ALUMINA REFINERY WATER MANAGEMENT DESIGN IN TROPICAL AND SUBTROPICAL CLIMATES

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Abstract—*How to manage and treat liquid effluents is a determinant consideration in designing alumina refineries. Rainfall, evaporation rate, proximity to the coast, process design and layout, ore mineralogy, local environment, and potential impact on contiguous communities are all integral factors that must be taken into account when developing an appropriate refinery water management strategy. The goal is to achieve zero discharge of liquid effluent to the environment. However, this is not always the most feasible solution under the extreme rainfall conditions often encountered in tropical and subtropical locations. This paper explores, for both inland and coastal refineries, the following issues: methods to reduce and control refinery discharges, treatment design criteria, and socioeconomic aspects related to surface water use in settlements adjacent to the refinery.*

Keywords—*alumina refinery, environmental design criteria, wastewater*

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INTRODUCTION

The increased global focus of governments, international financing institutions, mining companies, and communities on sustainable development has brought a higher level of environmental and sociological regulation and scrutiny to new and expanding mining operations than in the past.

The plant water management strategy is a key consideration of regulators, investors, and communities when they evaluate the sustainability of a greenfield alumina refinery. The diminishing availability of clean water worldwide as a result of water pollution has led many governments and international financing institutions to introduce increasingly stringent water discharge quality requirements to minimize further impacts on water resources. The issue of effective effluent and hazardous waste management in the alumina industry was further highlighted by the accidental release of approximately 1 million cubic meters (1.3 million cubic yards) of bauxite residue, also called red mud, from the Ajka alumina refinery in Hungary in October 2010.

Many legislative frameworks allow existing operations to meet less stringent standards than those expected of a greenfield facility. Therefore, this paper pays the most attention to those regions expected to become future alumina sources and to the associated technical barriers to developing sustainable and viable projects.

As commodity prices increase and accessible bauxite deposits near coastal port facilities (needed to ship alumina to smelters for aluminum production) become depleted, the need to develop inland ore bodies is increasing. The relationship of a refinery's location to its bauxite deposit and transport infrastructure directly affects the project's material handling equipment costs and resulting economic viability. Selecting the optimum location for a refinery from a materials transportation perspective involves, in most cases, minimizing the distance that bauxite must be transported from the mine to the refinery. Therefore, there is a trend toward close-coupled mines and refineries.

Another consideration is the use of seawater neutralization—the established method of effluent treatment at alumina refineries. For inland locations, the cost of pumping seawater over long distances can prove prohibitive. A further consequence is that bauxite residue, a solid refinery byproduct, would not be able to be neutralized by seawater and would either:

- Have to be stored as a hazardous waste, which would require long-term environmental management
- Require neutralization by other means such as adding acid, which could be costly if the volume of acid needed exceeded the waste acid produced by the refinery

In short, at inland locations, the water management strategy becomes a key consideration in alumina refinery site selection studies because water management facilities can significantly affect project net present value (NPV).

ABBREVIATIONS, ACRONYMS, AND TERMS

BOD	biochemical oxygen demand
BRDA	bauxite residue disposal area
DSP	desilication product
EHS	environmental, health, and safety
GIIP	good international industry practice
IFC	International Financing Corporation
NGO	nongovernmental organization
NPV	net present value
PRC	People's Republic of China
SRT	sump relay tank
SWP	stormwater pond

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BACKGROUND

Aluminum is used to make airplanes, automotive engine blocks, beverage cans, window mullions, cooking foils, and thousands of other items. Only steel exceeds aluminum as the world's most used metal. Even with the high percentage of recycled aluminum, the demand for primary aluminum is increasing at about 6% per year. To smelt 1.0 metric ton (1.1 tons) of primary aluminum requires approximately 2.0 metric tons (2.2 tons) of alumina, and approximately 5.0 metric tons (5.5 tons) of bauxite are refined to make each metric ton of alumina. Aluminum smelters are located where electricity is inexpensive, and the alumina is shipped to them from around the world.

Bauxite is mostly formed by the weathering of lateritic rock caused by the high amount of rainfall in tropical and subtropical environments. **Figure 1** shows regions currently undergoing lateritic weathering. The generally well-defined

