DRY BAUXITE RESIDUE BY HI-BAR® STEAM PRESSURE FILTRATION

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Abstract

Bauxite residue is the main by-product of alumina refineries which has to be treated and disposed of in tremendous amounts. Proper bauxite residue filtration, treatment, long-termed disposal or even re-usage influence the sales cost per tonne alumina remarkably due to caustic loss in the disposed residue, residue handling and disposal technology, water consumption for washing and water recirculation from disposal area, maintenance of the disposal ponds and especially due to financial reserves per tonne mud for later recultivation of the disposal area. Numerous attempts have been undertaken to solve at least some of the problems of bauxite residue disposal or to make it available for any industrial re-usage. Semi-dry mud stacking by different treatment/transportation measures is the latest state of the art causing a series of new problems like (cost) intensive engineering, monitoring of the disposal area or even dust problems. Only exotic examples are known to re-use bauxite residue in industrial applications in amounts worth mentioning. This situation is mainly caused by major disadvantages of the dry bauxite residue, such as thixotropy, non bulk-like transportation and handling behaviour, high moisture content and high content of soluble soda. Any new technical solution which makes the bauxite residue acceptable for a really dry disposal or even industrial re-usage is directly linked with overcoming the above mentioned disadvantages. The Hi-Bar® Steam Pressure Filtration is an innovative technology already applied to the chemical industry, which has now been shown to be able to produce a really dry, easy to handle, bulk-like material. In a German alumina refinery a Hi-Bar® pilot plant using Steam Pressure Filtration has been operated for several weeks to produce a large amount of dry bauxite residue under industrial conditions.

1. Introduction

Bauxite residue results from bauxite processing in alumina refineries and is produced in large amounts of some 60 Mt dry solids per year. As a consequence of increasing aluminium production rates and decreasing bauxite quality the yearly bauxite residue production is assumed to be some 70 Mt of dry solids in the near future. In worst case studies 130 Mt per year are predicted.

Since available methods of bauxite residue processing do not allow utilization on a relevant scale, bauxite residue is a waste product which has to be disposed of. Disposal, however, is causing high costs and can lead to environmental problems. In some brownfield, and even for new greenfield plants, the economic disposal of the bauxite residue is the key factor for a go or no-go decision. Therefore, all major aluminium producers have made serious efforts in the last decades aiming at the development of new processing methods which may turn bauxite residue into a valuable product. Generally, different alternatives of recycling exist but each of them requires a special product quality. From an economic view these utilization possibilties are only feasible if bauxite residue is as dry and soda free as possible. Available methods of processing are not capable of producing a residue which meets these demands. The reasons for this unsatifactory situation are special material characteristics which make filtration, washing and dewatering challenging tasks and which subsequently create problems during transportation, storage and further processing of bauxite residue.

The Hi-Bar® Steam Pressure Filtration is an innovative separation technology developed by BOKELA which now offers the possibility to produce bauxite residue of the required quality in an economic manner.

2. Bauxite Residue — an Unavoidable By-Product of Alumina Production

2.1 *Formation of Bauxite Residue in the Bayer Process*

Bauxite residue is an unavoidable by-product of alumina production according to the Bayer process (and also the sinter process). In this hydrometallurgical process, the bauxite raw material is digested with hot caustic soda (NaOH) at high pressures and high temperatures to extract the aluminium compounds. In a downstream process the dissolved aluminium is precipitated as Al-hydrate which is then calcined to alumina. At the end of the process the caustic soda is separated and recycled back to bauxite digestion.

After digestion all bauxite residue solids which do not dissolve in caustic soda are separated from the pregnant liquor. This solids separation is one of the major steps in the Bayer process. In the first separation stage coarse sand particles over 100 µm are removed in liquid-solids cyclones or in simple settling devices, whereas the overflow with fine solids less than 10 µm enters the second separation stage. In large thickeners the fine solids are treated with flocculants, otherwise a stable colloidal suspension would exist with extremely poor settling behaviour, and sink to the bottom of the thickener forming red mud which is discharged from the thickener at a solids content of some 20–30 wt%. This means that each single tonne of residue solids contains 2–2.5 m^3 of valuable mother liquor which has to be recovered to minimise the loss of soda and dissolved alumina. For this reason the bauxite residue is further processed in the red area of the refinery where the caustic soda and the dissolved alumina are recovered in a multi-stage counter-current washing process consisting of up to 7 large wash thickeners. In order to minimise the loss of valuable product and to improve the bauxite residue characteristics with respect to disposal, the wash process is followed by a vacuum filter station where the bauxite residue is filtered at a temperature of some 85°C and washed again on vacuum drum filters. In the case of very poor filterable bauxite residues this last step before disposal is performed in deep cone thickeners.

2.2 *Quantities and Characteristics of Bauxite Residues*

The amount of bauxite residue depends on the bauxite quality and source respectively, and usually varies from 0.5 t up to 1 tonne dry solids per 1 t alumina produced (see fig. 1) whilst from some bauxites even 2 t residue solids result per 1 t alumina produced. This means that an alumina refinery typically produces a bauxite residue quantity in the range from 0.1 up to 1.5 Mt dry solids per year depending on the respective bauxite and the production capacity.

