent of this could be saved by painstaking maintenance and careful operation.

When exploiting all the above possibilities an average secondary heat requirement of 4 GJ/t can be expected in the typical alumina plants by the year 2010 and a slightly better figure (3.0-3.5 GJ/t) in the best ones. The environmental effect of this secondary heat demand will depend on the way the steam is generated.

The primary heat requirement of the alumina plants (as mentioned above) is for calcining the precipitated hydrate to alumina. Conventional rotary kilns used some 5 GJ/t or even more until about 1960. Recently a number of these have been reconstructed by adding cyclones to them at both ends for a better utilization of the heat content of the flue gases and of the calcined alumina, respectively. In this way their heat demand could be reduced to about 4 GJ/t. At the same time various types of stationary calciners (fluid bed, fluid flash, gas suspension) have been developed with specific heat consumption of 2.9 to 3.3 GJ/t. Though presently a number of unmodified and modified rotary kilns still operate, and it seems to be more economic to modify a conventional rotary kiln than to replace it by a stationary one (even though the heat saving is less in this case), it is most probable that the overwhelming part of the calciners operating in the year 2010 will be of the stationary type. This means that a 3 GJ/t primary heat requirement is expected in the long-term, covered by natural gas, where possible, and by fuel oil (preferably with a reduced sulphur content), where not.

Some 50 per cent of the electric power required by the process is consumed by centrifugal pumps and about 12 per cent by agitators of various slurry tanks [6]. A significant saving could be achieved by their careful maintenance and operation and by applying up-to-date control systems. It is expected that the average power demand of the alumina plants would drop to about 200 kW.h/t from the present 250 to 300 kW.h/t. The environmental impact of the power consumption depends on the system in which it is generated.

(b) The energy supply systems serving the process can be of different types, discussed in the following:

- separate supply of heat and power
- combined energy generation by back-pressure steam turbine, gas turbine, combined steam and gas turbines,
- energy supply on nuclear basis,
- energy supply on hydropower basis and
- energy supply on geothermal basis.

The widely used conventional solution is the separate supply of heat and power. This system was described at the beginning of section 2.1.4. and shown in figure V (Variant A). This system is the most disadvantageous both from the point of view of economy and the environmental impact as it requires the largest amount of fossil fuels and emits the largest amount of harmful compounds to the environment.

The split of the secondary heat requirement of the alumina plants into high and low temperature offers the possibility of passing the steam required in the low temperature range through a back-pressure turbine. By this means a part of the power demand of the plant can be generated in a very economic way. The principle of this solution can be seen in figure VI (Variant B). By using this solution the total primary heat requirement of an alumina plant can be reduced by 3 to 5 per cent depending on the parameters (concentrations, digestion temperature) of the process. This reduction will be realized in the outside power generating system by saving of fossil fuel and a reduction of emitted pollutants. The boilers of the alumina plant will actually consume a little more fuel. Since most of the low temperature heat consumed by the alumina manufacturing process is used in the evaporators and since the evaporation rate is dropping in most plants, as shown previously under (a), this solution will be less important in the future.

A new opportunity just being explored is the use of gas turbines in the Kombi process. According to this hot (450 to 600°C) exhaust gas of the gas turbine would be used (with some additional fuel) in a boiler for steam generation (see Variant C of figure VI). In alumina plants where (because of the large amount of red mud from low quality bauxite processed) evaporation cannot be eliminated, the high pressure steam would also be generated by using the heat content of the exhaust of the gas turbine (and some additional fuel) and some of this would be passed through a back-pressure turbine to supply the evaporation (and some other minor consumers in the process) with low pressure steam (see Variant D of figure VI). These systems could provide an additional saving of 0.5 to 1 per cent.

The environmentally harmful effects of using fossil fuels for the energy supply of alumina plants could be significantly reduced by the use of nuclear, hydro or geothermal energy. Power generation as described above exceeds the scope of this paper. It should be underlined that by supplying electric power from a non-fossil source to an alumina plant the total primary fossil energy requirement can be reduced by 20 to 25 per cent. However, this paper intends to draw attention to the possibilities of heat supplied by nuclear or geothermal sources. As a result of the development of nuclear energy the use of nuclear facilities for heat supply was already discussed in the 1970s [7]. During the 1980s the first designs of nuclear heating units for town heating purposes were elaborated [8]. Alumina plants could, of course, be supplied only by relatively small nuclear heating units (150-300 MW heat for a 1 million tpa capacity plant) and only HTGRs (high temperature gas reactors) could provide their high temperature heat requirement, if boehmitic or diasporic bauxites were processed. Any industrial plant could use steam only from the tertiary circuit of a nuclear facility because of safety reasons. An example of a nuclear reactor (THTR 300 developed by Hochtemperatur Kernkraftwerk GmbH (HKG) which can supply steam up to a temperature of even 600°C.

The use of geothermic energy for covering the secondary heat demand of alumina plants seems to be a very attractive proposition, however, there is little chance for its widespread use because of the limited number of suitable locations (e.g. Iceland) where the pressure of the geothermic steam is sufficiently high to heat a high temperature digestion system even after the pressure loss connected with its purification (removal of its salt content).

Should both the secondary heat demand and the electric power demand of alumina plants be provided by non-fossil sources, then only about a third of their primary heat requirements would have to be supplied from a fossil source. This could lead to a tremendous reduction of the atmospheric pollution caused by them.

2.2. RESIDUAL DISCHARGES

2.2.1. *Bauxite residue (red mud)*

The main constituents of red muds (Fe_2O_3, Al_2O_3, SiO_2, TiO_2, Na_2O, CaO) are present mostly in the form of non-toxic oxides and silicates. Environmental problems are caused by the large volume of mud, by the alkali content of the liquid phase of the red mud slurry and by the NaOH content being bound in the solid phase in the form of sodium aluminium hydrosilicates and tending to dissolve slowly and partially in a process of hydrolysis.

The environmental effects can be summarized as follows:

- the impoundment areas reduce the land available for agriculture,
- the alkaline solution seeping out of them may cause chemical imbalance of the soil around them and contaminate the groundwater,

- the dusting of dried-out mud lakes can be felt over wide areas. and
- they have an unaesthetic effect.

The huge amount of digestion residues produced annually and the long history of the Bayer alumina manufacturing process means that up to now about 1 billion (dry) tonnes of this material has been impounded and this figure increases by about 3 to 4 per cent every year. The efforts for reducing the negative environmental effects have been concentrated in the following directions:

- development of new storage methods. including the revegetation of abandoned impoundment areas.
- modification of the alumina manufacturing process to discharge a residue less harmful to the environment.
- utilization of red mud in agriculture for soil amelioration.
- utilization of red mud in industry as an additive and
- processing of red mud by complex waste-free processes.

2.2.1.1. Red mud discharge and storage

The last summary relative to disposal (and utilization) of bauxite residues (red mud) appeared in 1980 as a contribution of UNIDO in close co-operation with UNEP [9] as one of the major papers for the UNEP/UNIDO Workshop on the Environmental Aspects of Alumina Production held in Paris. France. January. 1981. The information in that paper was based on data received from some major alumina producing companies. institutions and governments. on the available technical literature and on the results of visits of the Aluterv-FKI team. In some alumina producing companies. as well as the experience gained over half a century in plants of the Hungarian Aluminium Corporation in the disposal (and use) of red mud.

Development in the field of red mud handling and disposal was rapid during the 10 years between 1980 and 1990. Processes mentioned in [9] as distant possibilities have now been realized in the majority of plants and environmentally sustainable technologies are now working [10]. The engineering designs of all new alumina plants pay special attention to this issue.

In the following a general survey of these methods will be given. The relative bibliography is too abundant to be incorporated in this paper. therefore only practical solutions realized on a large scale and promising new methods are dealt with.

From the practical point of view it seemed advisable to the author to keep separate the notions of discharge and storage of red mud.

Discharge is the state in which red mud leaves the limits of the alumina plant. This has two main forms:

- red mud filtered on press. drum or disc filters and transported to the storage area in trucks or pumped after agitation (liquefying) by appropriate pumps and
- red mud slurry as the final product of multistage washing or of repulping after filtration. Such slurry is stored in designated areas. but sometimes it is dumped into

rivers, estuaries, lagoons or into the sea (in some cases first into special ships from where it is discharged into the sea).

Storage can take place in areas mostly surrounded by dams (called generally 'red mud ponds'), in valleys closed by dams or in lagoons on the seashore. Storage of filtered and pumped red mud in ponds is the technology of the 1980s, more advantageous than the storage of slurries. Storage of 'deep-thickened red mud' is one of the most up-to-date techniques developed recently. This technology can be regarded as a synthesis of the two operations giving an economic and reliable environmentally sustainable solution to the majority of problems connected with discharge and storage.

The original form of the discharge of red mud from the plant was filtration on leaf filters, sometimes immediately after blow-off. The operation was discontinuous, expensive, required a large number of personnel and extensive environmental and health risks were involved.

Next came filtration on press (e.g. Kelly) filters. Their filtering surfaces have increased up to 400 m^2. The operation was discontinuous [11].

In order to eliminate the discontinuous character of filtration on press filters a number of alumina plants made efforts to use drum filters. The majority of these attempts were unsuccessful. With fine grain size muds the performance of the filters was low, because it was very difficult to remove the residue from the surface, and with better filtration characteristics the red mud cake fell back from the drum into the trough.

The solution to these problems is the use of drum filters with roller discharge [12, 13]. A discharge roller rotating with a slightly higher peripheral velocity is pressed against the drum. The mud is "taken over" by the roller from the drum, and can be easily removed from it by means of steel combs.

In the beginning trolleys (tip-carts) were used for transporting the mud to the storage area, but accident risks were high and the roads were frequently contaminated.

Some alumina plants use trucks. The Burntisland plant (UK) [14] eliminated the above problems by modifying the trucks used for transport, so that they are now completely closed.

The filtered mud is transported in most alumina plants by a pipeline to the storage area. This can be done either in a diluted form (by adding sufficient water to it to get a pumpable slurry) or after a mechanical treatment (and the addition of a flux in some cases). Red mud slurries with solids content even as high as 55 to 60 per cent can be pumped over a distance of 1 or 2 km by high pressure slurry pumps [15, 16]. The latter solution is the most modern. As will be shown later, it makes possible 'dry stacking' of the digestion residue.

Some alumina plants at one time discharged red mud slurry into rivers. Fish and other animals died, the water was seriously contaminated and the flora of the river bed was destroyed, and therefore this solution had to be abandoned.

Discharge of red mud slurry into lagoons seems to be a more attractive solution. It does not appreciably reduce the agricultural area and cultivation after filling of the lagoon can be carried out. Lagoons on the seashore are normally in contact with seawater and the caustic soda content of the liquors neutralized by the sea's magnesium-salt content forming a compound called thalcite. Careful monitoring of the area and of the seawater in the vicinity of the lagoon is indispensable.

Though discharge of red mud into the sea seems economically advantageous. the authors of this paper and a number of other experts expressed their reservations about this method.

The advantages of marine disposal are that no arable land is occupied. socio-economic impact on the population living in the vicinity of the plant are minimal. no recultivation is necessary. there is no dust formation and the seepage of caustic liquors into aquifers is eliminated.

The only danger is that the red mud settling on the sea floor kills some stationary species of the flora and fauna. Cod were reported to have died after five days exposure (suspended in a cage above the sea floor) and the metabolic rate of shrimps was reduced after an exposure to 10 gpl mud. Mortalities were demonstrated in herring embryos and extinction of algal cultures were reported.