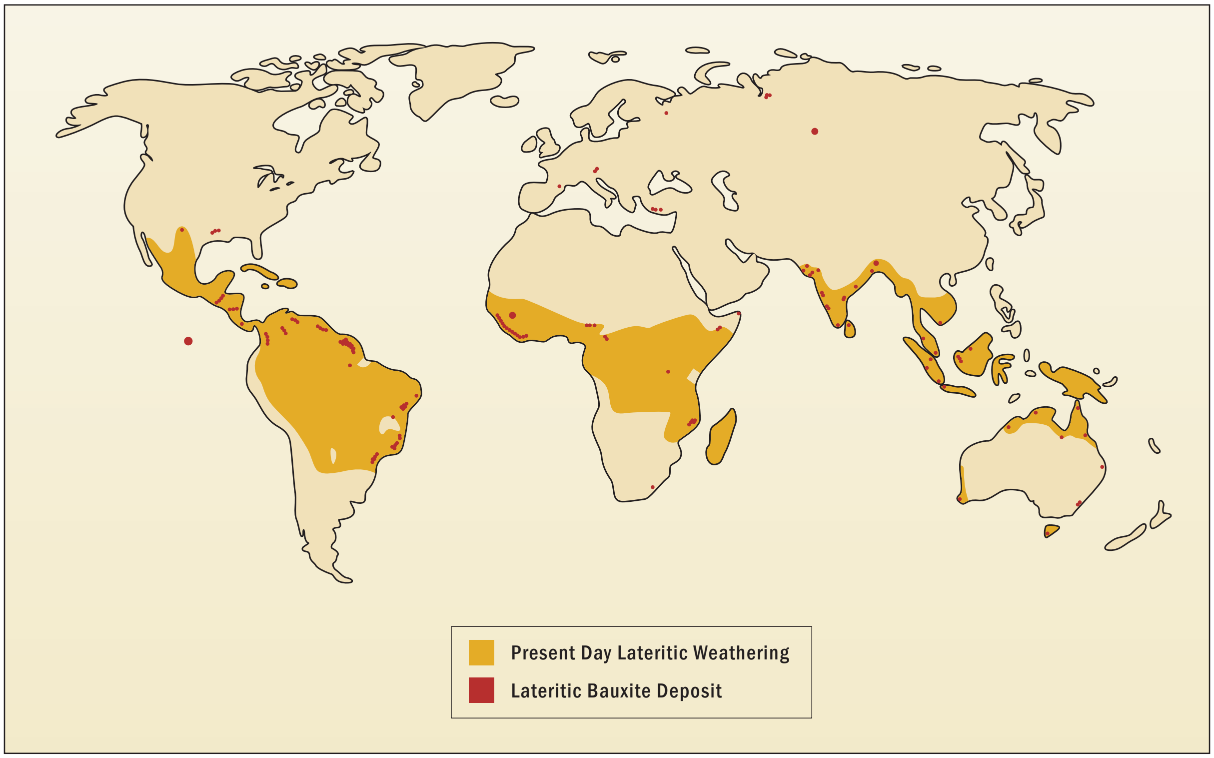

Figure 1. Lateritic Bauxite Sources (modified from Freyssinet et al. [1])

wet and dry seasons of these regions force refinery designers to address the "feast or famine" issue associated with water availability. Zero effluent discharge, while ideal for sustainability, is often impractical for water impoundment in these regions due to the size and consequent capital cost of the facilities required to store enough water during the wet season to provide sufficient water during the dry season.

Bauxite contains organic and inorganic impurities that increase the costs and environmental risks associated with processing it into alumina. These minerals and compounds are readily soluble in the liquor used by the Bayer process (the principal means of refining bauxite into alumina) and tend to accumulate therein. These impurities are discharged into water impoundments via runoff from contaminated surfaces in the process areas and are also discharged with bauxite residue into storage areas. The demonstrated methodologies used to treat the large-scale bauxite residue and to neutralize effluent before it can be discharged into surface or marine waters primarily employ seawater, either alone or supplemented by spent sulfuric acid, a byproduct of the refining process.

When refineries close-coupled to inland bauxite deposits are being considered, a complex tradeoff needs to be made among the following factors:

- The long-term sustainability of storing bauxite residue, in either a stable (neutralized) or a hazardous (raw) form
- The capital and operating costs of pumping seawater
- The capital and operating costs of materials handling and transportation, primarily of bauxite and alumina
- The cost of water treatment facilities to enable effluent to be discharged into streams and rivers, which may be used by local communities for drinking water (for both human and animal consumption), fishing, and irrigation
- The land availability for, and the capital and maintenance costs of, water and bauxite residue disposal areas

In summary, the key water management considerations are:

- Water availability for refinery consumption is highly variable from season to season.
- The impoundments needed to store water during the wet season for use in the dry season may be impractical in high rainfall areas due to the large capital costs associated with constructing facilities large enough to accommodate extreme events and due to the perception by contiguous communities that there is large-scale storage of liquid hazardous materials.
- In inland locations, water effluents may discharge into streams potentially used for drinking and primary industries (farming, animal husbandry, and fishing).
- Typical refinery wastewater treatment techniques, such as seawater neutralization, may not be feasible.

DEFINITION

This paper discusses the following topics related to alumina refinery water management system design:

- Methods to reduce and control refinery discharges
- Treatment design criteria
- Socioeconomic aspects related to surface water use in settlements adjacent to the refinery

These considerations are important both in the site selection and preliminary and detailed design of greenfield refineries and in the operational management of installed facilities. Furthermore, these considerations can play a major role in both the financial viability and the long-term sustainability of projects. Industry forecasts suggest that global demand for aluminum will continue to increase. This demand will likely result in the development of new bauxite deposits and, consequently, refineries in tropical and subtropical locations.

Increased demand for aluminum will drive the development of new bauxite deposits and, consequently, in tropical and subtropical locations.