The most important mineralogical compounds of bauxite residue are titanium dioxide, silicon dioxide and iron oxide of which the latter is responsible for the colour and the name of this waste material. Some bauxites are also known for their content of radioactive materials the concentration of which, however is below critical values. The composition of bauxite residue varies in a wide range depending on the origin of the bauxite, the individual process design and the process conditions of a refinery. Not only the chemical composition but also the particle size distribution varies both of which influence the residue characteristics with respect to filtration, washing and dewatering and consequently the residue behaviour at disposal.

Bauxite residue consists of very fine, lamina-shaped particles in the range of $\mathbf{x_{50} < 10\ \mu m}$. An especially problematic characteristic of bauxite residue is the thixotropic behaviour which impairs the possibilities of utilisation. Under mechanical stress, which may occur e.g. by shaking during the transportation, bauxite residue which seems to be of a firm consistency is liquefied again and becomes sticky. This phenomenon leads to very poor bulk characteristics and complicates handling significantly. Thixotropy first disappears when the moisture content is reduced below a value of < 25–28 wt%. However vacuum filters, which are the established and only available continuous filter technology for bauxite residue, are limited in their dewatering capability and produce thixotropic filter cakes with moisture contents = 35–50 wt%. The high liquid content in the cakes and poor washing results in the bauxite residue possessing a high amount of soluble soda of some 6–12 g/kg. Thus, further processing or direct utilisation of the bauxite residue is not feasible by either technical or economic criteria.

3. Disposal and Recycling of Bauxite Residue

Although most of the bauxite residue materials have no particular toxic characteristics, the disposal of this residue is the problem with the most environmental relevance for refineries and therefore it is an important technical and economic challenge.

3.1 *Current Disposal Techniques — Status Quo*

Since the available methods of bauxite residue processing do not enable its utilisation up to now, this residue is a waste product destined for disposal. Some refineries that are located at or near the coast dispose of their bauxite residue by pumping the residues into the sea. The largest amount, however, is pumped or transported to open disposal sites, where five different methods of disposal exist. Some 66% of the disposed bauxite residues world wide are pumped to different types of storage sites in a liquid state with a solids content of only 20wt%–30wt% (wet discharge). In this category belong the typical red mud lagoons which receive some 33% of the world wide quantity. About one third of the residue is stored by “dry stacking” with the higher solids content of vacuum filter cakes of some 50%–65%. Due to environmental problems’ e.g. alkali contamination of ground water due to effluent penetrating through poor bottom sealing, the disposal is subject to many legal regulations and public approval.

Central aspects of actual disposal methods are the loss of valuable product, the large required area and the costs for the construction and operation of the disposal site. A typical procedure for bauxite residue disposal by “dry stacking” includes the following cost creating measures and process steps:

- transportation to disposal site usually by pumping through pipelines with positive displacement pumps fed by screw conveyors (up to 2 km bauxite residue with a moisture of some 45wt% can be pumped without liquifiers or dilution water, longer distances require liquifying or dilution anyway)
- building of a secure bottom sealing of the disposal site
- construction of secure surrounding dams of some 30 m in height preventing alkaline water escape

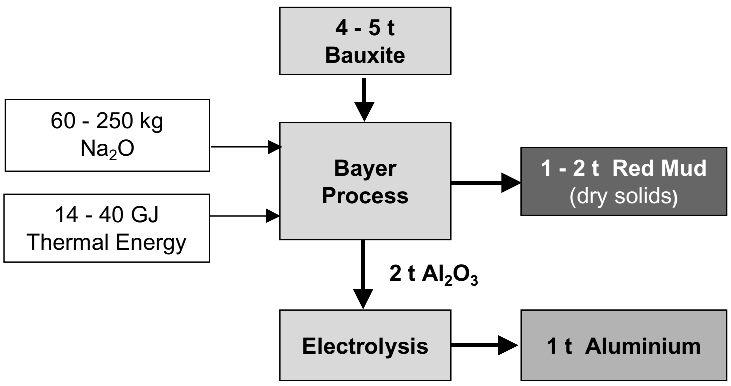

Figure 1 — Schematic flow sheet and material balance of aluminium production.

- providing for an even and fast drainage of the residue e.g. by construction of drainage towers
- operation of the disposal site including good distribution of the residue, control of the sealing, groundwater, the water balance and consolidation, treatment of the drained water and rain water
- protection of the sun-dried surface against wind-erosion to avoid red-coloured dust pollution
- financial reserves for recultivation of the storage site

3.2 *Recycling of Bauxite Residue*

All major aluminium producers have undertaken research in the last decades for alternatives to bauxite residue disposal which would allow this residual product to be used as a valuable product and which would be able to prevent the economic and environmental problems of disposal. Experiences from this research work have shown that a lot of possibilities for bauxite residue application in different industries exist. Some of them are listed in Figure 2.

All of these alternatives could not be realised up to now in a scale worth mentioning.To allow direct usage or further processing in an economic way, it is required that bauxite residue is made available by the refinery with a very low soda content and a non-thixotropic and non-sticky behaviour to ensure secure transportation and problem free handling. However actual methods of filtration, washing and dewatering are not able to produce bauxite residue that is clean and dry enough to meet these requirements. This has to be seen against the background that thermal drying of wet bauxite residue is too energy and cost intensive and, therefore, not a feasible and profitable process alternative to produce dry bauxite residue for utilization.

4. Status Quo of Bauxite Residue Filtration

Since the early 1960s drum filters with roller discharge have been established as the leading technology for bauxite residue filtration. Typically, they are installed behind 3 to 4 wash thickeners and form the last step of bauxite residue washing and dewatering. The filter cake is only 1–3 mm thick and is washed with hot water via wash bars when emerging out of the slurry. If the wash water is distributed film-like it can help to prevent cake cracks. Cake discharge is usually performed with a discharge roller which removes the cake from the cloth.

