

## Process Control in a Refinery Based on NIR Real Time Analysis of Bauxite or Coal

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### Abstract

Online analysers are increasingly adopted in mineral processing to provide real-time insight into key material streams. Major industrial players are deploying a multitude of sensors throughout their operations, from mine feed to process input and by-product recycling, to improve process control and material balance.

Among available technologies, near-infrared (NIR) spectroscopy has gained wide acceptance across minerals industries due to its unique advantages. Unlike elemental sensors, NIR is sensitive to both organic components (including moisture) and minerals as it interacts with the bonding structures, enabling direct measurement of complex material properties with high accuracy and representativity, often surpassing that of conventional sampling and laboratory analyses.

In bauxite refining, NIR enables direct, real-time quantification of available alumina and reactive silica, rather than relying on calculations based on oxide content. It also effectively measures impurities (organic) that impact the operation the precipitation circuit.

For coal, a critical energy source in some refineries and smelters, NIR provides immediate analysis of total carbon, volatiles, elemental composition (C, H, N), as well as ash and sulphur, supporting optimized combustion and emissions control.

This paper presents case studies from China demonstrating the long-term accuracy, robustness, and process representativity of online NIR analysers applied to bauxite feed characterization and coal quality monitoring. The results illustrate how real-time chemical and mineralogical data can enhance process control, improve operational efficiency, and reduce downtime.

**Keywords:** Near infrared, Online analysis, Reactive silica, Available alumina, Coal.

### 1. Context

Alumina refineries face increasing demands to optimize productivity, energy efficiency, and product quality while minimizing environmental impact and operating costs. Achieving these goals in a complex, multi-stage chemical plant requires precise control of key process parameters in real time. However, one of the persistent challenges in refinery operation is the high variability of input raw material streams, particularly bauxite feedstock, which can exhibit wide fluctuations in mineralogy and chemical composition due to sourcing from various domestic and/or international mine sites and inadequate bauxite stockpile blending

The mineralogical composition of bauxite, specifically the proportions of available alumina (typically as gibbsite, boehmite, and diaspore) and reactive silica (usually from kaolinite and other

soluble silicates), directly influence digestion extraction efficiency, caustic consumption, scaling propensity, and ultimately, alumina yield. Conventional laboratory-based analysis of bauxite feed is often too slow to support proactive process adjustments. As a result, many refineries operate with conservative margins in digestion conditions and caustic dosing to compensate for unknown feed variability which can lead to suboptimal performance.

Near-infrared (NIR) online spectroscopy offers a practical solution to the problem of delayed laboratory bauxite analytic results which impairs feedforward process control. NIR analysers provide continuous, real-time measurements of bauxite mineralogy, enabling advanced process control strategies such as feedforward and feedback loops. When integrated into the refinery's Distributed Control System (DCS) or Advanced Process Control (APC) platform, NIR data can significantly enhance process responsiveness, reduce variability, improve yield, and lower reagent and energy consumption.

This paper explores the role of online NIR analysis in addressing key process control challenges in alumina refineries, with a focus on its application for monitoring bauxite feed composition/mineralogy and its integration into digestion and product quality control loops. The discussion also considers the broader context of real-time monitoring of other critical input streams required for efficient and uninterrupted production.

## 2. Challenge: Impact of Bauxite Mineralogy on Digestion and Process Efficiency

In the Bayer process, bauxite is digested at elevated temperatures and pressures in a relatively concentrated caustic soda (NaOH) solution, weak in sodium aluminate dissolving the soluble alumina-bearing minerals and some other impurities. The resulting sodium aluminate liquor is clarified and cooled then subjected to precipitation, recovering alumina trihydrate, which is then calcined to produce smelter-grade alumina.

Each stage of the process, from digestion to precipitation to calcination, depends critically on the chemical and mineralogical characteristics of the feed materials and process streams. Variability in bauxite feed composition, liquor chemistry, etc. introduces significant challenges for process control and optimization.

