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DIRECTIONS FOR LARGE SCALE UTILIZATION OF BAUXITE RESIDUE

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Abstract

Solving the problem of large-scale utilization of Bayer process bauxite residue (red mud) becomes more and more vital for an increasing number of alumina refineries around the globe. Till now, in spite of the fact that many technically sound process routes have been developed, only a few of them have been implemented due to favorable local economic and market conditions. Being a complex and poor ore for extraction of iron, alumina and titanium, treated red mud has to compete with other low cost materials; this is often uneconomic. In this paper the most promising utilization directions are discussed and focus areas for research by the world scientific community are outlined.

1. Introduction

Currently about 2.7 billion tones of bauxite residue (BR) are accumulated in the world with a growth of over 120 million tons per year [1]. Every year the legislation with regard to man-caused wastes becomes more severe especially in the industrial countries. Today in European countries and in the USA the fee for storing 1 tonne of waste such as BOF / Blast furnace sludge or EAF dust reaches USD 60-100 per year [2]. Cost of the land also shows stable growth tendency. This compels manufacturers to recycle the maximum amount of their waste, often with adverse financial consequences. We can expect a tightening of legislation in the field of storage of industrial wastes related to red mud in different countries first of all BRIC, now having maximum alumina production capacities in the world. It leads us to the conclusion that *in longer prospective, instead of disposal areas, red mud handling and loading complexes will have to be built.*

There are examples of successful processing of industrial wastes generated in other industries such as blast furnace slag and fly ash [3, 4]. In 2007 the USA produced 131 million tons of coal combustion products, of which 43% was used beneficially [5]. In the Netherlands 100 % of the fly ash is recycled. USA holds a biannual World of Coal Ash (WOCA) conference where technologies of coal ash utilisation are explored and improved [6].

As one of the strategic goals in Alumina Technology Roadmap (2010 edition) by the Bauxite and Alumina Committee of the International Aluminium Institute [7], the world alumina industry should utilize at least 20% of the BR by 2025. In advance of this objective, by decision of the Chinese government utilization level of 20% (8 million tons annually) of BR in China shall be achieved by 2015.

BR differs significantly from other recyclables in composition and properties, which make it less suitable for processing by conventional methods. At present, the amount of BR processing is limited by several factors, and under favorable circumstances makes up to 10-30% of the produced volume for a particular plant. Worldwide BR processing does not exceed ~2.0 million tons per year, i.e. less than 2% of the produced amount. It means that *a comprehensive technology for complete bauxite residue processing to marketable products with value addition is still to be evolved.* This paper examines various factors affecting developments in this field and highlights the prospective areas of processing and full utilization of bauxite residue.

2. Utilization of alumina process tailings in the USSR / CIS, from research to practice

2.1. Complete industrial utilization of nepheline residue achieved

Technology for waste-free alumina production has been implemented on an industrial scale in the USSR since 1952, when the method for nepheline sintering with limestone, for production of alumina, soda, potash, cement, construction materials and gallium was mastered [8]. At present the technology is used at the Pikalevo and Achinsk alumina refineries. The high production cost of the basic product – alumina – is more than compensated by the production of the above by-products. In fact, the complex use of resources ensures alumina production from nepheline at better economics than processing of bauxite by the Bayer process [9].

This is a practical example that *it is more profitable to produce a range of products from one type of raw material than producing these same products separately from different ores.* In particular belite mud (mainly β-C_2S), resulting from sintering of nepheline with limestone, is a preferred raw material for cement production, road construction, production of aerated concrete, etc. Since 1960s, Russian scientists [10-13] carried out research and industrial application on the use of the mud as a component in the raw mix of cement production showing that: (i) the content of mud in the raw mix can be as high as 30-45%; (ii) the productivity of rotary kilns using the belite mud increased by 22-28% due to reduction of energy requirement for calcination of the raw mix; (iii) fuel consumption for clinker formation reduced by 25-35%.

Technology for producing Portland cement using nepheline mud as a raw mix component has been implemented in the Pikalevo and Achinsk cement plants. Currently investigations are in progress for the use of belite mud as an active mineral additive in other cement plants (up to 20% of mud can be added to the clinker after crushing) and as an active filler in dry building mixtures (up to 15 % of the mass), with results showing further prospects in this direction. Similar developments have taken place in China, where BR from the sintering process is used for above and other applications, with increasing industrial success [14].