Typical apparatus and operational data of bauxite residue vacuum filters are given in table 1. An essential weak point of vacuum filtration, which can not be overcome, is the low filtration pressure difference which is limited under technical conditions to some $\Delta p = 0.7$ bar. During bauxite residue filtration this low pressure difference reduces even more since bauxite residue is filtered with a high slurry temperature of about 85°C. At this temperature the filtrate has a vapor pressure of 0.58 bar which means that the theoretically available pressure difference by vacuum is only 0.42 bar. So, the efficiency of washing and dewatering on vacuum drum filters is limited, the content of soluble soda Na_2O in the cake of 6–12 g/kg is high whilst the moisture content is 35%–50%, which means that the discharged cake has a thixotropic behaviour. These operational values as shown in table 1 are characteristic data which, however, are not achieved in every refinery either due to special product characteristics or due to insufficiently working filters.

In many filter revamping projects BOKELA has upgraded bauxite residue vacuum drum filters from many

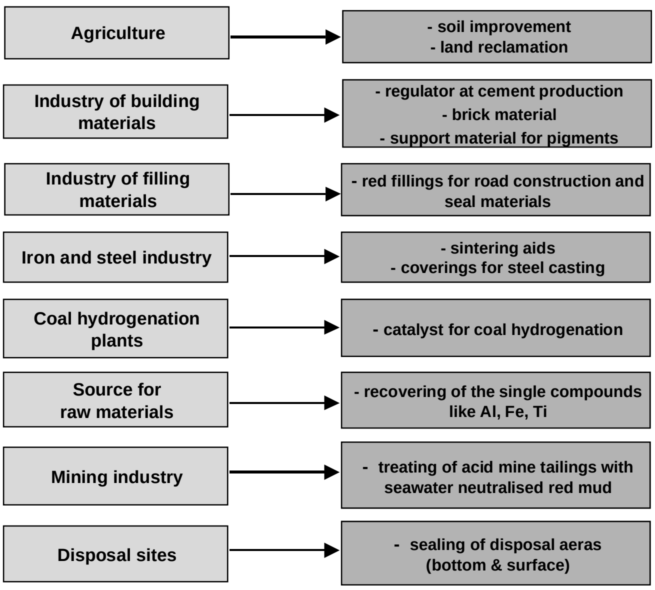

Figure 2 — Selection of some target industries and application possibilities for bauxite residue utilization.

Table 1 — Apparatus data and typical results of vacuum drum filters for bauxite residue filtration.

Bauxite Residue Vacuum Drum Filters		Operation Data	
filter area	up to 100 [m^2]	solids throughput	150–300 [kg/m^{2}h]
drum diameter	up to 4.2 [m]	cake moisture	35–50 [%]
drum length	up to 7.6 [m]	content of soluble Na_2O	6–12 [g/kg]

OEM's. The main improvement targets are increasing the filter capacity and reducing the soda content in the cake whereby cake washing and cake discharge are main weak-points of running filters. By upgrading measurements and design modifications the filter performance can be improved often up to 100%.

5. Targets of Bauxite Residue Filtration

New methods of bauxite residue treatment must be capable of improving the product characteristics of this residue to such an extent that utilization becomes a real alternative to disposal and that the loss of valuable content is minimised. This requires a significant improvement in bauxite residue washing and dewatering by an economic process solution. The main targets are

- reducing the moisture content below the actual values down to 25% or less by an improved filter cake dewatering in order to achieve a non-thixotropic and non-sticky product with
  - sand-like bulk characteristics
  - good transport and handling characteristics
  - a high utilization potential.
- reducing the content of soluble Na_2O far below the actual values of 6–8 [g/kg] by improved washing
  - to minimise the loss of soluble soda
  - to achieve a better product quality for bauxite residue utilization possibilities
- ensuring an economical process for achieving the above mentioned targets by avoiding/reducing crack formation in the filter cake by a minimum input of thermal energy.

Filtration tests with different bauxite residues from many refineries showed that pressure filtration leads to distinctively higher throughput capacities and reduced moisture contents compared to vacuum filtration. Solids throughput rates of up to some 1,000 kg/m^{2}h with moisture contents = 30–34% can be reached. However for achieving target values of 25% moisture content or less and soda contents far below actual values the filter cake has to be treated with steam. Steam pressure filtration tests with different bauxite residues proved the feasibilty of this innovative process with solids throughput rates of 200–300 kg/m^{2}h, moisture contents in the range of 23–25% and soda contents down to 3 g/kg.

6. HI-BAR® Steam Pressure Filtration

The innovative Hi-Bar® Steam Pressure Filtration is a patented process already applied in the chemical industry, which has now shown its capability to produce a really dry and easy to handle, bulk-like bauxite residue material in an economic way.