The mineralogical composition of bauxite feed exerts a primary influence on digestion performance, caustic consumption, and scaling behaviour. Key mineral phases of interest include:

- Gibbsite, boehmite, and diaspor — sources of **available alumina**.
- Kaolinite and other reactive silicates — sources of **reactive silica**, which consume caustic and promote scaling.
- Iron oxides (hematite, goethite) and titanium minerals — typically inert (depending on digestion temperature) but affect red mud characteristics and product quality.
- Other minerals (here listed in their oxide form) like MnO<sub>2</sub>, V<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, and also the above mentioned TiO<sub>2</sub>, contaminate or consume the liquor and may promote scale formation.
- Organic carbon affects liquor productivity, precipitation kinetics, reduces filterability of alumina hydrate and impact alumina product quality.

Variations in the relative proportions of these minerals can have significant operational impacts. For example, wide fluctuation in reactive silica leads to greater consumption of caustic soda to form desilication products (DSP), reducing available soda for digestion and increasing scaling in heat exchangers (see Figure 1).



**Figure 1. Impact of reactive Silica increase.**

Currently most alumina refineries rely on laboratory-based analytical techniques, such as X-ray diffraction (XRD), X-ray fluorescence (XRF), and wet chemistry for bauxite characterization and process control. While these methods offer high accuracy, they are typically too slow and not sufficiently representative to support real-time process control:

- Each step in the sampling process, from bulk sample collection to preparing the final analytical portion, introduces a risk of bias, impacting the representativity of the sample.
- Sample collection, transport, and preparation introduce time delays of several hours to days.
- Analytical cycle times limit the frequency of updates, forcing operators to make process decisions based on historical information.
- Laboratory analyses are resource-intensive and may not be feasible at the required frequency for dynamic process control.

As a result, many refineries operate with conservative process setpoints to accommodate unknown variations in feed and process streams. This leads to

- suboptimal use of caustic soda,
- increased scaling,
- energy inefficiencies,
- higher production costs and
- higher risk of process disturbances or interruptions

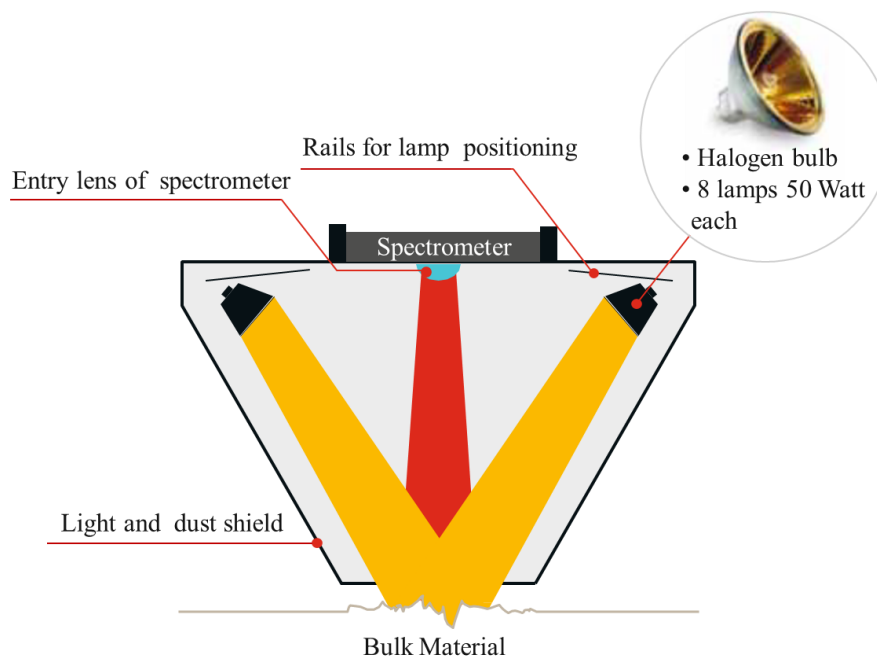
Near-infrared (NIR) spectroscopy is ideally suited for providing in-process, real time analysis of minerals in the raw material feed (bauxite, coal, lime to alumina refineries and mining operations which often operate blindly. It provides the critical data required by Advanced Process Control (APC) platforms, such as available alumina, reactive silica, mineral impurities and organic content, to facilitate optimization of process parameters throughout the Bayer plant.