Adding to resource utilization, the technology of gallium extraction (galam process) with different preparation steps developed by National Aluminium and Magnesium Institute (VAMI) was realized industrially at 7 alumina refineries processing bauxite and nepheline in USSR, making 40% of world Ga production from mid 1970s till the end 1980s.

2.2. Approach for bauxite residue utilization

Bauxite residue, with low content of major elements (iron oxide, alumina), interpenetrating complex phases, fine particle size distribution and variable composition cannot compete with natural ores. However, following alumina extraction, BR contains double the amount of macro-and micro impurities (for example mud of Ural plants of Russia contains 120 - 150 g/t Sc, 300-350 g/t Y and La, and 600 g/t Ce) and can be seen as preferable raw material when compared with higher NORM containing conventional sources for these metals [15]. BR neutralization shall be made self-sustaining due to the recovery of caustic soda. Following the same philosophy as applied for alumina production from nepheline, more profitable extraction of rare earths can compensate for the potentially less profitable bulk use of main fraction of BR in other industries (construction, steelmaking, etc.).

2.3. Overview of BR utilization activities in the USSR / CIS

Since the early 1970s the Soviet Union conducted research on a wide range of applications for red and sintering mud of different plants, some of which have been successfully implemented. The studies coordinated by VAMI included lab tests and 47 trials at more than 30 industrial plants [16]. The work was done based on Government decisions and programmes, as well as directly with customers. Leading professionals in the specific fields were involved. As a result, the CIS countries are today in the second place, after China, in terms of utilization of bauxite residue.

Table 1 shows the work done and potential of utilization volume for 2 alumina refineries located in Urals part of Russia producing slightly more than 2.0 mtpa of BR. The column "Technology works" accounts for how much proven preparation and utilization technology at customer site is, and "Marketing works" state for how much BR was presented at plants of potential customers. As can be seen, potential of use exceeds the BR production volume.

Table 1. BR prospects for application in different industries [16]

Name	Target industrial application areas	Supply potential		Technology works, %	Marketing works, %
		ktpa*	USD/t		
Ferraloks	Cement production	200 (300)	3-5	100	50
Fakrint	Iron and steel industry	700-1000 (50)	20-40	100	10
Altbento Fakrint	Iron and steel industry	100-150 (10)	20-40	80	10
UMK-Gr	Fertilizer	1500 (10)	< 50	70	50
	Earthworks	2500 (5)	< 10	50	50
Feral-sorbent	Chemical industry, etc.	> 1500	15-50	50	-

* in brackets is shown amount of BR industrially tested in specific application

2.3.1. Bauxite residue in cement production

As early as in 1974 [17] it was established that introduction of red mud in an amount of 2.5 - 10% in the raw feed of cement production as source of Fe and Al is effective, as it facilitates the strength of cement in the first 1-3 days and regulates the setting time. On the basis of extensive lab and pilot plant studies, industrial experience at cement plants was achieved and specifications for red mud use as part of raw meal were developed.

In order to obtain moisture (25%) that is acceptable for cement producers, the Nikolaev refinery in the beginning of 2000s built a filtration and unloading complex, utilizing press filters. Due to the high cost of processed red mud, the complex is no longer used for BR, and now BR preparation is done in the open air, including draining in a special section of mud disposal area, followed by air drying at a suitable area above the water level (Figure 1). BR is prepared and shipped by an intermediary company to 11 cement plants in Ukraine, Russia, Georgia, Moldova and Belorussia. Transportation distance by train transport is as much as 1,500 kilometers. The recycled mud volume is about 300,000 tonnes per year, i.e. about 15 % of the annual mud production of the refinery. Brand name "Ferraloks" and trade name "aluminous cake" with lowest rail tariffs applied are also attributed to this product.

Figure 1. Arrangement of red mud drying and loading at Nikolaev Alumina refinery (Ukraine).

It is expected that upon receipt of REACH certificate for red mud, it will be possible to supply red mud to Bulgaria, Romania and Poland, doubling the amount of mud shipments. This success demonstrates the critical role of an intermediary firm in the supply organization, since shipping of mud is usually not a core business of an alumina producing company.

2.3.2. Bauxite residue as component of geopolymers

Geopolymers present a potential clinker free alternative to Portland cement, reducing greenhouse gas emissions in the cement industry by 80% and reducing energy consumption by 45-60% compared with Portland cement. Also, they have same or better mechanical properties, high resistance to aggressive environments and extreme temperatures, and better ability to immobilize toxic and radioactive waste [1, 18].