6.1 *The Process Design of Hi-Bar® Steam Pressure Filtration*

The continuous Hi-Bar® Steam Pressure Filtration is realised on rotary drum or disc filters and applies filtration pressure differences up to 6 bar and superheated, pure steam for filter cake treatment (thermal heating and mechanical pore emptying). The application of over-pressure instead of vacuum with pressure differences up to 6 bar ensures a high specific throughput and dewatering capability even with filter cakes with fine particles such as bauxite residue cakes where high cake resistance and capillary forces in the cake have to be overcome. As can be seen from equation (1), which is derived from the DARCY equation, the solids throughput depends linearly on the square root of the applied pressure difference Δp.

$$M = \dot{m}_s \cdot A = \rho_s (1-\varepsilon) \cdot \sqrt{\frac{2}{\eta_L r_c}} \cdot \sqrt{\kappa} \cdot \sqrt{\Delta p} \cdot \sqrt{n} \cdot \sqrt{\frac{\alpha_1}{360°}} \cdot A \quad (1)$$

m_S	[kg/m^{2}h]	= specific solids throughput
A	[m^2]	= filter area
ρ_S	[kg/m^3]	= solids density
n	[rpm]	= filter speed
α_1	[°]	= cake forming angle
κ	[–]	= concentration parameter
r_c	[1/m]	= cake resistance
η_L	[kg/ms]	= viscosity

The treating of the filter cake with dry, superheated and pure steam is performed in a specially designed steam cabin which the cake enters immediately when emerging out of the slurry. Here, the steam condenses on the colder cake surface and forms a layer of condensate which is forced after cake formation into the cake by the pressurised steam like a "condensate front" and displaces the mother liquor as shown in Figure 3.

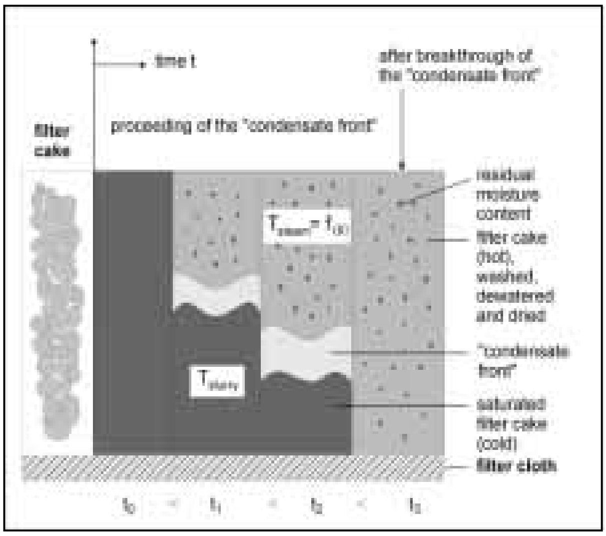

Figure 3 — Model of the "condensate front".

It is the target of to ensure an even and nearly complete, piston like washing and demoisturing of the filter cake by overcoming the capillary forces in the cake pores with steam. The piston like flow of this "condensate front" effects a highly effective displacement of the mother liquor which leads to an intensive cake washing. When the "condensate front" arrives at the filter cloth the hot cake leaves the steam cabin and now compressed air is forced through the cake pores which causes an effective thermal drying. Due to the stored energy in the heated cake a great part of the residual liquid is evaporated. These thermal/mechanical phenomenon inside the cake lead to a homogeneous and intensive washing and demoisturing of the cake and can also prevent or reduce the formation of cracks in the filter cake.

6.2 *The Plant Design of Hi-Bar® Filtration*

The continuous Hi-Bar® Filtration can be realised as pressure filtration with compressed air or as steam pressure filtration with pressure differences up to Δp = 6 bar.

The plant design is based on rotary disc or drum filters, which are installed inside a pressure vessel that is filled with compressed air from a compressor. The filtrate pipes of the rotary filter are connected to the environment via the control head and the suspension is pumped into the filter trough in the pressurized vessel. The filter cake is discharged from the cloth by an air-blow-back and removed out of the vessel by a sluice. The pressurized air which enters the vessel for the cake discharge is then available for the filtration process.

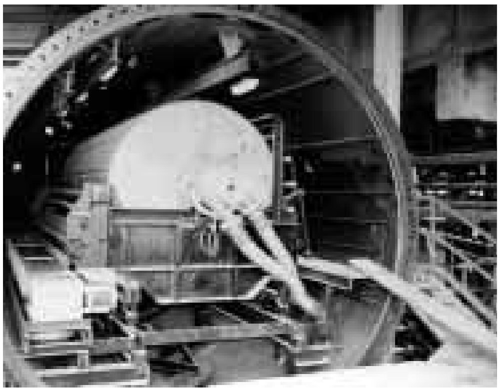

Figure 4 — Open pressure vessel of a Hi-Bar® Drum Filter Plant.

In the standard version of Hi-Bar® Filtration the compressed air inside the vessel is used both for filtration and cake dewatering. At the Hi-Bar® Steam Pressure Filtration the specially designed and patented steam cabin covers a part of the filter area and forms a separated room with pure steam inside the vessel. The drum or disc filters are designed for the filtration of mass products and for sophisticated applications with highly valuable products. Drum filter areas are available up to 40 m^2 and disc filter areas up to 120 m^2.

7. Steam Pressure Filtration of Bauxite Residue at the AOS Refinery

The test trials were carried out on the mobile Hi-Bar® pilot plant of BOKELA at the refinery of Aluminium Oxid Stade GmbH (AOS), Germany during a period from May to December in 2001.