REFINERY WATER BALANCE

Water Supply and Demand

An alumina refinery using the Bayer process consumes 2.0–2.3 metric tons (2.2–2.5 tons) of raw water per 1.0 metric ton (1.1 tons) of alumina produced. The actual rate of consumption depends on bauxite quality, process design, demand for nonprocess applications (e.g., for potable water), and the extent to which water is recycled within the facility. About 10% of the total water intake is accounted for by free moisture in the bauxite feed and in the 50% caustic soda solution used as the primary process reagent.

Figure 2 depicts water inputs and outputs across the outer system boundary between the refinery—including the bauxite residue disposal area (BRDA)—and the external environment. This water balance assumes 100% diversion of potential run-on to the site and no water discharge from the BRDA to groundwater (by seepage).

Only three sources supply the remaining 90% of the total raw water demand: natural surface sources, subsurface sources, and rainfall. This means that a significant proportion of the water intake is from rainfall onto the refinery, which is *uncontrollable* and, under certain circumstances, may far exceed the capability of the refinery to manage the quantities involved.

With the notable exceptions of the People's Republic of China (PRC) and Russia, most refineries have been established in tropical and subtropical regions in proximity to the principal lateritic bauxite provinces. These locations are not only exposed to high seasonal rainfall, but are also at risk of extreme flood events. New capacity planned in Brazil, Guinea, and Southeast Asia will likely face these issues.

Environmental Control Requirements

It has long been recognized that effective environmental management is critical to the viability of any project. Stringent environmental control standards and industry best practices with regard to operations and maintenance must be reflected in the refinery design criteria.

The focus of this paper is on managing liquid effluent, any release of which—treated or untreated—is potentially harmful to the environment and consequently deleterious to the well-being of the community. The refinery's Bayer plant itself handles a large volume of process liquor, the bulk of which is an aqueous

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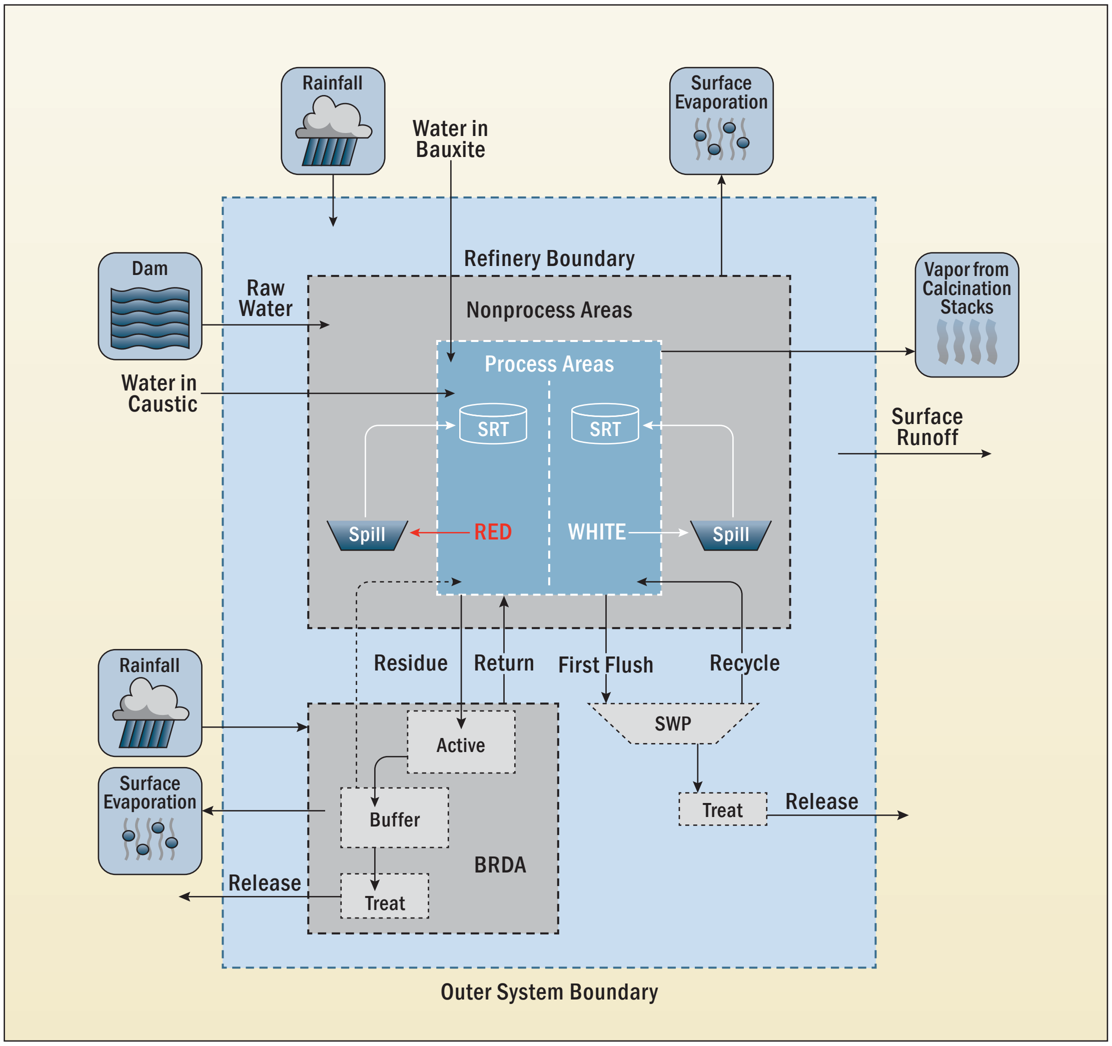