The study [9] deals in more detail with this problem. All these facts supported V.G. Hill's (Jamaica) opinion "direct marine disposal of red mud must not be permitted" [17].

Following the multistage washing of red mud in a series of thickeners (called washers) the underflow slurry of the last washer (fifth to eighth in the row) or mud repulped after filtration is pumped to a storage area. Originally there was no consideration given to the selection of suitable territory. Valleys of touristic interest. areas near communities were selected for this purpose more or less on an economic basis so as to save pumping energy.

However within a short time it was noticed that the caustic liquor pumped to the storage area with the mud penetrated the subsoil and contaminated the underground water. Red mud ponds can occupy huge agricultural areas and have a detrimental effect on plants and trees in the vicinity. On the other hand as red mud settles. the supernatant liquor can be repumped. thus making red mud ponds form an additional washing stage.

In order to eliminate or minimize the penetration of the caustic liquor into the soil the sealing of the subsoil and the dams was undertaken. To reduce penetration of liquor (to reduce the permeability index below 10^{-8} m/s) the following are considered normal plant practice:

- compaction of the upper layer of the soil (suitable only in the case of certain soils and not wholly reliable).
- construction of a clay blanket (a layer of about 0.6 m thick clay with an optimum water content of 18 per cent is able to ensure a permeability of 10^{-9}m/s).
- sealing with plastic foil (mainly in carstic limestone areas where sealing of red mud ponds is sometimes very difficult the area is covered by plastic foils).
- fly ash mixed with gypsum.
- sealing with consolidated red mud (plant tests have shown a permeability of 10^{-8} m/s). The advantage of this method is that the sealing material is available on the spot.

According to [16] lime-stabilized red mud has self-sealing properties as it consolidates. The permeability coefficient may reach 10^{-13} m/s.

It is common to build the first storage area only for a period of 5 years and to build subsequent adjacent ponds (chambers) after a couple of years. This can have two advantages:

First of all, the first chamber will begin to dry as soon as it is filled up and as a consequence of the shrinkage it can be used once again after one-half to one year.

Secondly, the dried red mud itself can be used for the construction of new dams on the inner side of the original, raising the height of the "pond" up to some 30 m depending on the properties of red mud. Red mud can be stabilized by the addition of lime, which increases its hydraulic stability and improves its cohesion.

In order to accelerate the consolidation of red mud ponds VAW (Germany) erects drainage towers within the storage site [16].

A valley situated in the vicinity of the alumina plant can also be used when closed by a barrage. Preliminary tests have to be performed on hydrogeological conditions, permeability of the soil and rocks, seismicity, defects in bedrock, etc. The design has also to meet regulations for the protection of groundwater quality.

The above mentioned two possibilities correspond to the method named DEW (decantation, evaporation) process by Vogt [18]. This means that the water pumped together with the mud to the storage area partly evaporates (depending on climate), and may be partly repumped to the plant after decantation [19].

In another process, named DREW by Vogt (drainage, evaporation) (Kaiser, Gramercy Plant, USA; Alcoa of Australia, Pinjarra, WA) a sand drainage blanket is installed under the red mud disposal area [18, 20]. Water or liquor passing through the sand blanket is collected in pipes and can be repumped to the plant. Red mud is not covered by liquor and due to fissures formed inside it will dry in 0.5 to 2 years after filling.

With the thickened tailings disposal process [21] thickened red mud is sprayed through spigots into the storage area. This method takes into account the topography of the area but may cause dust dispersal problems.

Solar drying of red mud [22] requires a disposal area with a uniform slope. Thickened red mud slurry with 23 to 25 per cent solids is pumped to the top of the area, it flows down and reaches 75 per cent solids in 15 to 20 days, resulting in a dramatic volume shrinkage. Dried red mud is practically unaffected by wetting.

Pioneering work on the storage of red mud in filtered form was carried out by Gebr. Giulini, Ludwigshafen, Germany. Red mud pumped to the storage area after mechanical treatment, containing about 60 per cent solids can be stacked to a height of 20 to 30 m. The same is valid for deep thickened red mud (see later). Though no special sealing is needed, as this quasi-solid red mud does not contaminate the environment, certain precautions are recommended especially in carstic areas where it is advised to lay down a thin sandy clay layer or a plastic foil. Dams can be constructed, if necessary, from the original soil and later on from the solidified red mud.

The advantages of this method are as follows:

- the adhesive moisture of red mud can decrease owing to its shrinkage and formation of fissures to 30 per cent on the spot and can be considered as a highly cohesive soil.
- rainwater does not infiltrate into the stabilized mud. a part evaporates and another part flows off without dissolving (a surrounding ditch is to be built around the disposal area to channel rainwater).
- after filling up a certain disposal area operators can walk on the mud surface after 2 to 3 weeks and machines necessary for recultivation after 4 to 5 months (this means that the recultivation of the area can be started in a short time).
- 4 to 5 times more red mud may be stored in the same area than in the case of storing slurries with supernatant liquor.

When using deep thickeners [23] red mud can be thickened with the aid of synthetic polymers to a 700-800 g/l solids content. These values come close to the concentration of filtered red mud. Alcan's Vaudreuil plant has retrofitted conventional multideck thickeners converting them into deep thickeners [24]. Three of the four rakes of a high, single-deck thickener were eliminated. Red mud is concentrated to 44 per cent solids content with the aid of synthetic flocculants, corresponding to about 630 g/l solids concentration. This thickened slurry can be directly fed to the storage area and will behave like a filtered red mud with all its advantageous characteristics.

The greatest achievement in this respect was realized by Alcoa of Australia, at their Pinjarra plant. A 90 m diameter single compartment deep-thickener was erected in the storage area. One of 75 m diameter is working in the nearby Kwinana plant. Sand is removed by cyclones and wash towers, then synthetic flocculants are added to the feed. The overflow is pumped back to the plant, the rest is directly fed in the form of a high solids slurry to the base drained storage area in shallow layers in order to promote evaporation of water and compaction of mud of up to 65 per cent solids [1].

The advantages are, storage volume is minimized, formation of mud lakes is avoided, it can work for years without serious maintenance, whereas filters have to undergo periodical maintenance. There are no fast moving mechanical parts, no vacuum pumps, no vessels, and the risk of accidents is minimized.

Investment cost is about US$ 1.5 million for a 75 m diameter thickener (Wagerup plant), much less than for filters treating the same quantity of mud ($US 10 million to $US 15 million).

As compared to wet disposal in the opinion of Alcoa of Australia, "overall projected costs for dry disposal remain marginally less than projected costs for continued wet disposal, and environmental impact is very substantially reduced" [1]. Detailed development steps of the above residue disposal system are illustrated in figure IV.

Concerning the recultivation of storage areas 'the final objective is the reintegration and blending of the disposal site into the surrounding landscape' [16].

Dewatering of the red mud area is important as only red mud dried to at least 65 to 70 per cent solids content can support equipment necessary to do the preliminary work [15, 25]. During the 1980s a lot of experimental work was done to select species of plants that grow on red mud. A wide variety of plants (legumes and grass) are known to be alkaline and salt resistant and can grow without the addition of soil or fertilizers. A soil cover of 3 to 10 cm improves germination and survival of tropical pastures and some plant species and the use of fertilizers is also advantageous.

First successes were achieved by growing some grass species. Combinations of grass, legumes and acacia trees are more viable than single species on their own. Further they ameliorate the soil to develop into a natural bushland.

Alcoa of Australia established very successful experiments in cultivation of different vegetables and a variety of cereal crops.

2.2.1.2. Modifications of the alumina manufacturing process to discharge a residue less harmful to the environment

The sodium aluminium hydrosilicate content of the red mud can be partially transformed to calcium aluminium hydrosilicate by the addition of lime during various operations of the Bayer process or as an extra operation connected with it. A part of the chemically bound Na_2O content of the red mud can be recycled and an environmentally less harmful residue is formed with a lower alkali content.

With the addition of lime to the digestion of boehmitic and diasporic bauxites the Na_2O content of the digestion residue can be reduced by 10 to 30 per cent [26]. An atmospheric mud causticizing (around 90 to 100°C) enables the Na_2O content of the mud to be recovered with a yield of about 50 per cent [26, 27]. Carried out under pressure (around 140°C) it can increase the yield to about 65 per cent [27, 28]. Complex causticizing (see figure VII) combines the causticizing of red mud and soda ash [28 to 30]. The hydrothermal treatment of red mud [31] can be carried out at 260 to 300°C. By this process more than 80 per cent of the Na_2O content and 40 to 80 per cent of the Al_2O_3 content of red mud can be recovered.

Bio-hydrometallurgical processing of red mud should also be mentioned. This does not use lime but a microorganism called thiobacillus ferro-oxidans. As a result practically the total Na_2O content, 65 to 70 per cent of the Al_2O_3 content and 25 to 50 per cent of the rare earths can be extracted in the form of sulphate compounds, whereas the Fe_2O_3, TiO_2 and V_2O_5 contents increase by a factor of 1.5 to 2.5 in the extraction residue [32].

Up to the present date only the atmospheric causticizing and the complex causticizing processes are in commercial use.

2.2.1.3. Utilization of red mud in agriculture

Red mud is an alkaline whose pH value changes after a few years. It can be used for improving the fertility of acidic soils. It should not be applied to clay soils since it could lead to chemical imbalance, and in areas, where salines can be found within a distance of 10 km.

Red mud liberates the fixed nutritional elements from the humus. The advantageous effect of microelement content on plants has been demonstrated in Hungarian experiments. Green peppers were grown on a fostering soil composed of peat, red mud and dolomitic limestone. An average crop of 10 kg/m² was attained, compared to the 6 to 6.5 kg/m² for conventional soils. No toxic heavy elements could be detected in the produce. Some plants accumulate various metals found in the red mud, therefore the crops to be grown on soils treated with it have to be carefully selected [33].

2.2.1.4. Utilization of red mud in industry as an additive

A few examples for the use of red mud are given below:

- in road construction, for increasing soil strength [34], or as basic material [35].
- for crude and fine ceramics [36 to 38],
- for manufacturing light construction and heat insulating materials [39, 40].
- for cement production [39 to 42].
- as filler in the rubber industry [39].
- as pigment and for manufacturing paints [39, 43],
- for manufacturing gas purifying (Lux) mass [41, 44, 45],
- as an adsorbent and for manufacturing adsorbents [39],
- for the manufacture of catalysts [39].
- for manufacturing water purifying and settling agents [36, 46].
- as an additive to blast furnaces in the steel industry.

Crude and fine ceramics for cement production as well as additives to blast furnaces could consume the most red mud.

Floor and wall tiles and bricks can be manufactured from red mud after mixing it with various materials to produce proper plasticity. The strength of bricks manufactured in this way exceeds that of those manufactured from conventional materials [36 to 38, 41]. These processes could use the complete production of red mud of a whole alumina plant (especially of smaller ones).

2.2.1.5. Complex waste-free processes for red mud

A number of processes have been described for treating red mud and thereby extracting various metals in the form of salts [39, 47 to 53].

Halogen metallurgy was used for extracting rare metals from previously de-alkalinized red mud [54].

A number of processes intending to utilize not only the iron content but also other useful components (Na_2O, Al_2O_3, TiO_2, V_2O_5, rare metals) of red mud have been developed. Some of them may do this without producing waste. In the course of the processes, iron lumps, liquid iron, steel alloys, slag suitable for manufacturing alumina or cement, fertilizer and rare metals can be obtained [9, 43, 55 to 67].

A process developed in India [43] produces iron oxide and aluminium oxide.