7.1 *Product Data and Target of the Pilot Plant Test Trials*

During the test period AOS processed four different types and mixtures of bauxite leading to residues with different filtration characteristics. After washing in two wash thickeners the residue is filtered and washed on vacuum drum filters with roller discharge. The discharged cake is diluted with water and pumped to the disposal site. The vacuum drum filters have a specific solids throughput of 200–280 kg/m^2h and produce a filter cake with a moisture content of some 35% to 37% and a soluble soda content of 0.5% to 0.9%. With this moisture content the bauxite residue is difficult to handle and cannot be transported by mechanical conveyors. Therefore, AOS is interested in new technologies which are capable of producing a significantly drier residue which is not sticky and thixotropic and which also has a lower soluble soda content allowing at least a part of the bauxite residue to be used as valuable product.

For this reason Hi-Bar® steam pressure filtration pilot tests were carried out and some 30 tonnes of dry residue with very low soluble soda content were produced which now enable AOS to look for re-usage alternatives in co-operation with interested industries. A first series of tests was carried out with the same slurry as is filtered on the vacuum filters. Since this is the first residue filtration step, this series is called “first- filtration”. A second long-time pilot plant operation was then carried out with cake from the vacuum filters which was re-slurried with wash condensate. This test operation is called “second-filtration”. The feed slurry for the “first-filtration” had a temperature of 80°C, a pH-value of 12–13 and a soda content of 37.7 g/l, whilst the “second-filtration” feed slurry had a temperature of 80°C, a pH-value of 10–11 and a soda content of 3.2 g/l.

7.2 *The Hi-Bar® Pilot Plant*

The Hi-Bar® pilot plant is a mobile unit which allows pilot test operation on a technical scale with filtration pressure differences of up to 6 bar. The pressure vessel, the Hi-Bar® pilot disc or drum filter, the sluice and all peripheral equipment such as filtrate receiver, compressors, pumps, slurry conditioning unit and a PLC for an automatic operation are enclosed in two shipping containers.

For the bauxite residue pilot test operation the plant was equipped with a 0.4 m^2 drum filter with 20 individually exchangeable filter cells. Cake washing and steaming is performed by a wash and separate steam cabin with individually controllable wash bars and a variable steaming zone. The cake is discharged by blow back air. The homogenisation of the slurry is performed by an agitator. The main operation and filtration parameters such as filter speed, agitator speed, trough level, vessel pressure, steam throughput and sluice cycle time are variable and integrated in the PLC. The control head of the drum filter is subdivided into three process zones allowing the separation of the mother filtrate from the cake formation zone, the filtrate from the cake wash and the filtrate from the cake dewatering zone. The discharged cake was stored in large bags which were weighed and from which samples were taken for the determination of the solids throughput, the moisture content and the soda content.

7.3 *Results of the “First-Filtration” of Bauxite Residue*

The “first-filtration” test series were run with identical feed from the operating vacuum drum filters processing residues from bauxites of two different origins. The solids throughput, moisture content and cake washing were tested and optimized by varying different parameters such as filtration pressure Δp, filter speed n, cake formation angle α_1, wash zone and wash ratio V_w, steam zone (position steam throughput, steam pressure etc.), compressed air zone, type of filter cloth etc.

7.3.1 *Specific Solids Throughput*

In Figure 5 the specific solids throughput is shown as a function of the filtration pressure difference. The measurements show the solids throughput for two bauxites and for two different filter speeds n. The specific solids throughput increases linearly with the square root of the pressure difference as predicted by the filtration theory expressed in equation (1). With a pressure difference of 6 bar the specific solids throughput amounts to 330–410 (kg/m^2h) whilst the vacuum filters achieve 150–280 (kg/m^2h) which is a relatively high value compared to the pressure filtration results. The reason for this is the different filter setting which means that the Hi-Bar® pilot plant was run with a significantly reduced cake formation zone α_1 (see eq. 1) compared to the vacuum filters since it was the target to achieve cake moisture contents as low as possible. Furthermore, it can be seen from Figure 5 that increasing the filter speed also increases the specific solids throughput as predicted by eq. (1). However, increasing the filter speed reduces the cake thickness and is therefore limited by the thinest filter cake which can be discharged by air blow back.

Both the moisture content and cake washing are nearly indifferent to the filter speed.

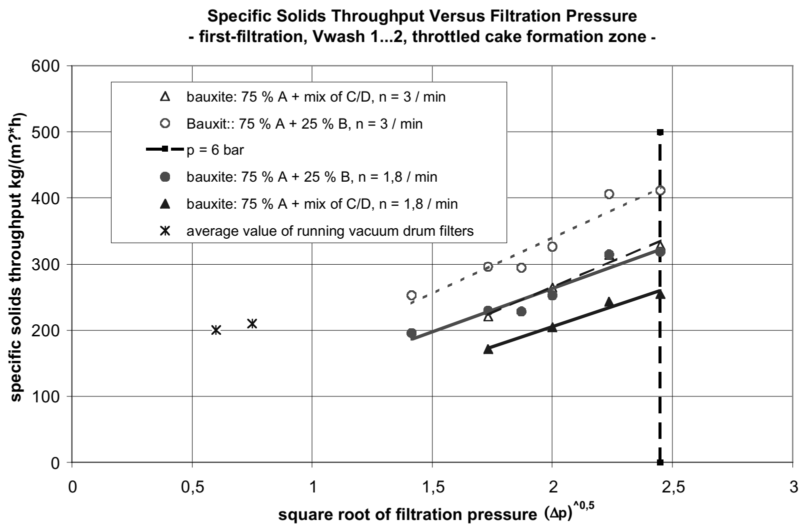

Figure 5 — Specific solids throughput as function of the square root of the pressure difference — "first-filtration" of 2 different bauxite types (filter speed n = 3 rpm and n = 1.8 rpm).