Figure 2. Refinery Water Balance

solution of caustic soda containing dissolved aluminum, silica, and many other organic and inorganic impurities, including trace metals such as molybdenum and vanadium, which occur in the bauxite.

The refinery is designed to contain the live liquor inventory, with minor spills within operating facilities being promptly returned to the process. Provision is also made to intercept larger, accidental spillages that could result from equipment failure or abnormal events such as the loss of electrical power. Spill ponds are installed at strategic locations and have sufficient capacity to handle the contents of one or more of the largest tanks in the various facilities. These measures minimize the probability of releasing highly concentrated, potentially toxic material that cannot be discharged except under the most extreme circumstances.

Environmental control measures for an alumina refinery must also include facilities to handle contaminated runoff occurring as a result of rainfall catchment within the facility perimeter. One or more stormwater ponds (SWPs) are provided and must be considerably larger than the process spill ponds. An SWP is intended to impound rainfall runoff collected from nonprocess areas. During the initial onset of rain, this runoff mobilizes relatively minor amounts of surface contaminants. After a short period, typically several hours, the runoff quality is similar to that found in neighboring areas outside the refinery perimeter. Although impure, impounded SWP water is suitable for recycling into the process for various duties, thereby reducing the intake of raw water. Finally, the BRDA, the impoundment area constructed to permanently store bauxite residue and other solid wastes, also accumulates contaminated water that may be returned to the process to recover the soda content.

Under normal operating conditions, the Bayer plant liquor inventory is controlled within narrow limits by varying the input rates of caustic soda, raw water, and in-plant evaporation. Operating procedures should be aimed at keeping the process spill ponds empty and the water levels in the SWP(s) and BRDA as low as possible during periods of little or no rain. The onset of heavy or sustained rainfall, typical in tropical locations, gives rise to large volumes of site runoff, as well as run-on if it is not effectively diverted. These volumes can rapidly exceed the finite limits of the available impoundments, despite the risk analysis and major investment involved in providing them. To handle situations where the maximum impoundment capacity is exceeded, the regulatory option often exists to impound only the so-called first-flush runoff, after which, all subsequent catchment is allowed to bypass the SWP(s) and be released to the environment.

Exceptional rainfall events could defeat even this strategy (assuming that it is permissible), and the refinery would then be forced to release contaminated water to the environment. Such a release may be diluted to mitigate the alkalinity of the effluent but would still result in contaminating receiving waters above background levels, probably in violation of license provisions.

Community water demand, including agricultural, may become a significant component of total consumption, and any shortage or degradation of the community supply would likely be a significant issue. These factors also need to be considered in the overall conceptual design of the water supply system.

The conclusion is that despite careful scenario planning and investment in major infrastructure, sooner or later an extreme event will cause an unacceptable environmental incident. Therefore, the refinery must be located where the receiving waters are able to sustainably withstand the impact. This explains why most major refineries are located near the ocean, which also facilitates applying seawater neutralization, the only current demonstrably effective liquid effluent treatment technology.

The refinery must be located where receiving water can sustainably withstand the impact of effluent resulting from an extreme rainfall event.

Refinery Design Principles

The unavoidable accumulation of contaminated water as a result of rainfall, reclamation constraints, and severe limitations on release to the environment has five major consequences for the design of the refinery. These consequences are discussed in this section.

1. **A refinery environmental policy that mandates compliance with relevant regulatory standards becomes a major driver in selecting the refinery and BRDA locations.**

   This policy also has a profound impact on refinery design features and the operational procedures that enable the standards to be met.

   A policy mandating compliance with liquid effluent standards is consistent with one for particulate emissions or any other form of environmental impact. The difference between implementation for particulates (e.g., installing dust collectors) and for release of impounded water is one of relative complexity for the latter and requires coordination of the total refinery design.

Facility design criteria must address the (water) environmental policy, which ranks along with safety and NPV considerations in importance, and evaluate the effects of complying with it before detailed design can proceed. Some objectives may be compatible, for example minimizing the caustic content of final-stage mud washer underflow significantly reduces operating costs.

2. **Departures from conventional refinery and waste impoundment design become necessary and can add to the cost of mitigating potential effluent management problems.**

A refinery in a location that experiences extreme rainfall events should incorporate features to minimize both the volume effects and the possible contamination of rainfall catchment. These features facilitate the segregation of concentrated process liquor (which cannot be released) from relatively innocuous nonprocess runoff that can be impounded, recycled during dry periods, and released subject to meeting license conditions.