According to a Soviet process [55] (see figure VIII) red mud is subjected to reducing melting to obtain iron and self-disintegrating calcium aluminate slag. Steel can be manufactured from the former, alumina from the latter. The residue of alumina extraction can be used as a raw material for cement manufacturing.

In a Hungarian process [58] the slag is subjected to a lime-soda sintering process and extraction yielding alumina and a residue to be used for cement production.

The process shown in figure IX was developed in the USA [60], it produces first a sinter from red mud in the presence of lime and reductant. Subsequently this sinter is melted, the iron is processed to steel by an oxygen process. The slag can be used for road construction or slag wool can be manufactured from it.

A Yugoslav process [64] produces iron by reducing melting of red mud. Subsequently alumina, fertilizer and a fraction containing rare metals can be obtained by treating the slag with sulphuric acid.

The fullscale realization of any of the above processes would increase the capital costs of an alumina plant by a factor of 4 to 6. The extraction yield on alumina (and the alumina plant's capacity) could be increased by some 10 to 15 per cent and its caustic soda consumption could be reduced by 30 to 70 per cent. However, the value of the by-products (steel, cement, etc) would only be in the same order of magnitude as that of the alumina itself. The energy consumption of the complex processes would be by a factor of 3 to 5 higher than that of the Bayer process.

2.2.2. Waste liquors and other effluents

Waste liquors arise from two main sources:

- overflow of tanks containing alkaline liquors or leaking of some packings, due to lack of technological discipline, faulty maintenance or to operating troubles,
- alkaline or acidic liquors poured on the floor during maintenance of the apparatus and washed up with water.

Elimination of the first type is possible by maintaining technological discipline. Any alkaline waste liquor or effluent has to be analyzed for soda content and returned to the process. Soda concentration can increase and must be regularly monitored.

The floors of alumina factory units have to be constructed of concrete (without fissures), have about a 3 per cent slope to collect waste liquors in sumps. Separations between concrete floor pieces have to be filled by bitumen or plastics. The more collecting sumps are installed, the better, as it makes possible a regular washing of the floor.

As regards acidic liquors (mostly wastes after acidic cleaning of digesters, evaporators and other equipment), these have to be neutralized after the cleaning process is finished, and the salt containing solution has to be pumped to the red mud pond.

2.2.?. *Dust*

Bauxite dust concentrations should not exceed 2 mg/m^3. Dust protection can be provided by wetting, covering belt conveyors and exhausting the dust by collectors. Exhausted dust is concentrated in cyclones or multicyclones and then fed to the wet bauxite grinding operation.

Alumina dust is formed in calcining kilns from where it can be separated by the aid of cyclones and electrostatic precipitators, as well as dust collectors. Alumina dust concentrations should not exceed 2 mg/m^3.

Fluid-flash calcining kilns with high calcination rates may cause a breakage of the alumina particles and though the granulometry as a whole corresponds to general prescriptions (less than 10 per cent -44 μm), submicronic particles with sharp edges can cause lung inflammation.

In the case of calcining limestone, or simply adding lime to given points of the process the same precautions have to be taken, as in the case of fine-grained alumina, keeping in mind that the health hazard connected with burnt lime dust is much higher. Therefore, its concentration should not exceed 1 mg/m^3 in the air. Lime used for control filtration of pregnant liquor can be substituted by lime hydrate ($Ca(OH)_2$), the handling of which is much less dangerous.

3. BARRIERS

3.1. BARRIERS TO MORE EFFICIENT RESOURCE UTILIZATION

3.1.1. *Bauxite*

Though most alumina plants extract practically all available Al_2O_3-content of the processed bauxite (technical barrier), some of the older ones, expecially in developing countries leave up to 10 to 15 per cent of it undigested. A more complete digestion would require better facilities (suitable for the application of a higher digestion temperature) and a more sophisticated process control system. Both of them involve high capital costs (US$ 10 to 100 million depending on the capacity of the plant) and are an economic barrier. The replacement of worn-out equipment after 20 to 30 years of operation gives a good opportunity for this kind of modernization. The digestion systems of the Hungarian alumina plants were replaced by more modern ones resulting in the improvement of the extraction yield by 2 to 3 per cent (compared to the theoretical value). Similar changes are overdue in the older alumina plants of China, India and some other developing countries.

Significant improvement could also be attained by better operating techniques involving more frequent chemical analyses. The workforce must be encouraged to apply improved work methods especially for laboratory personnel. Where the laboratory is not directly subject to plant management, some degradation of control methods may be seen.

3.1.2. *Caustic soda, burnt lime*

As already mentioned in section 2.1.2., 1 or 2 per cent of the caustic soda consumption could be saved by more careful operation and maintenance. For example, in the case where an operator is reluctant to wash the floor if nobody is available from the clean-up workforce, etc. clearly defined work assignments could be established. Economic barriers (capital and/or energy costs) can limit the more efficient washing of red mud. Quite often social barriers prevent alumina plant improvements. Modern lime burning facilities, even where economic considerations support the investment, cannot be set up because a number of independent small lime-burning plants would go bankrupt and their employees lose their jobs.

The use of burnt lime for reducing caustic soda losses (mud causticizing, complex causticizing, etc.) requires special operating and analytical attention. The processes are usually profitable only within a narrow range. Insufficient amounts of lime do not have the expected effect, too much may cause extra alumina losses. Reluctance to pay the required attention to these processes (especially during the afternoon and night shifts) can nullify all positive results of the causticizing. Workforce training and incentives are essential.

3.1.3. *Water*

Some alumina plants tend to waste water. The barriers to the efficient use of this natural resource are economic (it is frequently cheaper to use freshwater for various purposes than to recycle it in closed circuits) and often institutional management, worker attitudes and faulty practices play a role.

3.1.4. *Energy*

The largest saving potential is in the field of energy consumption. Most saving measures require large capital investment (heat exhangers, etc. costing millions of US dollars for medium-size alumina plants). This is an economic barrier to the realization of optimum energy usage. Efficient processes developed by some major aluminium producers are offered at high cost (technical barrier - typical know-how fees amount to US dollars 1 or 2 million). Further, negligent operation and maintenance can cause the highest losses.

Some potential solutions (such as nuclear energy for heating) require extensive and costly research and development efforts. Even the major producers cannot afford it (technical and economic barriers) and have to wait until the problems that make the new technologies affordable are worked out.

3.2. BARRIERS TO REDUCING RESIDUAL DISCHARGES OR THEIR ENVIRONMENTAL IMPACT

3.2.1. *Bauxite residue (red mud)*

There are environmentally sustainable solutions for red mud disposal and storage - dry stacking of filtered or 'deep-thickened' red mud - see section

2.2.1.1. The establishment of a mud filtration unit, however, requires a significant amount of capital (deep thickeners are less expensive) and it is usually difficult to justify because the savings of caustic soda are relatively small. In the case of a new plant a filtration unit can replace three conventional mud washing stages, and so compensate for 70 to 80 per cent of the extra costs. In existing plants the required number of washing stages is available, so this compensating effect can only be exploited if the capacity of the plant is significantly expanded.

Even less expensive solutions, like replacing red mud transportation by trucks to the storage area with the installation of a pipeline can have social disadvantages (a number of truck drivers might lose their jobs).

Though the chemical treatment (causticizing, etc.) of red mud reduces its alkalinity and so its negative environmental impact, the amount of mud increases in this process has an opposite effect.

The utilization of red mud in agriculture (see section 2.2.1.3.) seems very promising, but the costs of mud transportation limit the area where it can be economically exploited.

The economic utilization of red mud as additive in various industries (see section 2.2.1.4.) is limited by its relatively high water content compared to the natural raw materials (e.g. making bricks from red mud requires more energy than from natural clay because of its higher water content).

A few percents of red mud can be economically added to the feed of blast furnaces, however, its Na_2O content leads to a premature wear-out of their linings.

The complex waste-free processes of red mud processing (see section 2.2.1.5.) have the disadvantage that they are very expensive and usually require much more energy than if all products were made of their natural raw materials (e.g. steel from iron ore, caustic soda from sodium chloride and alumina from bauxite). The extra energy required would mean added pollution (acid rain, etc.) and increase the threat of global warming. With this in mind the dumping of a relatively harmless by-product (digestion residue), especially if done in an environmentally sustainable manner, seems to be more acceptable.

3.2.2. Waste liquors and other effluents, dust, stack gases

In order to eliminate the contamination caused by waste liquors and other effluents a very strict operating and maintenance regime has to be maintained. This runs usually into institutional barriers. Another possible solution, the establishment of completely closed systems, is quite expensive.

Dust can be most efficiently controlled by collectors and similar devices, however, these are quite expensive. Proper housekeeping can help to improve the situation but it requires effort.

Contamination caused by stack gases can be reduced by using cleaner fuels (natural gas instead of coal and fuel oil). In some places this is technically impossible, in others very expensive, and the CO_2 problem would not be eliminated. The proper cleaning of the stack gases is also an economic problem, and some solutions have still to be found (e.g. there is no solution for eliminating the SO_2 content of the flue gas of the calciners, if oil fired).

4. INDUSTRY

About a quarter of a century has passed since developed countries began to pay serious attention to the problems of environmental protection and the suspected harm modern industry does to the environment. Developing countries lag at least a decade behind them in this respect. This means that in the first alumina plants set up in these countries (Jamaica. India. Guyana. Surinam. Brazil, China, Eastern Europe) the problems of environmental protection were neglected. Though most of these plants have since made serious efforts to improve this situation, it is very costly and difficult. The large alumina plants set up recently with technical help and in some cases with the active participation of one or another major aluminium producer (Jamalco in Jamaica, Interalumina in Venezuela, Alumar in Brazil, Nalco in India) are much better in respect of environmental consciousness. Several open-cut bauxite mines were properly rehabilitated shortly after their exploitation. The same applies to some red mud storage areas. However, most of them are still left unsightly in some cases and as serious sources of pollution in others. Power plants belonging to alumina plants are usually less modern and lag behind the best in the electricity generating industry especially as far as atmospheric contamination is concerned. Some of them are slowly catching up.

5. GOVERNMENT

Developing countries rarely adopt strict limits for industrial pollution through lack of information and partly to attract industrial projects, which would be more expensive in developed countries through meeting environmental recommendations. A number of developing countries has already started to consider measures for reduction of pollution caused by various industries and among them alumina plants will also have to comply.

It is very important that the governments or governmental agencies take into consideration the difficulties connected with introducing very strict environmental rules to old and less efficient plants. The full impact of suddenly introducing very strict rules for every aspect of their operation (bauxite mining, red mud disposal, stack gases, effluents, etc.) could quickly bring these plants to a halt, especially during periods, when the price of alumina is low. This seems to be the case at present and for the next 5 to 6 years. Such action could lead to the sudden loss of hundreds or even thousands of jobs. Governments and their agencies should analyse what extra costs these plants could bear, and what priorities should be set up for pollution abatement. For example, if a nearby river were strongly polluted, the emphasis should be put on the effluents and red mud disposal; if atmospheric pollution were the greatest problem, stack gases should be treated first of all. Of course, the other aspects should not be neglected either. Breathing space should be left for the plants. In the case of setting up new plants (which will not occur too often during this decade) or significant expansion of old ones the strategy should be to recommend environmental rules prevailing in the developed countries. A compromise for expanded old plants could be an agreement that any pollutant emissions should not increase.