7.3.2 *Moisture Content*

Figure 6 shows the moisture content as a function of the filtration pressure difference Δp. It becomes evident that high Δp values lead to extremely dry cakes with moistures down to 23% at Δp = 6 bar. Figure 6 presents average values of different measurements for filter speeds of 0.8–2.5 rpm, for a wash ratio of 1–2 kg wash water/kg solids and a steam ratio of 0.4 kg steam/kg solids. In the tested Δp range of 2 to 6 bar the cake moisture decreases in a nearly linear manner so it can be expected that a further increase of Δp to some 10 bar will further reduce the cake moisture down to 20% or below.

7.3.3 Soda Content

The washing efficiency or the soda content of the filter cake, respectively, is a decisive characteristic for the bauxite residue utilization and marketability. The main parameter influencing the wash result is the wash ratio which is defined as the ulilised amount of wash water referred to the solids throughput. During the "first-filtration" test run a soda content in the cake of 0.4% on average was achieved with a wash ratio of 2 kg_{WW}/kg_S and a pressure difference of 6 bar. Although there was a variation of the measured soda contents over the tested range of wash ratio values there was no dependency of the soda content on the processed bauxite type or mix. The variation in the measurements is assumed to be caused by variations in the upstream process such as different retention times in the wash thickeners or differences in flocculation respectively. Also different characteristics of the respective bauxite type can be responsible for these variations such as different contents of iron or differences in the particle size distribution. Furthermore, different cake cracking behaviour can be the reason for the variation in the soda content measurements. The trend of the average values of all soda content measurements is shown in figure 9.

7.3.4 Overview of"First-Filtration" Results

The "first-filtration" test trials on the Hi-Bar® pilot plant were carried out with bauxite residue slurry identical to the feed of the operational vacuum drum filters.

The results below prove that steam pressure filtration is the most promising technology for bauxite residue filtration leading to a significantly improved cake wash and extremely dry filter cakes. The values listed in Table 2 are valid for a 6 bar pressure difference while the 10 bar values are extrapolated figures showing prospective results:

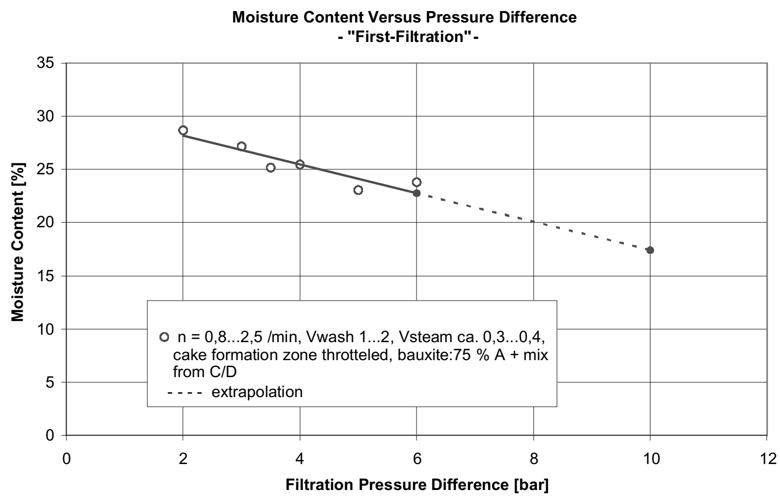

Figure 6 — Moisture content as a function of the filtration pressure difference.

Table 2 — Results of Hi-Bar® steam pressure filtration of bauxite residue ("first-filtration").

filtration pressure difference	6 bar	10 bar
filter speed	3 rpm	3 rpm
specific solids throughput	290 kg/m^{2}h	370 kg/m^{2}h
cake moisture content	23%	19%
wash ratio	2 kg_{WW}/kg_{Solids}	2 kg_{WW}/kg_{Solids}
steam ratio	0.55 kg_{steam}/kg_{Solids}	0.55 kg_{steam}/kg_{Solids}
soda content in the cake	0.5%	< 0.5%

7.4 *Results of "Second-Filtration"*

In order to produce a valuable, saleable bauxite residue which can be marketed easily to different industrial applications it has been decided to determine the process conditions for such an "industrial bauxite residue production unit". The "second-filtration" test series was carried out with the target of achieving as low as possible soda content in the filter cake to ensure best conditions for bauxite residue utilization. Cake washing should be improved whilst the cake moisture should be at the same or an even lower level as achieved in the "first-filtration" test operation. For this reason the cake of the operational vacuum drum filters was re-slurried with wash condensate and then filtered on the Hi-Bar® pilot plant. The pilot operation was run with a filter speed of n = 3 rpm and a pressure difference of Δp = 6 bar as used during the "first-filtration" tests while the wash ratio, the steam ratio and the cake formation zone were varied for optimizing the solids throughput, moisture content and cake washing.

7.4.1 *Specific Solids Throughput*

The "second-filtration" operation was run with a filter speed n = 3 rpm and a pressure difference of 6 bar but with a reduced cake formation zone compared to the "first-filtration" operation in order to generate a thin cake and thus to improve the cake washing. Therefore, the average specific solids rate reduced to 250 kg/m^{2}h. There was no dependency of the specific solids rate on the bauxite type or bauxite blend.

7.4.2 *Moisture Content*

In Figure 7 all relevant moisture values of the "second-filtration" period are presented versus the pilot plant operation time or the number of test trials, respectively. The high values for the low test numbers were achieved during the optimisation and filter adjustment period at the beginning of the "second-filtration".