### **3. State of the Art: NIR Technology and How It Is Applied to Industrial Mining Processes**

#### **3.1 NIR Technology Basics**

The working principle of the SpectraFlow Analytics NIR online analyser, illustrated in Figure 2, is based on the interaction of near-infrared (NIR) light with the molecular structure of the material. The system employs a broadband halogen light source, which emits light across the visible and infrared spectral ranges. For process applications, the focus lies on the 700 nm to 2500 nm wavelength range, where characteristic absorption bands of minerals, organic compounds (including moisture) occur.

When NIR light is directed onto a material surface, specific wavelengths are absorbed according to the molecular bonds and lattice vibrations of the material constituents. The unabsorbed portion of the NIR light is reflected. A high-resolution Fourier Transform Infra-Red (FTIR) spectrometer collects and analyses this reflected light to generate an absorption spectrum, from which the composition of the material can be determined.



**Figure 2. Working principle of the NIR online analyzer.**

The analyser continuously scans the moving material stream on a conveyor belt, acquiring 140 spectra per minute. For a typical industrial application, such as a conveyor belt operating at 2 m/s with a throughput of 900 t/h, this sampling frequency corresponds to coverage of approximately 120 meters of material per minute, analysing about 15 tonnes of material per minute. This high temporal resolution provides robust and statistically extremely representative measurements of process variability.

A key advantage of NIR technology over conventional offline and online elemental analysers (e.g. X-ray fluorescence, prompt gamma neutron activation analysis or laser-based technologies) is its sensitivity to organic as well as inorganic composition, rather than solely elemental concentrations (measuring sodium and above). This capability is particularly valuable in bauxite applications, where NIR can distinguish between:

- Total alumina ( $\text{Al}_2\text{O}_3$ ) vs. available alumina (digestible phases such as gibbsite, boehmite/diaspore)
- Total silica ( $\text{SiO}_2$ ) vs. reactive silica (from clay minerals such as kaolinite)
- Mineral impurities, possibly in the ppm range
- Organic content, including humic substances and other organics that impact liquor chemistry and scaling.

This mineralogical sensitivity enables more accurate process control based on parameters that directly influence digestion efficiency, scaling, and caustic consumption.

### 3.2 Industrial Implementation

The industrialization of NIR online analysis for minerals processing began in 2006. Through successive development stages, the technology was initially optimized for cement production, where NIR online analysers are now widely deployed.

In cement manufacturing, NIR systems are used to provide continuous, real-time measurement of the chemical composition (oxide-based) of raw materials such as limestone and clay. This enables dynamic control of the raw mix to ensure stable and optimized feed to the kiln, thereby improving clinker quality and process efficiency.

Two main configurations of NIR analysers are employed in industrial settings:

- Crossbelt analyser (Figure 3, left): mounted over conveyor belts, used to analyse coarse material streams such as bauxite feed or crushed limestone which also have varying moisture content. This is the typical installation for bauxite measurement applications in alumina refineries.
- Airslide analyser (Figure 3, right): installed on top of air gravity conveyors (airslides), used for monitoring fine powders such as calcined alumina or finished cement. In alumina refineries, this configuration is applicable to final product quality control for alumina.



**Figure 3. Left: crossbelt analyser, Right: airslide analyser.**

The technology was subsequently adapted for a wide range of mineral processing applications, including iron ore, bauxite, coal, phosphate, gold, and other mineral commodities. Its versatility and robustness in analysing both organic and inorganic phases have enabled successful deployments across diverse process environments.

To fully leverage the value of real-time NIR analysis, the analyser output, typically a one-minute averaged result, is transmitted either directly or via the plant Distributed Control System (DCS) to the Advanced Process Control (APC) platform. This integration enables both feedforward and feedback closed-loop control, allowing operators to dynamically adjust key process parameters and stockpile blending strategy in response to changing material characteristics. The result is more controlled average bauxite composition to the alumina refinery which results in improved process stability, improved process troubleshooting, enhanced product quality, and optimized resource utilization.

Building on these capabilities, the technology has been successfully implemented in a growing number of alumina refineries, where it provides critical real-time data on both bauxite feed composition and fuel quality, supporting tighter process control and improved operational efficiency.