The waste impoundment design must satisfy the following criteria:

- Effective, permanent sequestration of red mud waste, which will continue to generate alkaline leachate over the longer term
- Recovery of supernatant liquor and impoundment drainage back into the refinery process
- Sequestration of solid-phase organic and inorganic waste from process liquor purification facilities
- Disposal of other environmentally sensitive wastes (e.g., ash, scale, and waste acid)

3. **Measures must be adopted to minimize the controllable intake of raw water, particularly during the wet season, thereby reducing the total inventory to be managed.**

The probable excess of rainfall over evaporation in the regions under discussion dictates strict control of raw water intake to minimize the total volume under management. It follows that the consumption of raw water in the Bayer process should be minimized by using as much water as possible that is already within the outer system boundary.

Raw water is needed for a number of essential process duties, for domestic (potable) water (after treatment), and for the fire control infrastructure. The number of water entry points into the refinery must be minimized and all volumes accurately metered. Strong design discipline is necessary to ensure that water control policies and practices are consistently enforced. Some measures may conflict with the customs and practices employed elsewhere, but the capital and operating costs associated with treating this water may be excessive. For example, using hoses for process area housekeeping is perceived as improving employee safety by minimizing the hazard of caustic liquor exposure, but the same results may be achieved by proper safety procedures and training while minimizing water usage.

4. **Introducing measures to enforce economic use of controllable process and domestic water can significantly reduce usage.**

Water consumption may be allocated to two broad categories: uncontrollable, which is governed by the combined requirements for essential services, and controllable, which allows some degree of flexibility as to the quantity used.

Most of the process requirements fall into the uncontrollable category; for example, boiler feedwater, flocculant, and lime preparation. These examples of end uses are directly related to the refinery production rate and to the demand for raw materials and additives. Domestic water demand is closely related to the number of employees. Effective control depends on installing water-saving devices such as tap restrictors, educating employees regarding conservation, and prohibiting usage for nondomestic purposes.

The final disposition of water in this category is important in limiting the potential environmental impact. Applications such as dust mitigation can help dispose of excess impounded catchment under dry season conditions. Other applications, such as vehicle washing, may create additional problems caused by runoff turbidity or contamination by hydrocarbons and other chemical agents.

The water supply for end users beyond the outer system boundary should be from an independent source. This measure imposes a physical constraint on consumption and avoids uncontrolled influence on the infrastructure provided for the refinery itself.

5. **Several tiers of impoundments must be established to segregate process liquor, contaminated effluent, and rainfall catchment.**

   - Process spill containment—A process spill is any form of liquor, slurry, or solids released during routine operational tasks within the plot limit of any facility. Spills of this nature are normally small and are promptly collected and returned to the process. The concentrations of process chemicals are too high to permit release to the environment.

     There is a possibility that large process spills may occur due to equipment failure, such as a pipeline rupture. The refinery design should incorporate process-only spill ponds to intercept and return material that may overtop the limited facility containment capacity. The contents of spill ponds cannot be released and should be recycled to the refinery via large sump relay tanks (SRTs), which provide additional surge capacity and operational flexibility.

     Process design modeling should incorporate provision for large process spills to ensure adequate total containment facilities and return rates to the process and to prevent defined events of this nature from compromising the refinery's rated production and other key parameters.

   - Runoff management—Runoff is rainfall catchment from the refinery plot limit that must be monitored for contaminants and handled accordingly. Runoff falls into two categories:

     - Catchment within process facility plot limits—This may be relatively dilute but is still far too contaminated for release. It must be returned to the process via the SRT system, and it negatively affects the process and energy demand. These effects must also be considered for the refinery mass and energy balance. The impact must be minimized by reducing the process catchment footprint, i.e., by roofing large tanks and routing rainwater catchment to surface drains outside the facility plot limit.
     - Catchment from nonprocess areas—Runoff mobilizes soluble contaminants such as oil, dust, and dirt, the concentrations of which may be appreciable depending on such factors as paving and drainage design, control of fugitive dust from the refinery, and general housekeeping standards. Under tropical rainfall conditions, the initial (or first-flush) nonprocess runoff will exhibit short-term contaminant loadings that must be sampled, and the flow must be directed to a large SWP.

     In practice, the volume of runoff from average rainfall intensities can be far greater than SWP capacity because the costs to construct these facilities large enough to collect the rainfall volumes experienced in tropical and subtropical locations can be prohibitive. This can mean that all but a small fraction of nonprocess runoff must be released, and the refinery must be designed with this in mind. Water diverted to the SWP(s) can be reclaimed for use as process water, diverted to the BRDA buffer zone, or (as a last resort) treated and released.

     The tendency to work with average rainfall data can be highly misleading and could result in erroneous assumptions underlying the planning for the capacities of spill ponds, SRTs, the SWP(s), and the BRDA. A credible environmental control strategy should be based on scenario planning for abnormal events, such as 1:100-year-return rainfall events.