The results presented in Figure 7 show that Hi-Bar® steam pressure filtration is capable of achieving uniquely dry bauxite residue filter cakes. Independent of the processed bauxite, moisture contents are below 23% and the cake is a well washed, dry, non-sticky and sand-like material with excellent bulk characteristics. Bauxite residue with this consistency can be easily stored, transported and processed.

7.4.3 *Soda Content*

With the "second-filtration" long-time pilot plant operation a distinctively lower soda content in the filter cake was achieved as with the "first-filtration" test series. In Figure 9 the wash results are shown versus the wash ratio and it can be seen that, even with a low wash ratio of 1 to 1.3 kg_{WW}/kg_S and a steam ratio of 0.55 kg_{steam}/kg_S, a soda content < 0.3% is securely reached. For a comparison the trend line of the "first-filtration" cake washing is also shown in the diagram.

7.5 *Cake Cracking and Air Consumption*

During the pilot plant operation the formation of cracks in the bauxite residue filter cake could not be prevented completely. But due to the applied high filtration pressure of Δp = 6 bar and the low cake thickness of h_C < 5 mm, cake cracking was reduced. So the air consumption varied in the range of 0.2 to 2.0 m^3_{air}/kg_S which means that sometimes most of the air passed through cracks. During the long-time pilot plant operation the average air consumption for achieveing a moisture content of < 23% was easy to handle. The air consumption can be further reduced by

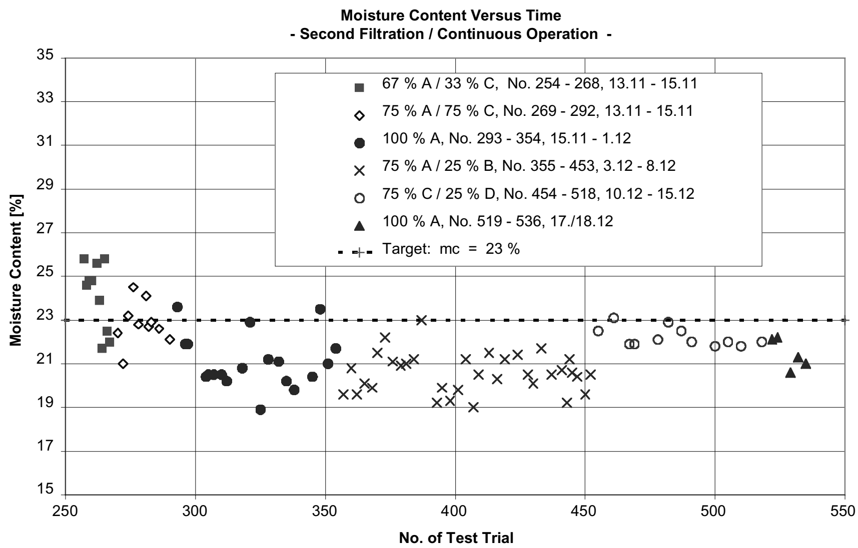

Figure 7 — Moisture content values of the "second-filtration" operation period for different bauxites.

Figure 8 — Bauxite residue filter cakes: sticky and pasty with 35% moisture from vacuum filtration, dry and sand-like bulk material with 23% moisture from Hi-Bar® steam pressure filtration.

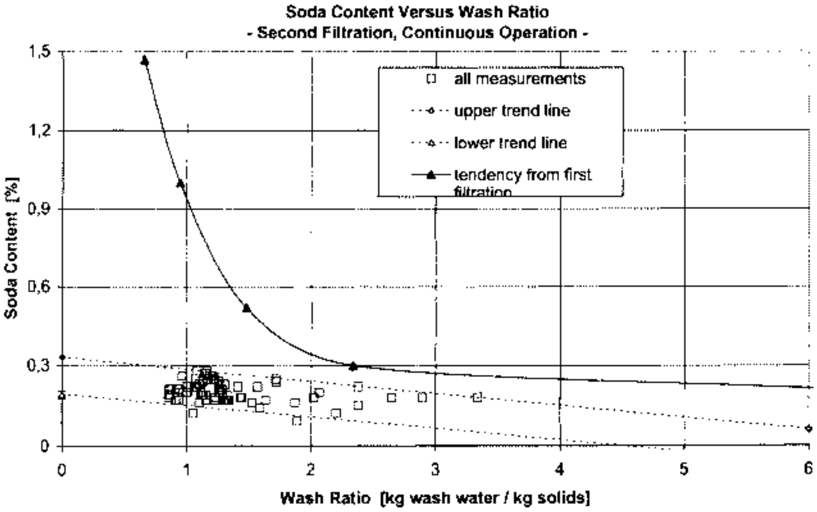

Figure 9 — Soda content versus wash ratio for “second-filtration” and “first-filtration”.

some design modifications in the control head and by a separately controllable air dewatering zone. Therefore, it can be predicted that for an industrial plant, the air consumption does not exceed 0.6 m^3_{air}/kg_S.

7.6 *Plant Scale Up*

The results of the pilot plant operation are a reliable basis for scaling up and for calculation the operating costs of a Hi-Bar® steam pressure filtration plant. In Table 3 the scale up data of a Hi-Bar® steam pressure filtration plant with a 40 m^2 drum filter is presented which is actually the largest Hi-Bar® drum filter size. The drum filter is 3 m in diameter, has 30 filter cells, a wash cabin and a steam cabin and the cake is discharged by air blow back. The scale up calculation is carried out for the “first-filtration” and for the “second-filtration” alternative with the target of 23% moisture content and a soda content of 0.5% for the“first-filtration” and 0.3% for the “second-filtration”. The plant is assumed to run 6,800 hours per year which is an availability of 85%.