Slag alkali geopolymers have been scarcely used in practice since 1950-ies, with most strong development in the work of V. Glukhovskiy (USSR) in 1960s [18, 19]. His efforts were a serious attempt to implement slag alkali binders in the industry. Commercial production of building blocks for houses, fences, etc. started in the 1960s. In 1970-1980, based on slag alkali binders batches were prepared of different reinforced products, construction of different objects was done – parts of the roadway of solid concrete, silo trench for dairy farm, drainage systems, multi-storey buildings with cast concrete and reinforced concrete (Figure 2), which, as we see now, after several decades, have stood the test of time.

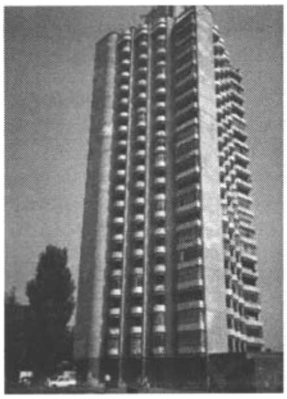

Figure 2. Building constructed from alkali-activated slag cement (end of 1980-ies, Lipetsk).

The principle of geopolymer formation is dissolution of silica and alumina in an alkaline environment followed by re-precipitation to form an amorphous solid polymer [1]. Unlike the Portland cement binder systems where BR is used as a filler, in the geopolymer formation liquid part of mud acts as an alkaline activator, while solid part being a source of alumina and silica. Thus BR may play a role in making geopolymer one of the major building materials and geopolymers production can be a major application area of red mud as it allows producing cheap building materials (pre-cast wall panels, railway sleepers, sewer pipes and other products of prestressed concrete) with low energy consumption. However, as shown in above example it requires vision, persistence and time.

2.3.3. Bauxite residue utilization in sintering for steel production

VAMI, in cooperation with ore treatment and metallurgical institutes, developed and tested at 8 Russian and Ukrainian iron and steel plants a technology of red mud preparation (including dewatering and liming) and utilization as addition to agglomeration feed and production of pellets. Pilot and industrial tests were conducted for feeding red mud to the agglomerate charge and the pelletizing process from 1978 to 1992 [20]. It was established that addition of 2% red mud to the agglomerate charge enhances the mechanical strength of agglomerates and their resistance to spontaneous destruction, with an increase in blast furnace productivity of 1.2-2.5 % and with a simultaneous decrease in consumption of metallurgical coke by 1.5-1.8%.

In the production of pellets, replacement of bentonite by red mud enhances their strength (abrasion test of the drum shelf is below 3%). Required properties of pellets are achieved with a three-fold increase in dosage of red mud as compared to bentonite. The content of iron in pellets slightly increased. A negative factor is the reduction of temperature shock resistance in pellet, which requires an expansion of the drying area and causes some performance degradation of the drying unit. In the end, the negative effects were fully offset by energy savings resulting from a reduction in the firing temperature by 30-40 °C [20].

These results provide for a commercially proven ability for the use of up to 30% of the locally produced red mud in the steel industry of the Urals region in Russia. For processing of 100,000 tons of BR there must be an agglomerate plant with capacity of 4 mtpa of agglomerate or pelletizing plant of 3 mtpa, within economic distance from an alumina refinery.

2.3.4 Beneficiation of bauxite residue to increase its iron content

Beneficiation studies comprised a combination of separation processes by size (classification), magnetic properties (magnetic separation) and density (in a centrifugal field). As a result of research the greatest effect was observed using magnetic and gravity methods with pre-treatment [15]. The content of iron oxide in magnetic products rose from 43 to 59 - 60%. Taking into account the LOI (approx. 9%), high calcium content (approx. 10%) and low silicon content (approx 6%) this corresponds to a low-grade industrial concentrate with total iron at the level of 48-50%. Blast furnace technology requires high concentration of Fe with limitations on Na_2O (below 0.5%) Al_2O_3 (has to be absolutely below 5 %) and TiO_2 (has to be below 2-3 %). Also minor impurities (S, Zn, P) in the concentrate were higher than acceptable values, thereby restricting that only 10 - 12% concentrate can be mixed to the sinter charge in a steel plant [21].

With the concentrate yield of 25 - 30% the entire volume of red mud produced in Urals region of Russia (about 600 Ktpa concentrate) can be totally consumed at the nearest steel plants.