   - BRDA—The BRDA is one of only two impoundments from which low-level contaminated water may be released (the other being the SWP[s]), provided that the regulatory and/or best environmental control practices can

A credible environmental control strategy should be based on scenario planning for abnormal events, such as 1:100-year-return rainfall events.

be addressed. It may be possible to optimize the total capital investment for these impoundments by linking them so that the BRDA provides the final and somewhat larger capacity for low-level effluent.

The BRDA must be designed to prevent contamination of impounded runoff outside the deposition areas for red mud and the other solid wastes that have special sequestration criteria. Liquor that is either released from the residue slurry or accumulates from rainfall directly onto the mud deposition areas must be recycled to the refinery.

A buffer zone should be provided between the active solid waste deposition areas and the outer BRDA perimeter to allow for abnormal rainfall events that may temporarily exceed the active area's capacity. Liquor and any other leachate from other waste disposal areas should not be allowed to mix with impounded low-level water.

The remaining area of the BRDA may be used to either store and reclaim or treat and release excess water. The final treatment and disposition method is site-specific and depends on a number of factors (alkalinity, toxic ionic species, biochemical oxygen demand [BOD], temperature, and turbidity) associated with the effluent itself and the background conditions in the receiving waters.

- Final-stage mud washer underflow slurry handling—This residue slurry contains solid-phase compounds that release highly alkaline leachate over a long time frame as a result of unavoidable contact with supernatant liquor and rainfall. This tendency cannot be controlled at the source due to the presence of sodium aluminum silicates and calcium compounds that are formed in the Bayer process. The only control is at the margin, by minimizing the concentration and quantity of liquor disengaged from the residue and reducing direct contact of the consolidated mud with liquor or rainwater.

  The major controllable variables for residue disposal are the density of the slurry and the alkaline concentration of the liquor discharged with the slurry into the BRDA disposal area. Paste thickening is the most effective means of preparing a very dense, immobile slurry that releases little or no liquid as it further consolidates under its own weight.

  The remaining design issue is to minimize the total soda content (usually measured as grams of Na_2CO_3 per liter) of the final-stage mud washer underflow. A typical target is 5 g/L, based on the number of washing stages to be installed, the ratio of wash water to mud, and other factors. The target is established by considering the steady-state refinery mass balance and by making certain assumptions related to equipment reliability, washer stage efficiency, etc. Under actual conditions, major departures from steady-state operation and the other assumptions cause excursions in the amount of last-washer soda by as much as a factor of 10, resulting in values of 50 g/L or more. This implies that the number of installed washing stages and spare pumps should go beyond that suggested by steady-state modeling; otherwise, the environmental control objectives become unachievable.

In areas where bauxite mining and alumina refining are emerging, legislation and compliance monitoring are often not sufficiently developed to address contaminants of interest.

Discharge Criteria

In areas where bauxite mining and alumina refining are emerging, local and national legislation and associated compliance monitoring are often not sufficiently developed to address contaminants of interest associated with these activities. Consequently, drinking water, primary industries, and ecosystems may not be adequately protected by the existing environmental legislative framework.

Many international mining and mineral processing companies have implemented sustainable development policies that require them not only to meet the requirements of in-country legislation, but also to consider the use of the best available technologies and international guidelines. For projects seeking external financing, the International Financing Corporation (IFC) has developed specific environmental, health, and safety (EHS) guidelines that are "technical reference documents with general and industry-specific examples of Good International Industry Practice (GIIP)." These guidelines are used by the IFC for project appraisals. IFC EHS guidelines have been developed for both mining and base metal smelting and refining. [2, 3] However, these may not include all contaminants of interest relevant to alumina refinery effluent discharge. For example, the base metal and smelting guidelines state that toxicity should be considered on "a case specific basis" and do not provide guidelines for discharge of heavy metals associated with alumina refining.

Assuming that local legislation is not sufficiently defined, guidelines from international organizations and other countries with highly developed legislative frameworks can also be used to develop robust design criteria for effluent discharges from the project site.

Design criteria for effluent disposal must consider the environment to which the effluent will be discharged—a primary consideration is whether the discharge is to fresh water or to a marine environment. Quality requirements for discharge to marine water are often less stringent than for discharge to fresh water because of various factors such as higher naturally occurring baseline concentrations of compounds in marine water compared to fresh water, increased dilution of effluent when discharged to open water, and less sensitive receptors in saline water, from both an ecosystem and a downstream user perspective.

Surface water is used for drinking, recreation, and primary industries in many countries. In developing countries it is more likely to be used for these purposes without treatment. To control population influx and resulting water usage, strict and enforced industrial zoning legislation is required where industrial effluent is discharged; however, this is often lacking in the regions currently experiencing growth in bauxite mining and associated refining. In these situations, it must be assumed that human and animal ingestion of surface water could take place at any point outside the industrial fence line. Therefore, as a minimum requirement, drinking water quality standards must be attained at inland refineries discharging to streams and rivers.