Table 3 — Operating data of a 40 m^2 Hi-Bar® drum filter for steam pressure filtration.

	“first filtration”	“second-filtration”
filtration pressure difference	6 bar	6 bar
specific solids throughput	290 kg/m^2h	250 kg/m^2h
solids throughput	11.6 t/h	10 t/h
solids throughput per year	78.880 t/a	68.000 t/a
wash ratio	1.5–2.0 kg_{WW}/kg_S	1.3–1.6 kg_{WW}/kg_S
wash condensate	17.4–23.2 m^3/h	13–16 m^3/h
steam ratio	0.45 kg_{steam}/kg_S	0.55 kg_{steam}/kg_S
steam consumption	5.2 t/h	5.5 t/h
air ratio	0.75 m^3_N/kg_S	0.6 m^3_N/kg_S
air consumption	9,200 m^3_N/h	6.500 m^3_N/h
electric power (filter, pumps)	46 kW	46 kW

7.7 *Operating, Invest and Total Costs*

The operating costs for the above scaled up Hi-Bar® steam pressure filtration plant are presented in Table 4. It is assumed that the dry bauxite residue from the Hi-Bar® plant is marketed as valuable product and that the disposal site is less demanded, which leads to costs savings.The optimised cake washing also leads to costs savings.

In Table 4 the investment and capital costs for the scaled up plant are calculated which are valid for a turn key plant including pumps and compressor. The costs are given as specific costs — referred to tonnes of residue solids — and are calculated for a requested 2, 5 and 10 years period for return of investment.

The total costs for producing a clean dry, sandy bauxite residue are attained as a sum of the investment and operating costs, which depend strongly on the required moisture content, purity and investment return period. Whilst a moisture content of 21%, excellent washing ("second-filtration") and a short 2 year period for return of investment lead to costs of 26.8 Eur per t bauxite residue the product costs can be more than halved if a 25% moisture and 10 years for return of investment are accepted. If the requirements on the cake washing are not so strong the steam pressure filtration can be performed in the "first-filtration" modus for which product costs of < 10 Eur per t bauxite residue can be achieved

8. Summary

The Hi-Bar® steam pressure filtration enables the industrial production of an extremely dry and well washed dry bauxite residue with a crumbly, sandy-like and non-sticky consistency and a low soda content. These product characteristics ensure simple product handling and are the precondition for transforming bauxite residue from a disposal product into a valuable product. One Hi-Bar® plant using a drum filter can produce 60,000 to 80,000 t/a dry bauxite residue. With a disc filter one Hi-Bar® plant can produce 180,000 to 240,000 t/a dry bauxite residue (mc = 25%). The pilot tests at the Aluminium Oxid Stade (AOS) refinery prove that with the steam pressure filtration very low moisture contents down to 21% and soda contents in the filter cake of only 0.3% are feasible. In the first pilot operation period the tests were carried out with feed identical to the operating vacuum drum filters and moisture contents of 23 to 26% were achieved with a soda content in the filter cake of 0.5%. To further improve cake wash a second pilot test series with re-slurried vacuum filter cake was run and the soda content in the cake reduced to 0.3% whilst moisture contents of 21 to 25% were attained. Since different types of bauxite were processed during the test period the results of the pilot operation show that the steam pressure filtration works rather indifferently to the bauxite residue origin. The total cost for a clean and dry, sandy bauxite residue, however, depend on the required moisture content, on the purity and on the required return of investment period. A very low moisture content of 21%, excellent washing ("second-filtration") and a short 2 year period for return of invest lead to costs of 26.8 Eur per t bauxite residue. If a 25% moisture and 10 years for return of invest are accepted the product costs can be more than halved. If the requirements on the cake wash are not so strong, the steam pressure filtration can be performed in the "first-filtration" modus for which product costs amount to some 10 Eur per t bauxite residue. The pilot test results show the process technological feasibilty of the Hi-Bar® steam pressure filtration. This breakthrough technology in bauxite residue filtration leads to product characteristics never achieved before in one process step which offer new chances for dry bauxite residue usage.

Table 4 — Invest and operation costs of a Hi-Bar steam pressure filtration plant.

	Cost basis	**"first filtration" [Euro/t residue]**	**"second-filtration" [Euro/t residue]**
		mc = 23%	**mc = 23%**
		soda content = 0.5%	soda content = 0.3%
electric power (filter drive, pumps)	0.05 Euro/kWh	0.20	0.23
air consumption	0.1 kWh/$m^3{}_N$	3.97	3.25
steam consumption	15 Euro/t steam	6.75	8.25
filter cloth	30 Euro/m^2	0.21	0.25
costs savings:			
on the disposal site	1.0 Euro/t residue	–1.00	–1.00
reduced soda consumption	250 Euro/t soda	–0.25	–0.75
reduced power consumption on the vacuum drum filters	0.15 Euro/t residue	–0.15	—
total operating costs mc = 23%		**9.73**	**10.23**
total operating costs mc = 25%		**8.03**	**8.33**
invest costs			
return of invest: 2/5/10 years	Euro/t residue	**12.40/5.80/3.50**	**14.40/6.70 4.10**

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