#### **4. Industrial Case Studies of NIR Implementation in Alumina Refineries**

##### **4.1 South 32, Worsley Alumina, Australia**

The Worsley Alumina NIR project was installed in 2018 and already presented at the 2018 ICSOBA Conference [1], marking a significant milestone as the first industrial NIR online installation implemented within the alumina refining sector. The project successfully demonstrated that NIR spectroscopy, previously utilized only for laboratory analysis at Worsley, could be effectively deployed for continuous, in-process monitoring. The implementation,

comprising hardware, software, and calibration models developed by SpectraFlow Analytics, has proven to be long-term stable, robust, and operationally easy to maintain under industrial conditions.

The analyser is installed at the refinery entry point, analysing mined bauxite prior to stockpiling. While this location is upstream of the core Bayer process, it provides valuable early visibility into bauxite feed quality, enabling better stockpile management and feedforward control opportunities. Following the success of this initial installation, the Worsley team is now evaluating the deployment of additional NIR analysers at the mine itself to enable earlier control of material quality during the mining phase.

#### 4.2 Chalco Refinery “A”, China

In 2023, Chalco Refinery “A” commissioned a SpectraFlow Analytics near-infrared (NIR) online analyser at the feed to the ball mills to enable high-frequency, real-time monitoring of the variability in ore quality, specifically focusing on available alumina (AA) and reactive silica (RSi).

Following a comprehensive evaluation of various online analytical technologies and high-frequency sampling systems, NIR spectroscopy was selected due to its unique ability to provide direct, real-time quantification of mineral phases and organic constituents (including moisture). Unlike alternative technologies that rely solely on elemental analysis, NIR spectroscopy delivers critical mineralogical information essential for effective Bayer process control. Furthermore, NIR technology offers superior measurement representativity, eliminating the need for extensive laboratory sampling and mitigating concerns related to sample representativity and analysis delays.

With continuous access to key parameters, including available alumina (AA), total  $\text{Al}_2\text{O}_3$ , reactive silica ( $\text{RSiO}_2$ ), total  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , Total Organic Carbon (TOC), Vanadium and moisture operators in the control room can now initiate adjustments of caustic soda addition and optimize spent liquor composition and flow. These adjustments are first conducted manually, with plans to transition to fully automated closed-loop control once operational confidence has been established. This real-time process control enables improved alumina recovery and more consistent digestion performance.