2.3.5. Bauxite residue as a source of rare and trace elements

Introduction of scandium and yttrium in alloys greatly improves their mechanical properties. Scandium in the Soviet Union was produced mainly as by-product in the uranium and titanium industries. Extraction of scandium from red mud is more economical compared to conventional methods because red mud is fully prepared for recycling and contains much more rare & trace elements and less radio nuclides.

Scientists of Russian Academy of Science with VAMI and Mekhanobr Institutes in the mid of 1980's developed the technology of magnetic- hydro chemical extraction of scandium oxide from red mud. Laboratory and pilot tests have shown high efficiency of extraction of scandium into the magnetic concentrate (Sc_2O_3 content reached 350 - 400 g/t) at the concentrate yield 7% from the mass of initial mud. From the concentrate almost all Sc_2O_3 was extracted [15]. Works are underway for commercial extraction of rare earths with high profit with objective to trigger the bulk utilization of remaining part of BR.

Alternate scenario under elaboration is extraction of rare and trace elements during CO_2 neutralisation of the main residue, also allowing to store BR it in the environmentally friendly way [22]. Under laboratory conditions Sc_2O_3 with purity of 99.0 % was obtained.

In addition to scandium, there is growing interest in yttrium, which content in red mud reaches 350 g/t, nearly three times higher compared to scandium. The improved method was developed allowing at the first stage for extraction of 80% of yttrium, which was then selectively concentrated. This treatment keeps most scandium in the mud which is then further processed as described above for Sc extraction. Under laboratory conditions, yttrium oxide with 99.5% purity was obtained [22].

2.3.6 Bauxite residue use in agriculture

Studies conducted at Nikolaev alumina refinery in the period of 1995-1998 with participation of specialized organizations [23] revealed that a wide range of macro- and micronutrients contained in BR (phosphorus, potassium, iron, sulfur, manganese, boron and in smaller quantities - magnesium, molybdenum, vanadium, cobalt, nickel) are easily assimilated by plants. In all cases, the use of BR (2 - 5 t/ha) had increased plant growth, root development and crop yield. It was found that due to BR adsorption properties, fixation of potassium improved by 30-40%, nitrogen by 11%, phosphorus by 20-25% compared with control tests. It was also shown that red mud introduction in the soil does not increase NORM content. As a result of this research, the production of certified fertilizers (brand name YMKa) was organized in 1996.

Also in the investigations at Nikolaev alumina plant [24] it was established that performance of red mud as ameliorant to reduce soda content of soil exceeds the performance of gypsum. It should be noted that the introduction of excessive amounts of calcium in the case of gypsum prevents the absorption of other cations by plants (K, Mg, Zn, etc.) which is not observed using BR.

Currently although all the certificates, specifications and conclusions of appropriate authorities are in place, the Nikolaev BR is not used in agriculture because of perception of red mud as hazardous waste, an impression that mass media helped to increase especially after the events in Hungary. Work towards the change of this perception shall be continued on a larger scale, including at international level with more and more cases of safe and effective use presented to the public.

2.3.7. Other applications

In addition to the above examples, technologies of modification and use of BR as complex alumino-ferric coagulants, pigments, sorbents, etc. were developed [25] and finding limited use.

Further technical developments and economic assessment are underway for bulk and minor, higher added value applications of BR in order to achieve overall positive processing scenario.

2.4. Processing bauxite residue in liquid phase reduction furnace

Currently above 1.1 billion tones of pig iron per annum are produced globally requiring 1.7 billion tpa of iron-ore concentrate (Fe 60-65%). Considering average Fe content in BR ~ 30%, from the whole global annual generation of BR (120 mtpa), about 35 mpta (or only 3 % of global output) of pig iron can be produced.

At the current cost of iron-ore concentrate in China and other importing countries 170-180 $US/t, BR even with lower content of Fe can be a potentially attractive raw material for production of pig iron if an efficient technology for its processing would exist.

Sinple methods of utilizing BR in a blast furnace process are limited by impurities content (Na, K, S, P, As) and low level of Fe which does not allow to produce an agglomerate sinter consisting of BR only and to achieve required efficiency. So one should consider other ways, outside of the blast furnace process, where about 40 technologies exist tried in a pilot plant scale or being in industrial operation. These methods are divided into direct reduction and liquid phase reduction processes.