6. INTERNATIONAL CO-OPERATION

Various agencies of the United Nations, first of all UNIDO and UNEP, have made serious efforts towards pollution abatement and environmental protection. A few examples of these efforts are:

Organization	*Title*	*Place (where applicable)*	*Date*
UNEP	Guidelines for the Environmental Management of Alumina Production		1984
UNEP/UNIDO	Workshop on the Environmental Aspects of Alumina Production	Paris	July 1981
UNIDO sponsored	Study on the Disposal and Utilization of Bauxite Residues	Vienna	1980
UNIDO	Expert Workshop on Hazardous Waste Management Industrial Safety and Energy Planning		June 1987
UNIDO (E.T. Balazs contribution)	Projects and Achievements in Preparing Industrial Scale Utilization of Red Mud Bauxite Residues		
UNIDO Project	Techno-Economic Study for Industrial Utilization of Red Mud Waste from Bauxite Processing in Korba (India)		
UNIDO sponsored	World Review on Environmental Aspects and Protection in the Bauxite/Alumina/Aluminium Industry (Training Kit)		1986
UNIDO sponsored (F. Puskas, S. Batri)	Feasibility Study for the Utilization of Brown Mud of Shandong Aluminium Works as Building Materials		1985
UNIDO sponsored (F. Puskas)	Techno-Economic Study for Industrial Utilization of Red Mud Waste from Bauxite Processing in India		1986

Organization	*Title*	*Place (where applicable)*	*Date*
UNIDO sponsored (F. Puskas, A. Geszti)	Pilot Scale Testing of Representative Samples of Bauxite Residue (Red Mud) for Profitable Utilization in the Building Materials Industry		1981
UNIDO sponsored	A new Approach to Economic Utilization of Bauxite Residues		1986

Some International Organizations of the bauxite/alumina/aluminium industries like IBA (International Bauxite Association) and IPAI (International Primary Aluminium Institute) also play a very significant role in the exchange of information among the producers, including the field of pollution abatement and environmental protection. IBA's Quarterly News quite often carries articles dealing with environmental problems.

There is also significant dissemination of information, transfer of know-how and technology from the major aluminium companies to their subsidiaries in developing countries. As information on environmental protection is not a secret, good solutions are shown to every visitor and leaflets are printed and distributed.

7. CONCLUSIONS

The most important ways of reducing the negative environmental impact of the alumina industry are the following:

(a) Reduction of the amount of natural resources (primarily energy) consumed per unit amount of alumina manufactured.

(b) Reduction of the residual discharges (effluents, dust, stack gases) per unit amount of alumina manufactured.

(c) Environmentally sustainable discharge and storage of digestion residue (dry stacking of red mud), recultivation of the filled-up storage areas.

The above can be realized by

(a) better operational and maintenance practices (e.g. preventing leakages, proper heat insulation, maintaining the prescribed parameters of the process, etc.),

(b) economically reasonable measures for efficient resource utilization, pollution control and waste disposal (e.g. increasing the number and size of heat exchangers, washing stages, etc.), and

(c) measures necessary to meet environmental requirements conforming with the generic ESID norms (e.g. installing dust collectors, scrubbers, dust filters, red mud filters or deep thickeners, recultivating mined-out areas and filled-up mud disposal areas, etc.) even if costly.

The ways and measures are arranged in logical order in table 4. As can be seen, priorities are slightly different in the case of existing plants, those plants being expanded and new alumina plants. In some cases only marginal differences may decide whether a certain measure can be classified to be economically reasonable or just necessary in order to meet environmental requirements.

In general, it can be said that whereas modifications to existing old plants are relatively costly (they may reach even 30 to 50 per cent of the original investment costs), those incorporated in the engineering designs of a new plant (or of a significant expansion of an existing one) do not increase the capital costs by more than 5 to 10 per cent. At the same time the latter usually enable such savings to be made (both in related investment and operating costs) that they can make the application of environmentally sustainable solutions profitable.

TABLE 1. LOCATION OF ALUMINA PLANTS WORLDWIDE IN 1989 (BY REGION) AND THEIR CAPACITIES (ktpa)

Developed Countries

Western Europe

Gardianne (France) - 700
Stade (Germany) - 600
Bergheim (Germany) - 350*
Ludwigshafen (Germany) - 130*
Schwandorf (Germany) - 200*
St. Nikolas (Greece) - 600
Shannon (Ireland) - 800
Porto Scuso (Italy) - 700
Porto Marghera (Italy) - 350*
San Ciprian (Spain) - 800
Burntisland (UK) - 100*
Sub-total WEu - 5330

North America

Arvida (Canada) - 1,200
Bauxite (USA) - 300*
Point Comfort (USA) - 2,150
Baton Rouge (USA) - 900*
Gramercy (USA) - 700
Corpus Christi (USA) - 1,400
Burnside (USA) - 500
Sub-total NAm - 7,150

Austrialia

Gladstone (Q) - 2,800
Gove (NT) - 1,400
Kwinana (WA) - 1,600
Pinjarra (WA) - 2,800
Wagerup (WA) - 650
Worsley (WA) - 1,100
Sub-total Au - 10,350

Japan

Yokohama - 600*
Shimizu - 500*
Kikumoto - 750*
Sub-total J - 1,850

Soviet Union

Achinsk - 800
Bogoslovsk - 400
Boksitogorsk - 160
Kamensk Uralsky - 400
Nikolaev - 1,000
Pavlodar - 500
Pikalevo - 500
Kirovabad - 250
Volkhov - 80
Zaporozhie - 250
Sub-total SU - 4,340

Total, Developed Countries 29,020

Developing Countries

Eastern Europe

Lauta (Germany) - 60***
Ziar nad Hronom (Czechoslovakia) - 200
Ajka (Hungary) - 470
Almasfuzito (Hungary) - 330
Mosonmagyarovar (Hungary) - 80*
Oradea (Romania) - 240
Tulcea (Romania) - 400
Zvornik (Yugoslavia) - 600
Mostar (Yugoslavia) - 280
Titograd (Yugoslavia) - 200
Kidricevo (Yugoslavia) - 80*
Sub-total EEu - 2940

South America, Caribbean

Ouro Preto (Brazil) - 150
Pocos de Caldas (Brazil) - 250
Sorocaba (Brazil) - 250
Sao Luis (Brazil) - 500
Ewarton (Jamaica) - 550
Kirkwine (Jamaica) - 800
Clarendon (Jamaica) - 800
Alpart (Jamaica) - 1,200**
Paranam (Surinam) - 1,400
Interalumina (Venezuela) - 1,300
Sub-total SAm & Carr. - 6,950

Africa

Friguia (Guinea) - 600
Sub-total Af - 600

China

Fu Shun - 400
Zheng Zhou - 400
Shan Dong - 200
Sub-total Ch - 1,000

South Asia

Korba (India) - 200
Renukoot (India) - 300
Belgaum (India) - 160
Muri (India) - 70
Mettur (India) - 60
Damanjodi (India) - 800
Seydisehir (Turkey) - 200
Sub-total SAs - 1,790

Total, Developing Countries - 13,280

* Produces only or mostly non-metallurgical alumina and/or chemical products, usually with a capacity significantly lower than the nominal [illegible].

** Restarted as a result of the increased demand of 1988/89 after a stoppage of several years.

***Closed in 1990.

TABLE 2. CHEMICAL COMPOSITION OF DIGESTION RESIDUES OF DIFFERENT TYPES OF BAUXITE

Digestion temperature:	Boké (Guinea) 24o°C	Weipa (Australia) 24o°C	Trombetas (Brazil) 143°C	South Manch. (Jamaica) 246°C	Darling Range (Australia) 143°C	Iszka (Hungary) 24o°C	Parnasse (Greece) 26o°C
Components %							
Al_2O_3	14.0	17.2	13.0	10.7	14.9	14.4	13.o
SiO_2	7.0	15.0	12.9	3.0	42.6	12.5	12.o
Fe_2O_3	32.1	36.0	52.1	61.9	28.0	38.0	41.o
TiO_2	27.4	12.0	4.2	8.1	2.o	5.5	6.2
L.O.I.	10.0	7.3	6.4	8.4	6.5	9.6	7.1
Na_2O	4.0	9.0	9.0	2.3	1.2	7.5	7.5
CaO	3.2	-	1.4	2.8	2.4	7.6	1o.9
Others	2.3	3.5	1.0	2.8	2.4	4.9	2.3

TABLE 3. MINERALOGICAL COMPOSITION OF DIGESTION RESIDUES OF DIFFERENT TYPES OF BAUXITE

Components %	Boké	Weipa	Trombetas	South Manch.	Darling Range	Iszka	Parnasse
Gibbsite	-	33.0	-	33.0	5.6	-	-
Hematite	20.0	3.5	38.0	3.5	14.5	33.0	38.0
Goethite	16.0	18.0	19.0	18.0	14.6	6.0	1.0
Cancrinite						22.0	16.0
SAHS	21.0	27.0	27.0	27.0	5.4		-
Sodalite	-	-	-	-	-	10.0	10.0
Illite	-	2.0	-	2.0	4.7	-	-
Boehmite	5.0	2.0	0.6	2.0	3.5	0.8	0.6
Diaspore	1.2	-	1.2	-	2.5	0.7	0.6
Ca-Al-Si	-	-	-	-	1.7	12.5	10.0
$CaTiO_3$	2.0	-	1.5	-	-	7.0	10.5
Calcite	4.6	0.5	1.4	0.5	2.3	3.0	3.6
Quartz	-	6.0	2.2	6.0	37.1	-	-
Anatase	7.0	2.0	2.5	2.0	1.0	-	-
Rutile	19.0	6.0	0.8	6.0	-	-	-
Na-titanates	2.0	-	-	-	0.6	-	-
Magnetite	-	-	-	-	1.3	-	-
Chamosite	-	-	-	-	-	-	6.0
Ilmenite	-	-	-	-	1.0	-	-
Others	2.2	-	5.8		3.4	5.0	3.7

TABLE 4. WAYS AND MEASURES FOR REDUCING THE NEGATIVE ENVIRONMENTAL IMPACT OF THE ALUMINA MANUFACTURING INDUSTRY

Ways/Measures	Reduction of natural resources consumed	Reduction of residual discharges	Environmentally sustainable discharge and storage of red mud, recultivation of sites
Better operational and maintenance practices.	Preventing leakages of caustic liquors, steam and condensate. Reducing dusting of bauxite, alumina and lime Improving the quality of lime burnt in own facilities.	Preventing leakages of caustic liquor. Reducing dusting of bauxite, alumina and lime.	Preventing leakages of red mud pipelines. Careful trucking of filtered red mud (in plants using this method of disposal).
Economically reasonable measures for efficent resource utilization, pollution control and waste disposal.	Higher digestion temperature for better Al_2O_3 extraction yield and heat economy (expanded and new plants). Introducing deep thickeners and/or red mud filtration for better mud washing (expanded and new plants). Use of stationary calciners (expanded and new plants) for better fuel economy. Reconstruction of old calciners for better fuel economy (old plants). Setting up own lime burning facilities. Increasing the liquor productivity for better heat economy. Installing more efficient boilers (expanded and new plants).	Installing more efficient and less polluting boilers (expanded and new plants). Introducing deep thickeners and/or red mud filtration for better mud washing (expanded and new plants). Use of geothermal energy for covering the secondary heat requirements (if available). Setting up new plants near geothermal heat sources.	Introducing deep thickeners and/or red mud filtration to obtain a red mud that can be stored in an environmentally sustainable form (dry stacking) (expanded and new plants).
Unprofitable measures necessary to meet environmental requirements (ESID norms).	Introducing deep thickeners and/or red mud filtration for better mud washing (old alumina plants). Installing more efficent boilers for heat economy. Complex processing (or other utilization) of red mud (might also be profitable under certain circumstances.	Increasing the height of the factory chimneys for better distribution of stack gases. Replacing the boilers with newer types with lower emission figures (old plants). Introducing deep thickeners and/or red mud filtration for better mud washing (old plants). Use of nuclear energy for covering the secondary heat requirements (future solution).	Introducing deep thickness and/or red mud filtration to obtain a red mud that can be stored in an environmentally sustainable form (dry stacking) (old plants). Recultivation of filled-up mud lakes and disposal areas.