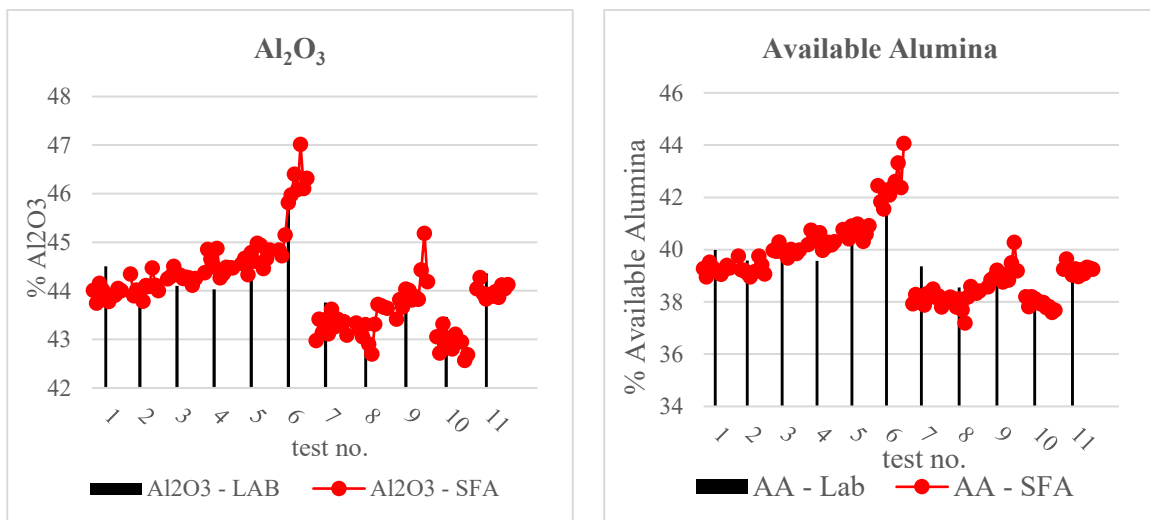
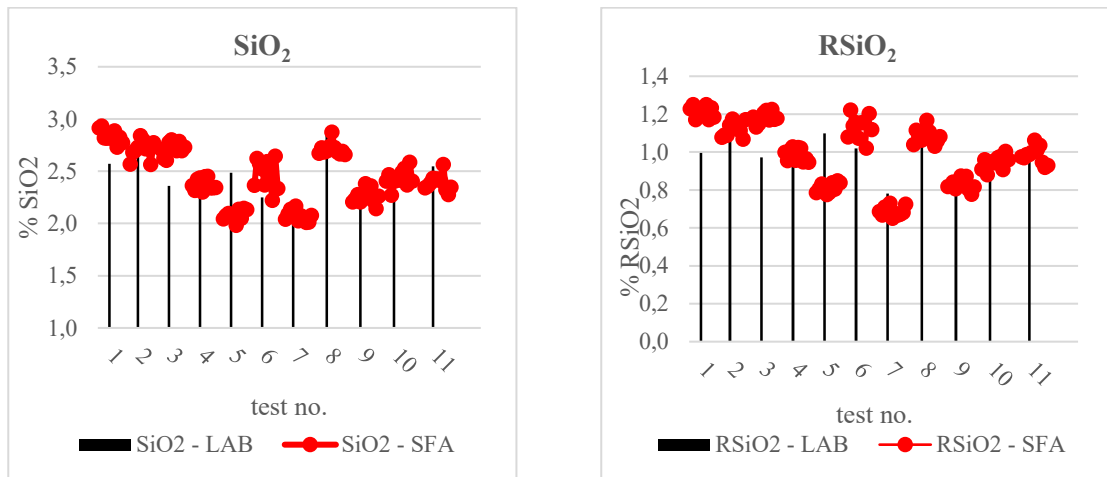
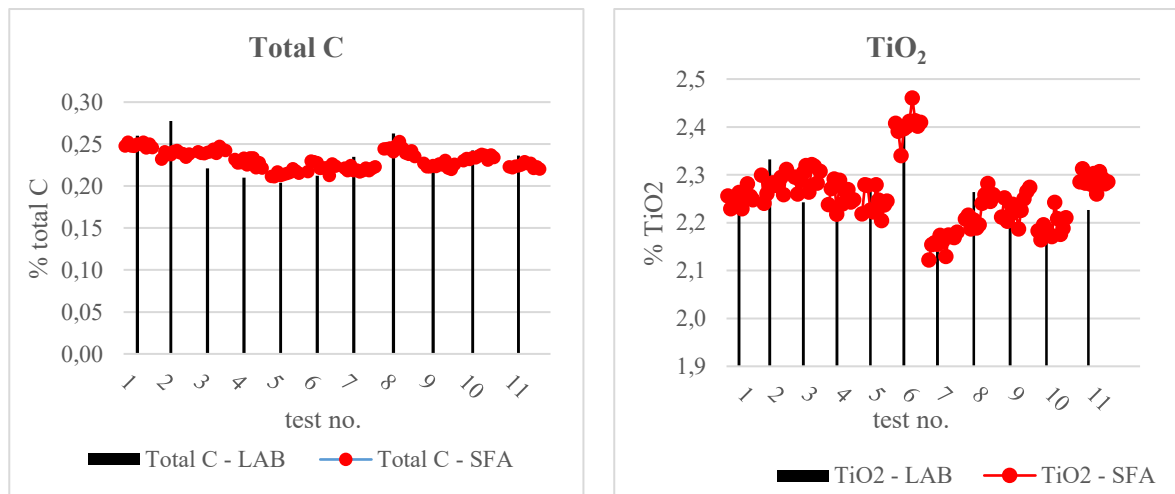


Figure 4. Comparison between SpectraFlow and lab results, Left: total  $\text{Al}_2\text{O}_3$ , Right: available Alumina.