Direct reduction processes (Midrex, HIL-III) for efficient operation require raw material of high quality containing Fe>60% and low level of impurities (S, P, Na, K). The ITmk3 technology occupies an intermediate position between direct and liquid phase reduction processes. This technology has lower specific productivity and requires high capital costs, besides significant part of sulphur and most of phosphorous will be transferred into final product – nuggets.

Liquid phase reduction processes are classified in processes with pre-reduction (Corex, Finex, Hismelt) and those without pre-reduction (Romelt, AusIron).

Applying a pre-reduction stage will result in accumulation of undesired impurities (S, P, As) in metal requiring expensive processes of pig iron refining. So be the processes without pre-reduction stage will be preferred, among which there are two well established – Romelt [26] and AusIron [27-29].

National University of Science and Technology (MISIS) together with NALCO and RSIL (India) studied processing of red mud by the Romelt process. The advantage of BR processing in the Romelt furnace is that BR preliminary treatment is not required, with the exception of a drying to achieve 10% moisture. The main obstacle to implementing Romelt for commercial BR processing is high energy consumption and low grade of product pig iron – it is not possible to remove more than 90-95% of sulphur and more than 30-40% of phosphorous. Thus, to achieve a target quality of pig iron, P content in initial BR should be reduced down to 0.02 - 0.03%, and S content - down to 0.15-0.20 % that is not feasible.

Based on the information available on the AusIron process [27-29] it is known that only 1 % of initial S and 20% of initial P transfer to the product. Higher degree of impurities removal in AusIron compared to Romelt probably can be explained by higher Fe content in slag (4 - 17% compared to 2 - 5% respectively). Higher oxidation potential in AusIron slag bath contributes to higher transition of S and P into slag and gaseous phase. However processing by AusIron process of non-beneficiated BR with 30-35% Fe considering higher iron content in slag could lead to high iron losses (up to 20%) and decreasing of process efficiency.

According to the data on AusIron in paper [27], at pig iron production rate of 500,000 tons per annum, furnace area is 200 $м^2$. Thus, calculated specific productivity of AusIron makes 0.30 - 0.35 t pig iron from 1 m^2 per hour, i.e. 3 times less than Romelt.

Hence, existing processes require further refinement to reduce specific energy consumption, improve specific productivity and product quality, with necessity for creation of a prototype unit.

At present, NUST "MISIS" is developing *next generation technology after Romelt* with reduced energy consumption, now at bench scale. Table 2 shows calculations of the main parameters of the new technology in comparison with those of Romelt.

Table 2. Comparative calculations of MISIS processes

Parameters	Technologies	
	Romelt	New MISIS
Area of furnace, m^2	20	20
Specific productivity, t/m^2h	1.0	1.0
BR consumption, kg/t pig iron	3,185	3,217
Coal consumption, kg/t pig iron	1,264	903
O_2 (95%) consumption, nm^3/ t pig iron	1,027	677
Chemical composition of pig iron, %:		
C	4.5	4.5
Si	0.1	0.15
S	0.15	0.010
P	0.41	0.035

Calculations were done for processing BR from Kamensk-Uralsky alumina refinery of Russia, having the following composition:

Al_2O_3-11.5; As-0.012; CaO-9.65; Fe_2O_3-46.5; K_2O-0.24; MgO-0.78; MnO-0.74; Na_2O-4.7; P_2O_5-0.76; TiO_2-4.3; SiO_2-13.5; C-0.69; S-0.83. others - 0.798; LOI - 5.0. Moisture is 10%. Thermal coal of the following composition is taken as a fuel source and a reducing agent: W = 10%, A = 10,8%, S = 0,4%, V = 14%.

The Table 2 shows 30-35 % lower energy consumption of the new technology as compared to Romelt and drastically improved pig iron quality. The payback time of the new technology using BR is estimated 3-5 years only.

There is no reference found in literature about energy consumption of the AusIron process depending on capacity and ore grade, however considering similarity of Romelt and AusIron processes, one can assume similar specific energy consumption and production cost of pig iron of both processes.

Significant advantage of the compared technologies of direct processing of BR in liquid phase reduction furnaces is the possibility to change the composition of the slags produced. That would allow to improve the efficiency of industrial operation due to slag based value added products (slag stone casting, mineral wool, etc.).