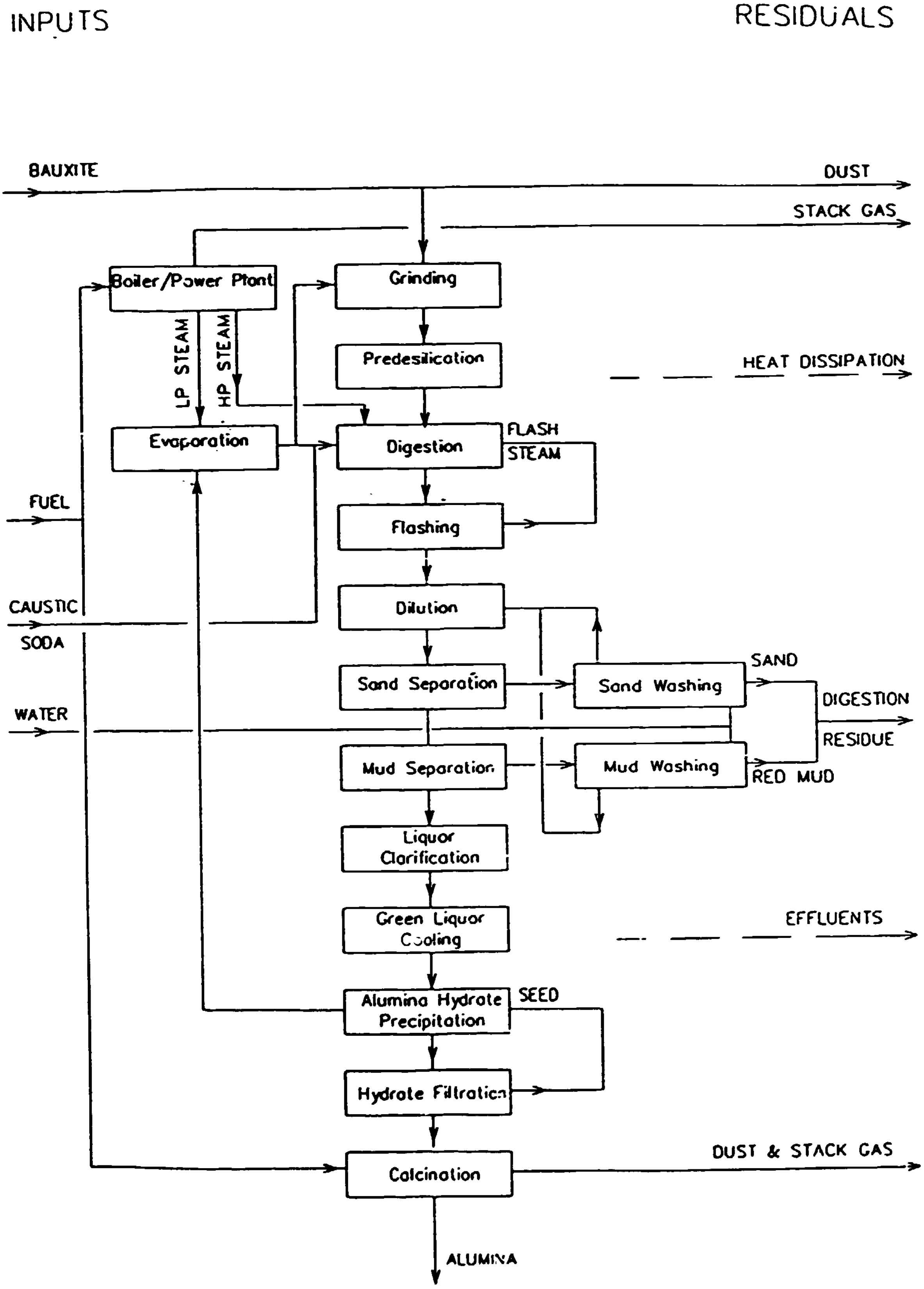


Figure I BLOCK DIAGRAM OF THE BAYER PROCESS

Figure II Chemical composition of digestion residues of different types of bauxite

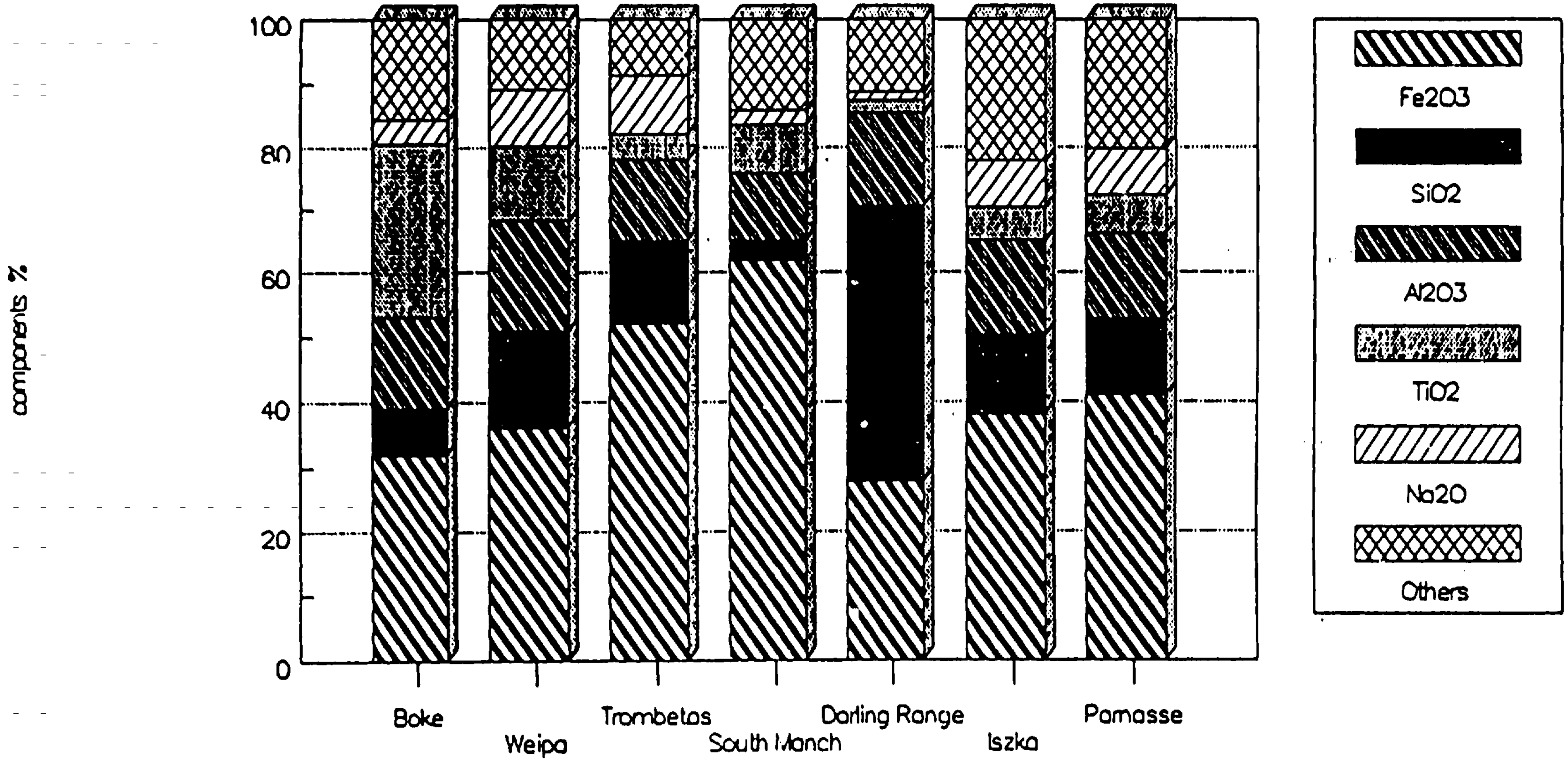
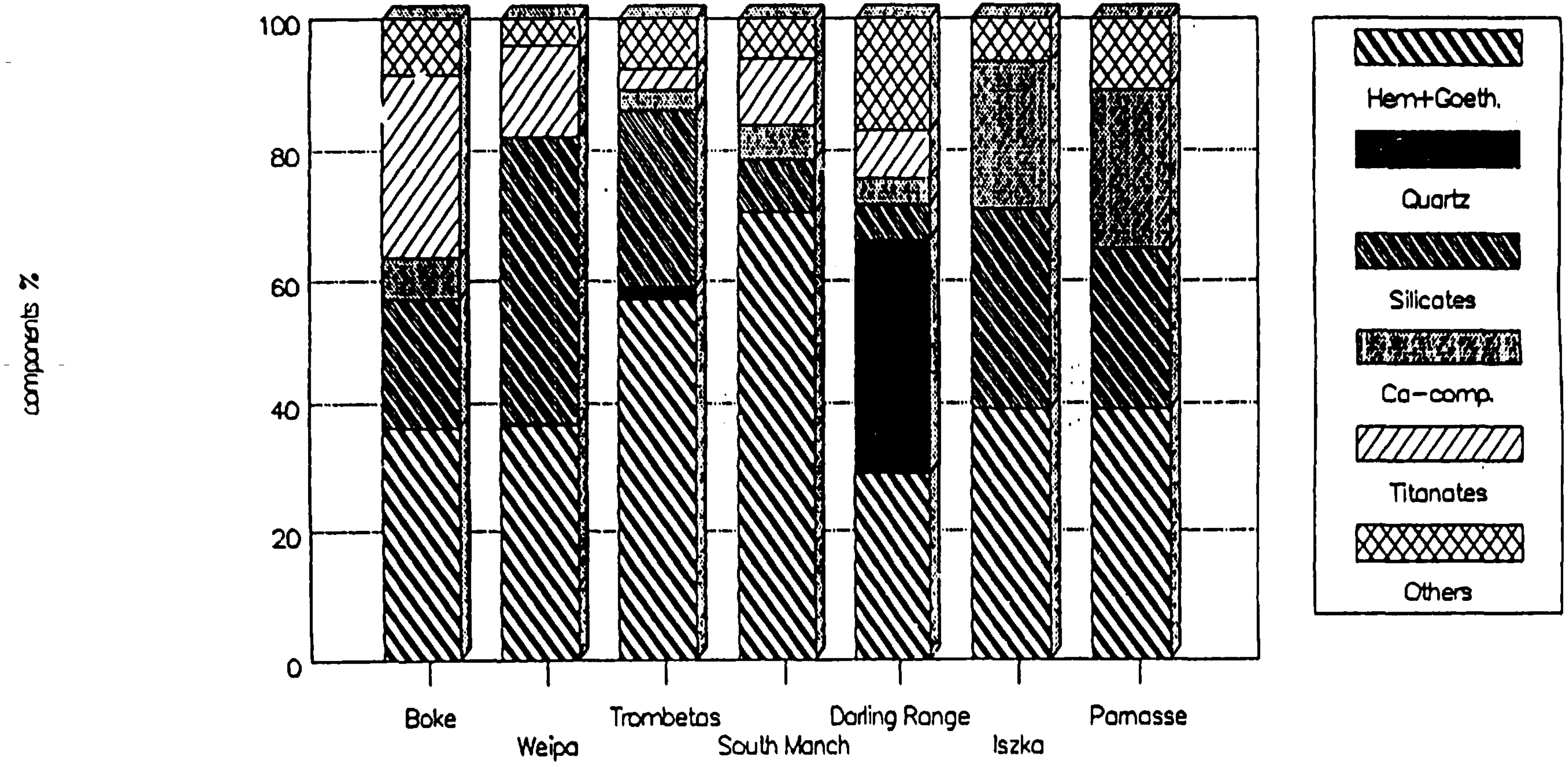