An alternative is to provide a separate, secure drinking water supply to the local populace and educate the general public regarding withdrawal of water; doing so may limit effluent treatment costs. If this can be achieved and is accepted by permitting authorities, then it may be possible to discharge at a higher concentration and allow for mixing until drinking water or other international standards are achieved at a compliance point downstream of the discharge location. Mixing-zone calculations need to take into account the lowest surface water flow rate when calculating dilution, because this rate can often mean that discharge criteria to achieve compliance at the edge of a mixing zone need to be more stringent during the dry season. This applies to impurity concentrations, temperature, and turbidity (visual impact).

Nongovernmental organizations (NGOs) are becoming increasingly prominent in enforcing environmental and sustainable development policies. The poor performance of some regulators and companies has contributed to an increasing public demand for independently verified information and action. Therefore, in countries without sufficient environmental legislation to protect the health of local communities, the livelihoods of the local populace, and the surrounding flora and fauna, large corporations are often under pressure to implement stringent environmental and sustainable development policies to protect their reputation.

In summary, developing project-specific effluent discharge criteria to meet sustainable development policies requires vigorous social, health, and environmental impact assessments of existing and potential future uses, and a one-size-fits-all solution cannot be applied. However, generally speaking, discharge quality requirements to marine rather than aquatic environments are less stringent and consequently more achievable.

Assuming that local legislation is not sufficiently defined, guidelines from international organizations and other countries can also be used to develop robust design criteria for effluent discharges.

Effluent Neutralization Technologies

In this context, neutralization refers to reducing the level of alkalinity in the stream to be treated. Neutralization processes are required for effluent that is to be permanently sequestered or, where there is no other alternative, released to the environment.

An alumina refinery generates large volumes of liquid- and solid-phase alkaline effluent from a variety of sources, predominantly waste mud and other process byproducts discharged with the mud, including:

- Diluted process liquor entrained with the bauxite residue (red mud)
- Insoluble fractions of the bauxite (iron and titanium oxides)
- Desilication product (DSP)—hydrated sodium aluminum silicates
- Calcium compounds, e.g., tricalcium aluminate, calcium oxalate

Other effluent streams are generated by contamination of rainfall runoff from the refinery site and the possible spillage and release of process materials to impoundments.

Effluent released from the waste mud stream invariably exhibits pH levels above 12. Both the liquid- and the solid-phase sources of alkalinity (hydroxide ions) must be brought into reaction with a neutralizing agent. The rate at which the neutralization reaction proceeds varies greatly, depending on reactants involved, pH, concentration, and temperature.

The primary objective of treating effluent is to reduce the immediate and longer-term environmental risk of the waste stream by reducing its alkalinity to the minimum practicable level.

Principles of Effluent Treatment

The primary objective of treating effluent is to reduce the immediate and longer-term environmental risk of the (solid or liquid) waste stream by reducing its alkalinity to the minimum practicable level. However, low alkalinity is not the only consideration. Potentially serious soluble pollutants such as aluminum and other elements (e.g., molybdates, vanadates, and arsenates) must also be targeted.

Neutralization options include reaction with seawater, dilute sulfuric acid, or a combination of both. Another option, carbonation, is in the early stages of development, and little process performance data is available to suggest this as a viable option at this point.

The application of either seawater or acid neutralization must take into consideration that a certain fraction of solid-phase alkalinity is released over long periods of time—weeks or months, depending on the prevailing conditions and the composition of the residue. In practical terms, there is no such thing as complete neutralization, due to the limited treatment time available.

Treatment with sulfuric acid invariably involves reusing the spent dilute acid used initially to clean refinery heat exchangers. During the cleaning process, the acid dissolves scale deposits that may contain additional pollutants. A corrosion inhibitor is also employed, the nature of which must be assessed if the reacted acid is to be released into the environment.

The chemical and physical properties of the particular bauxite to be processed have a determinant impact on the refinery's red-side process design, on the BRDA design, and on the technology selected to treat effluent. Significant effort and cost must be invested in characterizing the bauxite, and the same attention must be paid to establishing the environmental control requirements.

Design Basis

The refinery's design basis must specify the following fundamental criteria:

- The refinery's location
- The practicability of using seawater neutralization
- The climatic conditions—rainfall and evaporation
- The need to release effluent to the environment and the effluent's likely quantities
- The receiving waters into which effluent will be released
- The social, agrarian, and environmental factors associated with effluent release
- The applicable effluent discharge standards
- The critical parameters for the outfall point
- The waste streams to the BRDA
- The tonnages of solid and liquid waste to be discharged
- The composition of the red mud
- The variability expected in waste loadings and concentrations
- The probable toxicity profile and whether mitigation technology exists

Acid Neutralization

In acid neutralization, residue is mixed with dilute acid, which reacts immediately with soluble alkalinity to produce a rapid but temporary drop in pH. Acid neutralization is commonly achieved by adding (waste) acid after the last mud-washing stage. The attack by residual acid (if any) on the solid-phase alkaline content occurs over a much longer time frame and may lead to a gradual increase in pH. It is, therefore, impractical to neutralize the solid-phase component before residue disposal. Post-neutralization of waters released from the BRDA may be necessary.