**Figure 5. Comparison between SpectraFlow and lab results, Left: total SiO<sub>2</sub> ,Right: reactive Silica.**

During the commissioning phase, dynamic comparison tests were performed by correlating the NIR analyser’s individual minute results against conventional laboratory sampling conducted over a 10-minute timer period. The results (Figures 4–6) demonstrate a strong correlation and clearly illustrate the NIR system’s ability to track rapid fluctuations in ore composition. Notably, after the initial calibration refinement completed following sample 6, the alignment between online measurements and laboratory data improved significantly, confirming the robustness and accuracy of the NIR-based monitoring system for real-time process control in this application.



**Figure 6. Comparison between SpectraFlow and lab results, Left: total C, Right: TiO<sub>2</sub>.**

Considering the return on investment of an NIR online analyser system as provided by SpectraFlow and their partners PLA in China let’s take the following assumptions:

- Plant respectively line capacity: 1 million ton per annum Smelter Grade Alumina (SGA)
- Increase in recovery: 1 %, equalling 10 kt Al<sub>2</sub>O<sub>3</sub>/y
- Sales price for 1 t of SGA appr. 350 USD vs. cost of production at 290 USD results in a revenue of 60 USD per tonne of SGA
- Increase in revenue of 600 kUSD/y + the additional efficiency in the process
- ➔ Payback of the NIR online system is below 6 months
- ➔ Even if recovery would only increase by 0.5 % the payback is still below 1 year.

### 4.3 Chalco Refinery “B”

The successful implementation of the NIR online analyser at the Chalco Refinery “A” prompted a second Chalco refinery in China to adopt the same installation approach, with commissioning scheduled for Q1 2025. Unlike the first refinery, which maintains a stable bauxite supply contract with Guinea, the second facility requires enhanced flexibility to accommodate a more diverse range of feed materials, including bauxite sourced from Guinea, Australia, and Ghana.

The analyser is utilizing an identical configuration to the setup supplied to Refinery “A”, with a mounting frame positioned above the dual conveyor belt system to support the analyser measurement on the belt that currently transports the bauxite ore. A notable advantage of NIR technology lies in its operational flexibility: the system requires no fixed sampling apparatus or shielding, and the analyser can be automatically repositioned from one to the other conveyor belt.

Figure 7 shows the process flow whilst Figures 8 to 9 give an impression of the installation. The data evaluation for this recent project is also in progress.

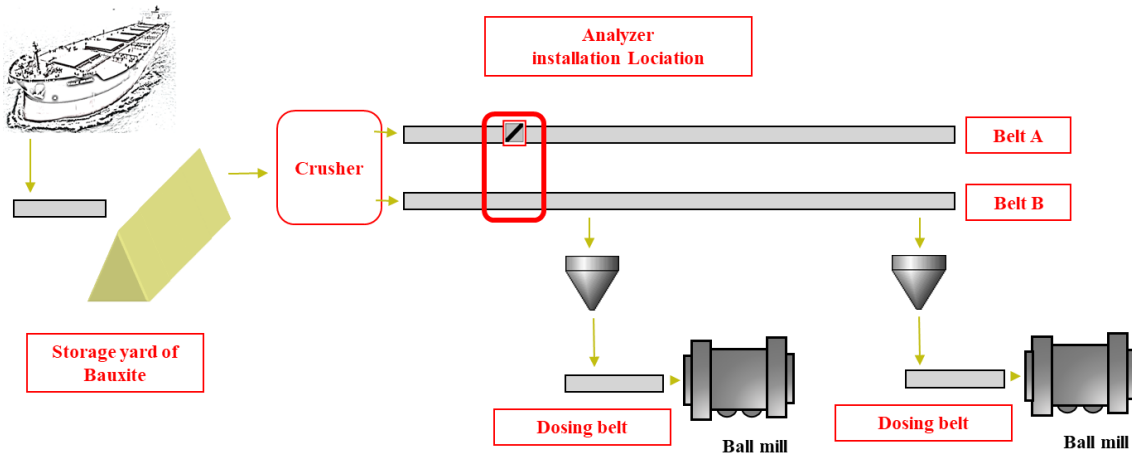


Figure 7. Process flow for refinery “B” mill feed analyzer.