Figure III Mineralogical composition of digestion residues of different types of bauxite



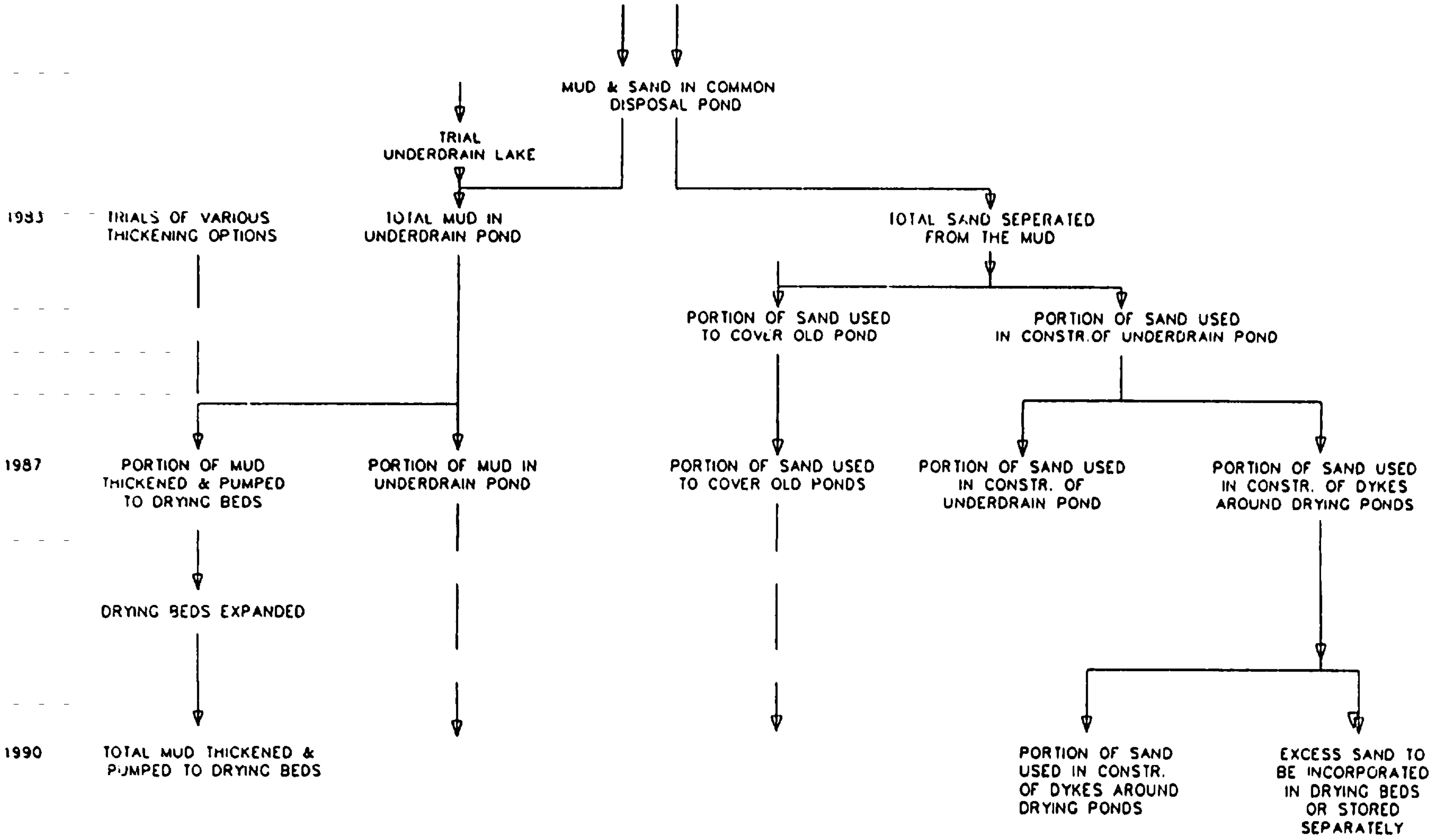
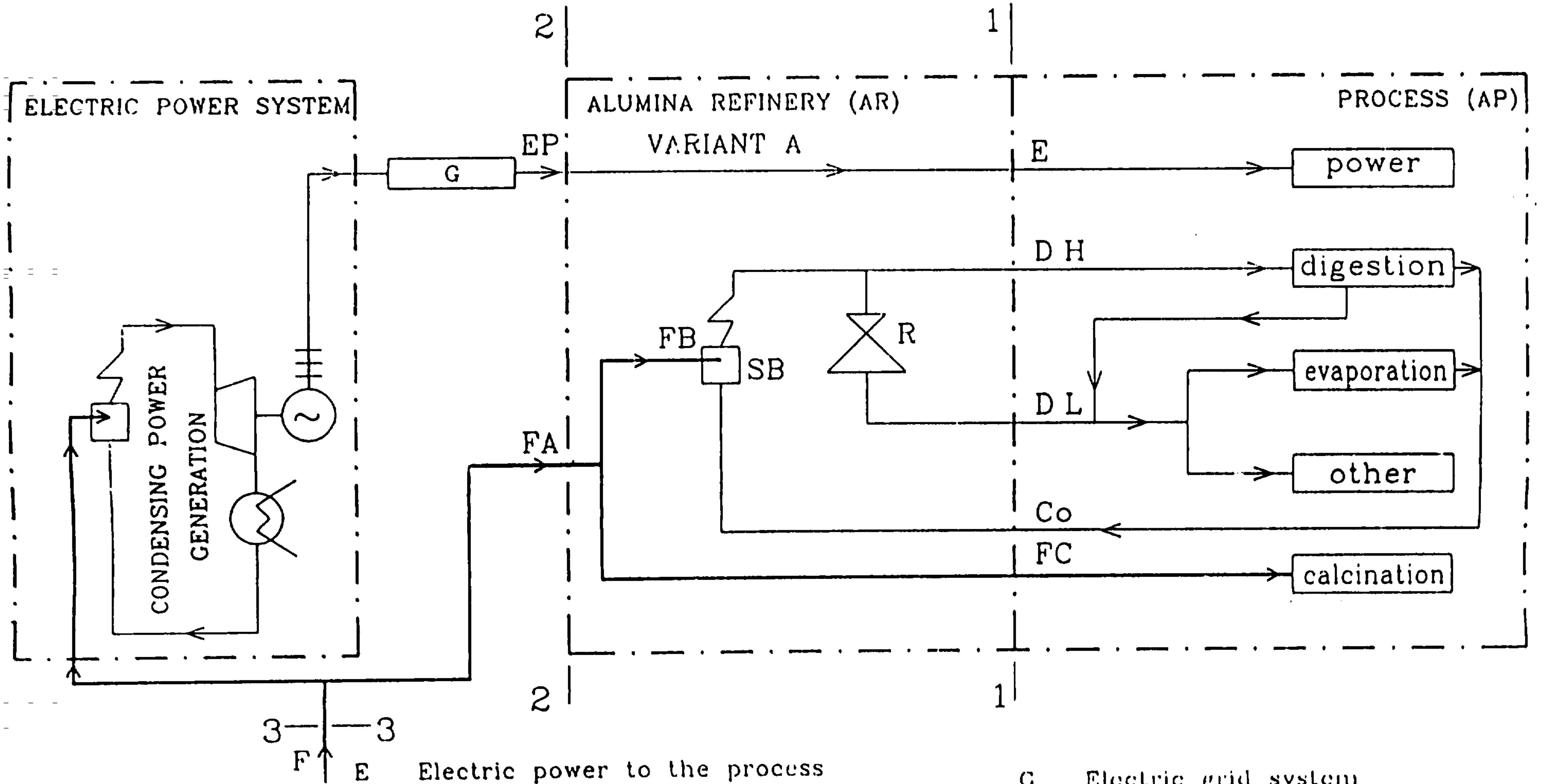


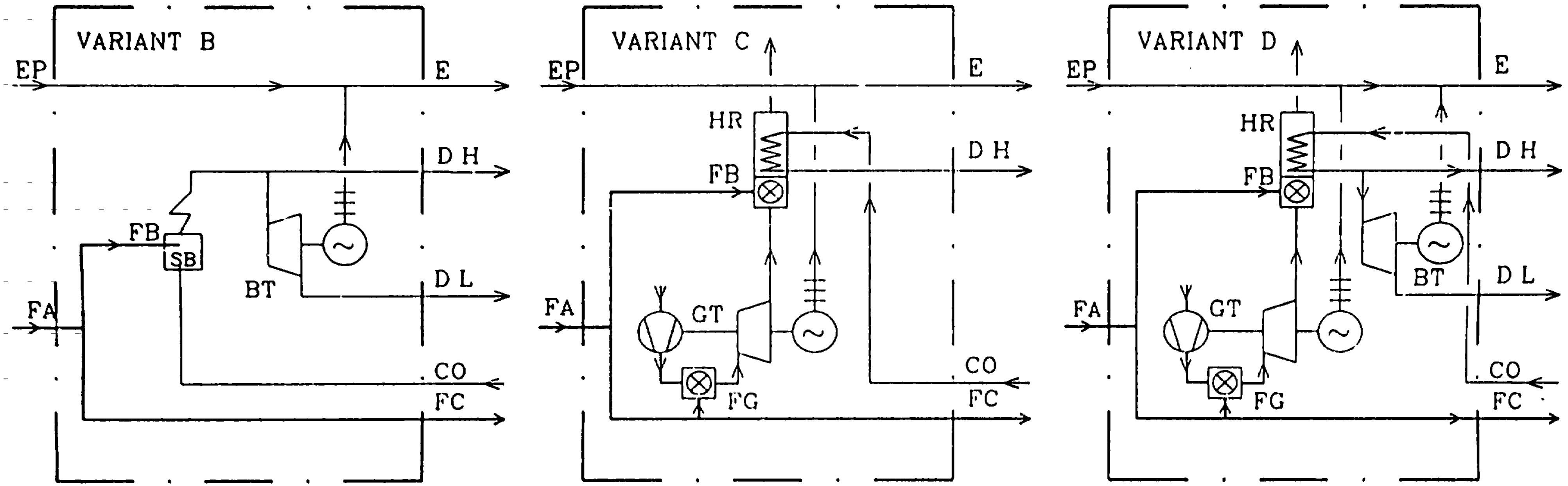
Figure IV DEVELOPMENTS IN RESIDUE DISPOSAL
(Fig. 3 of [1])



E	Electric power to the process
DH	High temperature steam
DL	Low temperature steam
CO	Condensate
FC	Fuel to calcination
FA	Fuel to AR
EP	Purchased electric power to AP
F	Fuel equivalent of the alumina production

G	Electric grid system
R	Reductor
SB	Steam boiler
1	Balance line – process
2	Balance line – alumina refinery
3	Balance line – production system

Figure V ENERGY FLOW – SEPARATE HEAT&POWER SUPPLY



E	Electric power to the process
DH	High temperature steam
DL	Low temperature steam
CO	Condensate
FC	Fuel to calcination
FA	Fuel to AR
EP	Purchased electric power to AP