Acid neutralization produces a dilute sodium sulfate solution, which, if released, may give rise to environmental impacts in its own right, such as algal blooms or local concentrations that exceed background levels or the level specified for potable water (<250 mg/L).

The availability of sufficient acid to treat primary/secondary residue or effluent must be carefully assessed. It is also necessary to establish that probable peak effluent discharge rates can be handled and that the potential heavy metal contamination of the spent acid is acceptable.

Seawater Neutralization

The important reaction in seawater neutralization is the precipitation of hydroxyl ions by their reaction with the magnesium ions present in the seawater. Again, the rate of reaction varies greatly—rapid in the liquor phase, much slower with calcium compounds and the DSP. The presence of sulfate ions inhibits the reaction with the DSP.

A major advantage of seawater neutralization is the precipitation of aluminum ions during the formation of hydrotalcite, the primary reaction product from the soluble alkalis and magnesium. Hydrotalcite formation has also been shown to remove vanadium, molybdenum, and phosphorus when the pH is in the range of 8–10.

If turbidity criteria can be attained, seawater neutralization of residue allows immediate effluent discharge, eliminating the need to separately contain and manage the liquor. Additionally, using excess seawater enables the neutralization and release of alkaline runoff generated by the slow dissolution of alkaline compounds.

The system design must ensure that the seawater supply and discharge capacities always exceed the magnesium demand of residue alkalinity excursions resulting from process problems. If the pH is allowed to rise, some of the trace metals in the hydrotalcite revert to the soluble phase and affect receiving water quality. If excess alkalinity cannot be precipitated within the BRDA, additional hydrotalcite precipitation occurs at the outfall, creating a visible plume.

Attempts have been made to augment seawater neutralization with sulfuric acid. This significantly alters the chemistry to the point that a much lower pH is necessary to remove aluminum from the solution. Oxalate removal is favored at high pH values, so the addition of acid may be counterproductive and costly.

Alternative Technologies

Other technologies for industrial water treatment, such as membrane treatment and ion exchange, are untested on alumina wastewater chemistry and at the scale discussed in this paper. If these technologies were proven to be effective, the volumes of water that would require treatment in tropical and subtropical locations would result in significant increases in capital and operating costs for alumina refineries.

CONCLUSIONS

Alumina refineries, whether coastal or inland, discharge effluent under both normal and extreme circumstances. To minimize the amount of effluent requiring treatment and discharge in tropical and subtropical climates, the environmental design features and operational controls detailed in this paper for managing raw water intake and the water balance should be incorporated into the design.

Inland refineries pose additional challenges due to the onerous discharge criteria applied to inland waterways. Discharge criteria can be imposed by government legislation or financial institution requirements or prescribed by company internal sustainable development and environmental policies. In either circumstance, effluent discharge requirements are often defined according to the expected use of the receiving water body by contiguous communities.

Inland refineries pose additional challenges due to the onerous discharge criteria applied to inland waterways.

The most demonstrated treatment method for large-scale refineries is seawater neutralization. However, transporting seawater to an inland refinery and then back for discharge can strain a project's capital and operating costs and may not be feasible.

Other water treatment methodologies are not proven at large-scale refineries that are required to meet stringent inland water requirements and may require expensive reagents to treat the effluent. These methodologies can increase a project's risk profile, drive up capital and operating costs, and result in breaching discharge design criteria, with consequential downstream impacts. ■

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BIOGRAPHIES

Lucy Martin is currently based in Brisbane, Australia, as a project engineer on the Frieda River project. She previously held the position of chief environmental engineer for Bechtel's Mining & Metals (M&M) Global Business Unit (GBU). In this capacity, she was functionally responsible for the environmental engineering activities executed from Bechtel's offices in Montreal, Canada; Brisbane, Australia; and Santiago, Chile. Lucy began her career with Bechtel as a process engineer with the Bechtel Water organization and transitioned to the Bechtel Oil, Gas & Chemicals GBU before joining M&M in 2003.

Lucy holds a BS degree in Chemical Engineering from the University of Sheffield, England, and is a registered Professional Engineer in Ontario, Canada.

Steven Howard is a senior process engineer with Bechtel's Alumina & Bauxite Centre of Excellence in Brisbane, Australia. A chemical engineer with over 40 years of experience in major alumina refineries in Australia and Jamaica, he gained his technical knowledge through direct involvement in facilities employing both low- and high-temperature bauxite processing technology and by assessing and applying process design and environmental control advances. Senior appointments in operations, technical, and environmental management afforded Steve the opportunity to devise and implement policies and procedures to address the demanding environmental standards facing the large-scale chemical process industry.

Before joining Bechtel in 2008, Steve spent 15 years in Jamaica, a location that typifies the challenges of operating in an emerging economy beset by the extreme climatic events alluded to in this paper.

Steve holds BSc App (Honours) and BE Chemicals degrees from the University of Queensland, Australia. He also has a Graduate Diploma in Management from James Cook University in Queensland and has completed the Management Development Program of the Australian Administrative Staff College of Mt. Eliza in Victoria.