3. Further Research directions

As stated by IAI, "Utilisation of BR as a resource for further extraction of metals (soda, alumina, iron, valuable trace elements) will require further novel research" [7]. Development of effective technology is the key factor for success in the above as well as in other applications, such as geopolymers, construction, and agriculture.

The proposed directions for further research are presented below.

Table 3. R&D and technology development efforts required for effective bauxite residue utilization

#	Research area	Research focus, deliverables
1	BR preparation and beneficiation to produce iron-rich fraction for use in iron and steel metallurgy / cement industry	1. Improved dewatering methods with lower costs; 2. Neutralisation technologies with caustic soda recovery; 3. Improved methods of beneficiation (dispersion, high intensity magnetic separation, floatation, etc.); 4. Reduction roasting method can be used to further increase content of Fe60% which is currently very expensive, so new methods with reduced energy consumption to be developed; 5. Joint processing of iron fraction with iron-rich wastes to be studied for improving iron content; 6. Removal of impurities undesirable for steelmaking process by hydrometallurgical treatment with subsequent extraction of REE and other valuable components, including acid methods, 7. Separation of REE in oxide and metal forms as separate products and improvement of their quality; 8. Capture and utilization of NORM rich fraction if required
2	Improvement of liquid phase reduction processes	1. Increase specific equipment productivity to reduce capital cost; 2. Significant (by 30-40%) reduction in specific energy consumption; 3. Improvement of extraction efficiency of useful components in product, reduction of slag output; 4. Improving the quality and range of products (pig iron, ferrosilicon, slag based products); 5. Industrial pilot/demonstration unit to be set up.
3	Use of BR as part of geopolymers	1. Development of optimal compositions, technologies of manufacture of geopolymer final products; 2. Intensive studies on the physical, mechanical and other properties as function of time; 3. Setting up demonstration units.
4	Use of bauxite residue as soil amendment	1. Extensive studies of useful elements and NORM behavior, methods to immobilize NORM if needed; 2. Study and demonstration of application in national and international level
5	Other applications	1. Search and identify new and innovative applications, including the joint processing of red mud with other wastes (slags, ashes, etc), applications with higher added value.

4. Practical steps for bulk red mud utilization

Although there are above 1000 patents and 3000 papers on bauxite residue utilization globally and many novel ideas emerge from time to time, lack of their implementation clearly shows the need to follow certain *criteria* for success. As per approach developed in VAMI [16], the criteria are the following:

A. Possibility for processing of the entire waste of at least for one alumina refinery;

B. Make sure that environmental performance of alumina plant and bauxite residue consumer plant is not deteriorated;

C. The utilization technology is adequately proven in industrial conditions;

D. Availability of official letters of intent from customers for all kinds of marketable mud products of a particular refinery;

E. Availability of regulatory documentation for production and sale of all marketable mud products or semi-products;

F. Investment payback in acceptable timeframe.

To meet these criteria, a step change is required from where we are today, including:

- the need of precompetitive projects to develop base of effective technologies, between alumina producers (that are otherwise in competition);
- the need of demonstration projects available for inspection by different research bodies and authorities (for example, house build using new materials based on geopolymers, etc.);
- development of small applications with high added value, helping the less attractive bulk applications of remaining BR;
- implementation of a complex technology by separate self-sufficient stages yielding commercial products;
- the customer of BR product shall be involved in all stages including research and industrialization whilst the supplier (alumina refinery) shall be responsible for continuity of utilization. Economic interests of supplier like desire to increase cost of red mud product can be harmful;

- the need of promotion of waste utilization from authorities via research grants, industrialization aid, tax holiday, no liability guarantees, establishment of lowest rail tariffs for BR and products thereof, regulation of free movement across borders of materials, apparatus and instruments for research in the field of mineral processing and industrial waste recycling;
- perception of red mud as harmful waste shall be overcome – via advanced technology and/or via support of authorities for utilization in other industries;
- the need to organize regular conferences specifically on bauxite residue utilization and storage practices, and enhance web resources promoting utilization and positive public perception of BR and its products.

5. Conclusions

Bauxite residues of alumina production are bulk wastes of aluminium industry. Transition from building bauxite residue disposal areas to creation of bauxite residue handling units for effective processing is inevitable in the long run as it will reduce production cost of alumina and aluminium with improvement of environmental side of the process.

A list of criteria is proposed for identifying those technologies and applications that are most ready and attractive for implementation.

The most urgent technology development areas and practical organizational steps are proposed.

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