BT	Back pressure turbine
SB	Steam boiler
GT	Gasturbine
FG	Fuel to GT
FB	Fuel to HR
HR	Heat recovery boiler

Figure VI ENERGY SYSTEMS

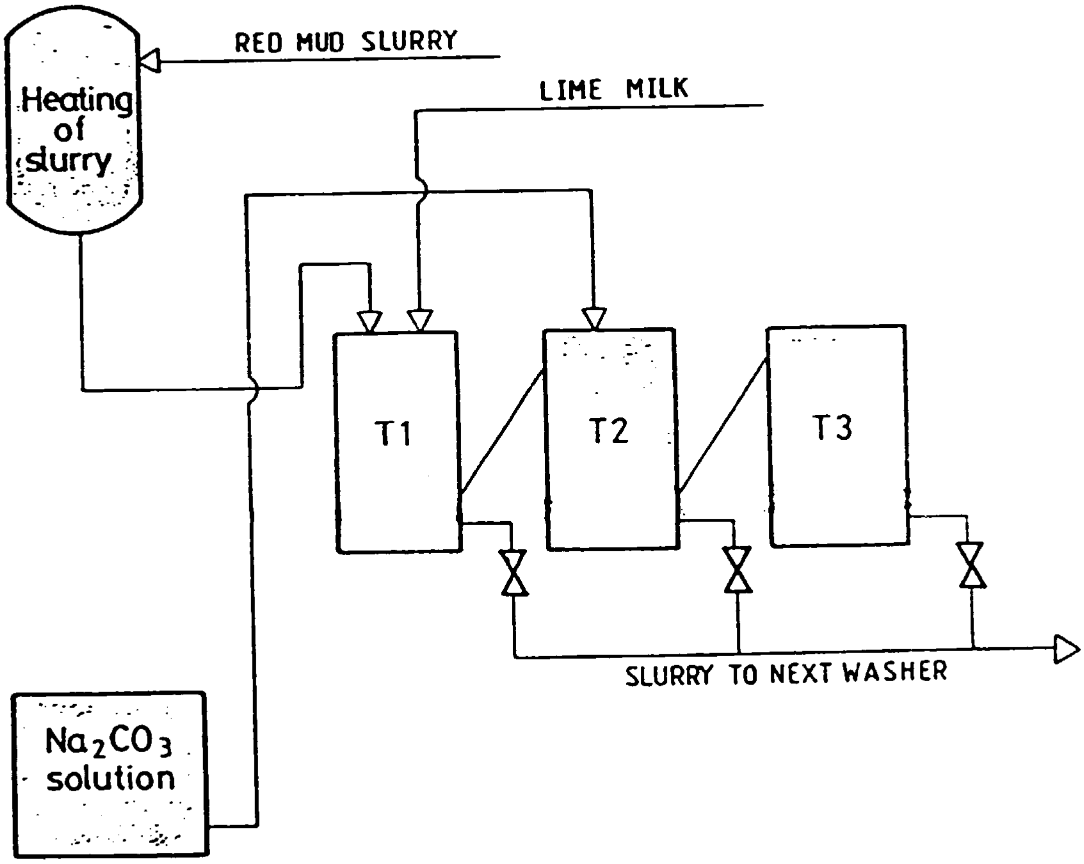


Figure VII

Flow-sheet of complex causticizing

(Fig. 5.1 of [9])

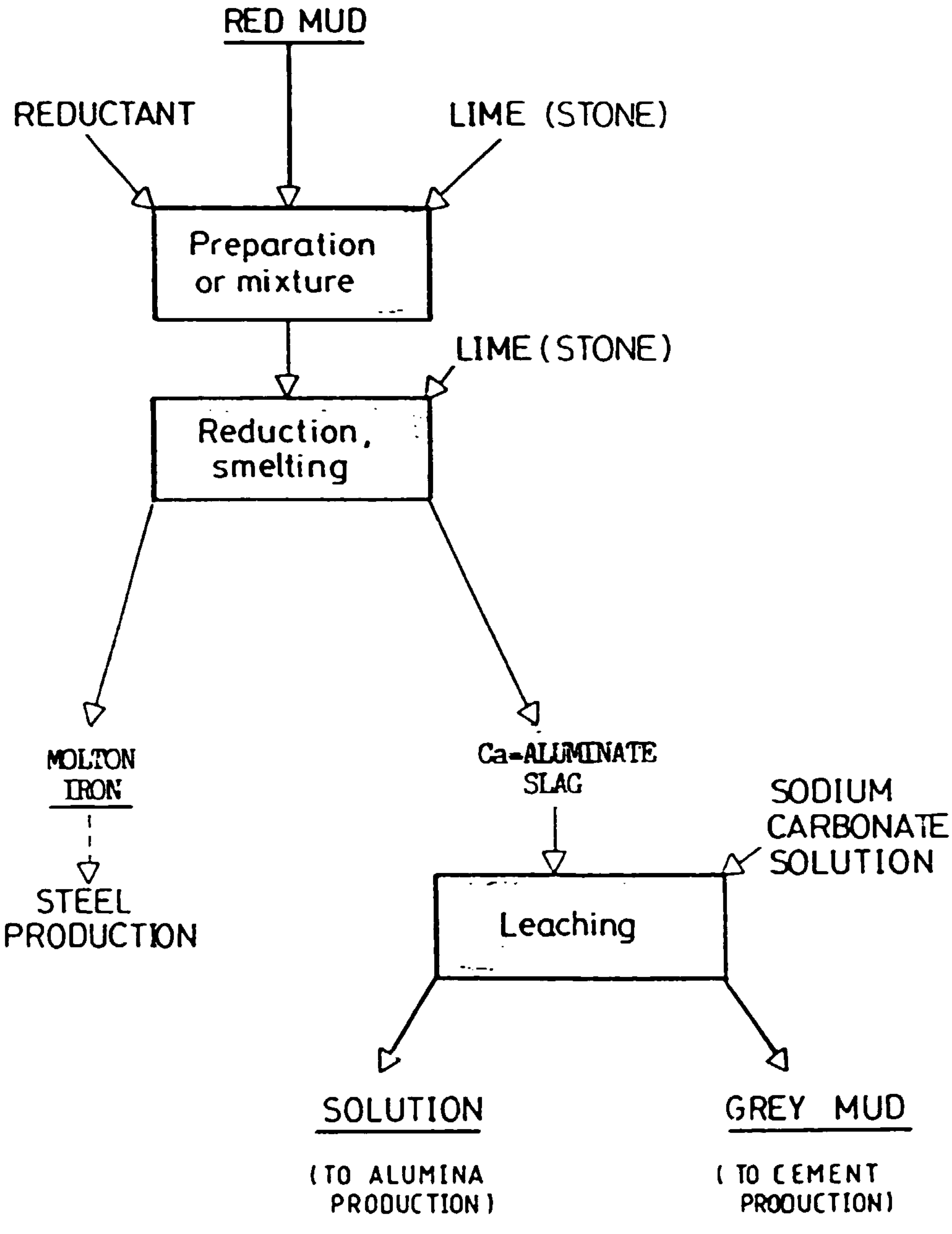


Figure VIII

Production of molten iron (steel), alumina and cement from red mud (Fig.5.1 of [9])

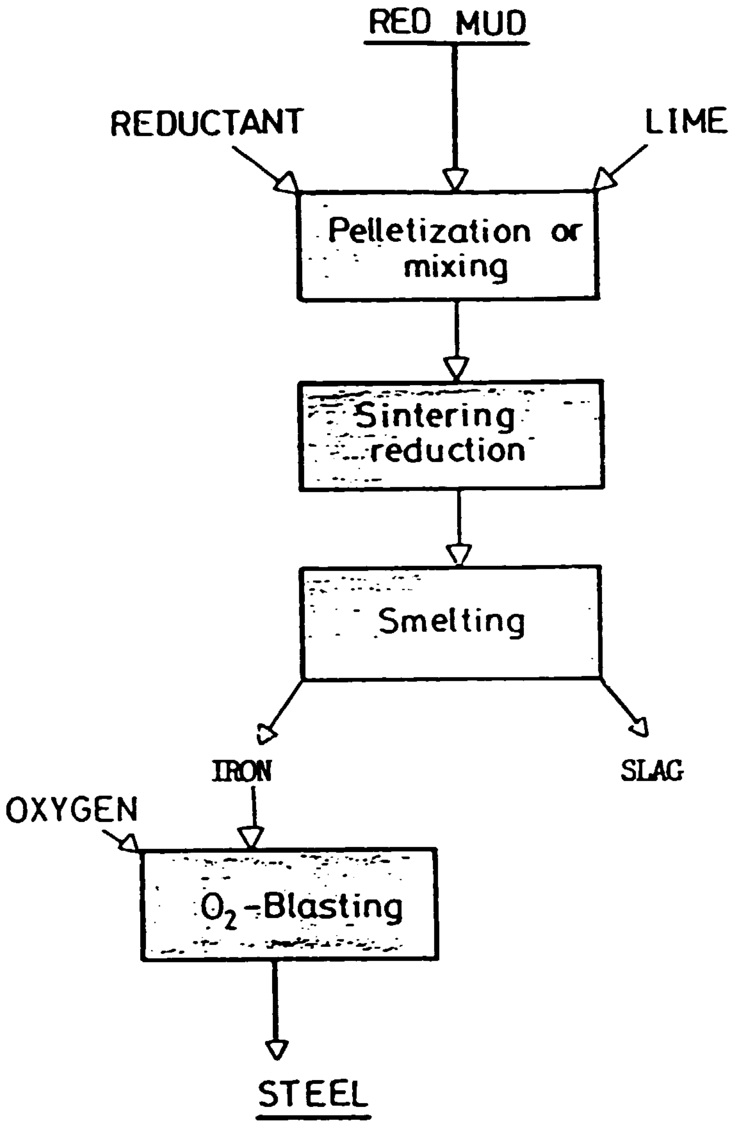


Figure IX

Production of steel from red mud (Fig.5.8 of [9])

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ALUMINA INDUSTRY

Case study No. 2

Executive Summary

Prepared by

the UNIDO Secretariat

V.91-28185

The Alumina Industry: Overview

Raw material for the worldwide-used Hall Heroult aluminium smelting process is alumina, which is a white crystalline, dustlike material consisting mainly of aluminium oxide. During the last 17 years, the annual amount produced have varied between 30 and 37 million tonnes. Over this same period the industry has shifted from North America and Europe to Australia and Latin America. As of 1989, worldwide there were 69 aluminium plants, with 32 in developing countries.

The shift in production capacity to countries with large bauxite reserves will continue. Practically no expansion can be expected in North America, Europe or Japan and some of their present plants may be closed or converted to produce non-metallurgical alumina. The regions best suited for expansion and new plants are in South America (Brazil and Venezuela), India and Australia, where large bauxite deposits are accompanied by abundant sources of energy, (hydropower in South America, coal in India, coal and natural gas in Australia), required for smelting alumina to primary aluminium.

In the Bayer process, bauxite is digested with hot, strong.alkali solution (generally sodium hydroxide) to form a solution of sodium aluminate, and a mud residue (commonly referred to as "red mud"). The amount of red mud varies between 0.3 and 2 tonnes dry residue per tonne of alumina depending on the quality (chemical and mineralogical composition) of the processed bauxite. The annual amount of this waste produced worldwide varies between 30 and 40 million tonnes (calculated as dry material) and constitutes the main environmental hazard of the alumina industry.

Cleaner Production Options

Bauxite Processing

The available Al_2O_3 content of processed bauxites is 98 to 99 per cent and of this 95 to 96 per cent is obtained as product. There is very little scope to further improve these high yields.

Use of Caustic soda and burnt lime

Most of the caustic soda used by alumina plants is bound to the silica content of the bauxite and left in the digestion residue. This cannot be saved by conventional methods. Improved maintenance (better packing, immediate repair of leaking equipment, frequent washing of the floor, etc.) can save 1 or 2 per cent of the caustic soda consumption. Widespread use of recently developed deep thickeners could result in better washing of the red mud.

Burnt lime can be better utilized, if it is of a better quality and if its active CaO content is leached more efficiently. Modern plants usually produce their own burnt lime (this is also an advantage from the environmental point of view, because the lime can be handled in a closed system.

Water

Alumina plants are flexible as far as water consumption is concerned. If necessary they can operate with 2 to 3 m^3 of water per tonne of alumina. Such low consumption figures can only be attained at the cost of a relatively high capital investment (closed water circuits, etc.) and increased maintenance and worker awareness.

Energy use

The possibilities for reducing the harmful environmental emissions resulting from the energy use can be found in two main areas:

(a) the alumina manufacturing process
(b) the energy supply system serving the above process

The primary heat requirement of alumina plants is for calcining precipitated hydrate to alumina. Conventional rotary kilns used 5 GJ/t or more until about 1960. Recently a number of these have been reconstructed by adding cyclones at both ends for better utilization of the heat content of flue gases and calcined alumina. In this way heat demand could be reduced to about 4 GJ/t. At the same time various types of stationary calciners (fluid bed, fluid flash, gas suspension) have been developed with heat consumption of 2.9 to 3.3 GJ/t. Whereas a number of unmodified and modified rotary kilns still operate, and it may be more economic to modify a conventional rotary kiln than to replace it by a stationary one (even though the heat saving is less in this case), it is most probable that the overwhelming part of the calciners operating in the year 2010 will be of the stationary type. This means that a 3 GJ/t primary heat requirement is expected in the long-term.

Some 50 per cent of the electric power required by the process is consumed by centrifugal pumps and about 12 per cent by agitators of various slurry tanks. A significant saving could be achieved by their careful maintenance and operation and by applying up-to-date control systems. It is expected that the average power demand of the alumina plants would drop to about 200 kW.h/t from the present 250 to 300 kW.h/t.

Bauxite residue (red mud). Disposal and Re-use

Up to now about 1 billion (dry) tonnes of red mud has been impounded and this quantity increases by about three to four percent every year. The main constituents of red muds are mostly in the form of non-toxic oxides and silicates. Environmental problems are caused by the large volume of mud, by the alkali content of the liquid phase of the red mud slurry and by the NaOH content. Efforts for reducing the negative environmental effects have been concentrated in the following areas:

(a) Red mud discharge and storage: Development in the field of red mud handling and disposal was rapid between 1980 and 1990. Red mud, leaving the limits of the alumina plant, has two main forms:

- red mud slurry as the final product of multistage washing or of repumping after filtration. Such slurry is dumped into rivers, estuaries, lagoons or into the sea or stored in sealed areas mostly surrounded by dams (generally called 'red mud ponds'), in valleys closed by dams.
- red mud filtered on press, drum or disc filters or concentrated in deep thickeners is transported to the storage area in trucks or pumped after agitation (liquefying) by appropriate pumps.

Storage of filtered and pumped red mud in ponds (dry stacking) is the technology of the 1980s. It is more advantageous than the storage of slurries. Storage of filtered or "deep-thickened red mud" is preferred because of the reduced moisture content, lack of rainwater infiltration, accelerated availability for cultivation and reduced area needed for storage. As compared to wet disposal, the overall projected costs for dry disposal remain marginally less than projected costs for continued wet disposal and the environmental impact is very substantially reduced.

(b) Modifications to the alumina manufacturing process to discharge a residue less harmful to the environment: The sodium aluminium hydrosilicate content of red mud can be partially transformed to calcium aluminium hydrosilicate by the addition of lime during various operations of the Bayer process or as an extra operation connected with it. A part of the chemically bound Na_2O content of the red mud can be recycled and an environmentally less harmful residue is formed with a lower alkali content.

(c) Utilization of red mud in agriculture: Red mud is alkaline with a pH value which changes after a few years. It can be used for improving the fertility of acidic soils. It should not be applied to clay soils since it could lead to chemical imbalance.

(d) Utilization of red mud in industry as an additive: A few examples for the use of red mud are:

- in road construction, for increasing soil strength, or as basic material,
- for crude and fine ceramics,
- for manufacturing light construction and heat insulating materials,
- for cement production,
- as filler in the rubber industry,
- as pigment and for manufacturing paints,
- for manufacturing gas purifying (Lux) mass,
- as an adsorbent and for manufacturing adsorbents,
- for the manufacture of catalysts,
- for manufacturing water purifying and settling agents,
- as an additive to blast furnaces in the steel industry.

(e) Complex waste-free processes for red mud: A number of processes are available for extracting various metals in the form of salts from red mud. Halogen metallurgy has been used for extracting rare metals from previously de-alkalinized red mud. A number of processes intending to utilize not only the iron content but also other useful components (Na_2O, Al_2O_3, TiO_2, V_2O_5, rare metals) of red mud have been developed. Some of them may do this without producing waste. In the course of the process, iron lumps, liquid iron, steel alloys, slag suitable for manufacturing alumina or cement, fertilizer and rare metals can be obtained.The complex waste free processes of red mud processing have the disadvantage that they are very expensive and usually require much more energy than if all products were made of their natural raw materials. The extra energy required would mean added pollution (acid rain, etc.) and increase the threat of global warming. With this in mind the dumping of a relatively harmless by-product (digestion residue), especially if done in an environmentally sustainable manner, seems to be more acceptable.

Waste liquor control

Waste liquors arise from overflow of tanks and alkaline or acidic liquors. Elimination of the former is technically possible through good operating practice. Acidic liquors (mostly wastes after acidic cleaning of digesters, evaporators) have to be neutralized after the cleaning process is finished, and the salt containing solution has to be pumped to the red mud pond.

Dust control

Bauxite dust concentrations should not exceed 2 mg/m^3. Dust protection can be provided by wetting, covering belt conveyors and exhausting the dust to collectors.

Alumina dust is formed in calcining kilns from where it can be separated by the aid of cyclones and electrostatic precipitators, as well as dust collectors.

Stack emission control

Contamination caused by stack gases can be reduced by using cleaner fuels (natural gas instead of coal and fuel oil). In some places this is technically impossible, in others very expensive, and the CO_2 problem would not be eliminated. The proper cleaning of the stack gases is also an economic problem, and some solutions have still to be found (e.g. there is no solution for eliminating the SO_2 content of the flue gas of the calciners, if oil fired).

Barriers

Technical Barriers

The utilization of red mud by other industries is limited. Its relative high water content compared to the natural raw materials for bricks requires the use of more energy. Its utilization in blast furnaces leads to a premature wear-out of their lining because of the Na_2O content.

Economic Barriers

Although most alumina plants extract practically all the available Al_2O_3 content of processed bauxite, some older ones, especially in developing countries, leave up to 10-15 percent undigested. A more complete digestion would require better facilities (suitable for application of a higher digestion temperature) and more sophisticated process control. Both involve high capital costs (US $ 10 to 100 million depending on the capacity of the plant.

The fullscale realization of any of complex waste-free processes for red mud would increase the capital costs of an alumina plant by a factor of 4 to 6. The extraction yield on alumina (and the alumina plant's capacity) could be increased by some 10 to 15 per cent and its caustic soda consumption could be reduced by 30 to 70 per cent. However, the value of the by-products (steel, cement, etc) would only be in the same order of magnitude as that of the alumina itself. The energy consumption of the complex processes would be by a factor of 3 to 5 higher than that of the Bayer process.

As stated above, there is considerable potential for energy conservation. Most of the saving measures, however, require large capital investment. For example, heat exchangers cost millions of US dollars for medium-size alumina plants. Energy efficient processors developed by some major aluminium producers are only available for US 1 to 2 million.

Social and attitudinal barriers

Significant improvements in yield can be attained by better operating techniques involving more frequent chemical analyses. The workforce must be encouraged to apply improved work methods especially laboratory personnel. Where the laboratory is not directly under plant management, there is often insufficient quality control.

Similarly, the use of burnt lime for reducing caustic soda losses (mud causticizing, complex causticizing, etc.) requires special operating and analytical attention. The processes are usually profitable only within a narrow range. Insufficient amounts of lime do not have the expected effect, too much may cause extra alumina losses. Reluctance to pay the required attention to those processes (especially during the afternoon and night shifts) can nullify all positive results of the causticizing.

Quite often social barriers prevent alumina plant improvements. Modern lime burning facilities, even where economic considerations support the investment, cannot be set up because a number of independent small lime-burning plants would go bankrupt and their employees lose their jobs.

Industry Initiatives

Trade associations of the bauxite/alumina/aluminium industries like IBA (International Bauxite Association) and IPAI (International Primary Aluminium Institute) can play a significant role in the exchange of information among the producers, including the field of pollution abatement and environmental protection. IBA's Quarterly News quite often carries articles dealing with environmental problems.

There is also significant potential for dissemination of information, transfer of know-how and technology from the major aluminum companies to their subsidiaries in developing countries.

Government intitiatives

Developing countries rarely adopt strict limits for industrial pollution through lack of information and partly to attract industrial projects, which would be more expensive in developed countries through meeting environmental recommendations. A number of developing countries has already started to consider measures for reduction of pollution caused by various industries and among them alumina plants will also have to comply.

The full impact of suddenly introducing very strict rules for every aspect of their operation (bauxite mining, red mud disposal, stack gases, effluents, etc.) could bring these plants to a halt, especially during periods, when the price of alumina is low. This seems to be the case at present and for the next 5 to 6 years. Such action could lead to the sudden loss of hundreds or even thousands of jobs. In the case of setting up new plants (which will not occur too often during this decade) or significant expansion of old ones the strategy should be to recommend environmental rules prevailing in the developed countries. A compromise for expanded old plants could be an agreement that any pollutant emissions should not increase.

Conclusions

The most promising ways of reducing the negative environmental impact of the alumina industry are the following:

(a) Reduction of the amount of natural resources (primarily energy) consumed per unit amount of alumina manufactured.

(b) Reduction of the residual discharges (effluents, dust, stack gases) per unit amount of alumina manufactured.

(c) Environmentally sustainable discharge and storage of digestion residue (dry stacking of red mud), recultivation of the filled-up storage areas.

The above can be realized by

(a) better operational and maintenance practices (e.g. preventing leakages, proper heat insulation, maintaining the prescribed parameters of the process, etc.),

(b) economically reasonable measures for efficient resource utilization, pollution control and waste disposal (e.g. increasing the number and size of heat exchangers, washing stages, etc.), and

(c) measures necessary to meet environmental requirements conforming with the generic ESID norms (e.g. installing dust collectors, scrubbers, dust filters, red mud filters or deep thickeners, recultivating mined-out areas and filled-up mud disposal areas, etc.) even if costly.

In general, it can be said that whereas modifications to existing old plants are relatively costly (they may reach even 30 to 50 per cent of the original investment costs), those incorporated in the engineering designs of a new plant (or of a significant expansion of an existing one) do not increase the capital costs by more than 5 to 10 per cent. At the same time the latter usually enable such savings to be made (both in related investment and operating costs) that they can make the application of environmentally sustainable solutions profitable.