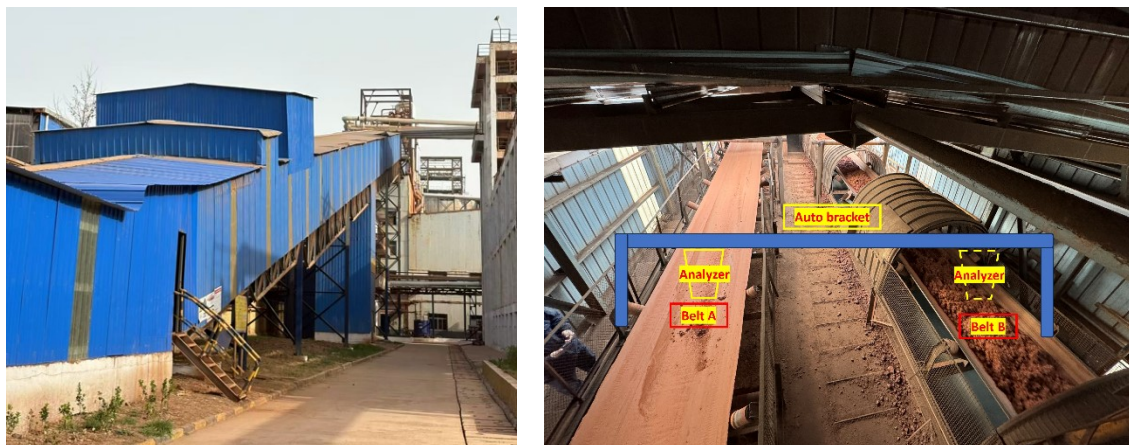


Figure 8. Left: overall installation location, Right: layout installation.

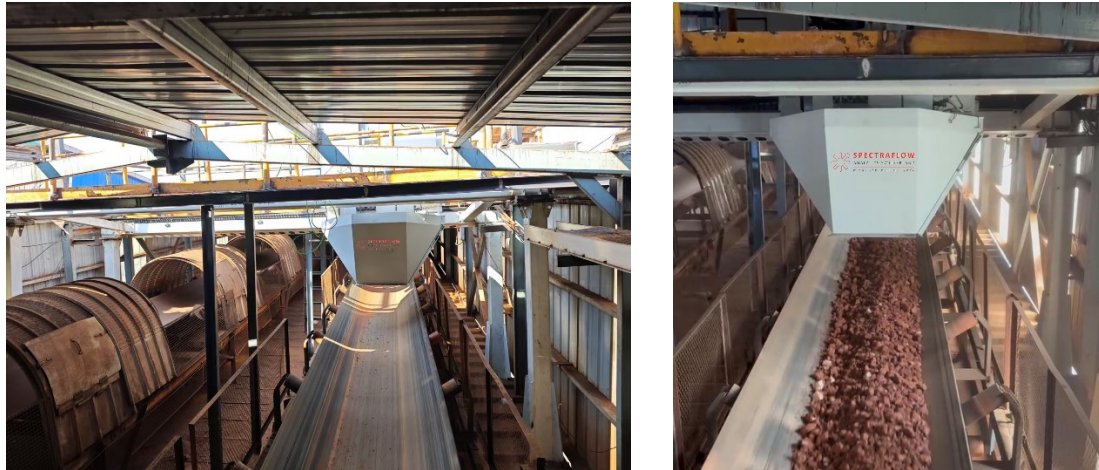


Figure 9. Left: implementation, Right: analyzer in operation.

#### 4.4 Coal Quality Control at Chalco Refinery “A”

As part of its digitalization and process optimization initiatives, Chalco implemented a SpectraFlow NIR online analyser in April 2025 to facilitate real-time evaluation of incoming coal deliveries. Despite the global trend towards reducing coal usage, it remains a critical energy source for many industrial operations worldwide. To maximize efficiency when utilizing coal, it is imperative to monitor the quality of incoming shipments, which are predominantly delivered by truck.

In practice, the quality of delivered coal can vary significantly from contractual specifications. Due to the discontinuous nature of truck deliveries and the high frequency of shipments, tracking material quality on a per-supplier or per-batch basis poses a logistical challenge. Traditional sampling methods with a corresponding laboratory analysis take too long for decision making prior to unloading and hence are operationally impractical.

To address this, Chalco newly established a rapid testing station where truck samples are collected and analysed within two minutes of sampling. This expedited analysis enables immediate go/no-go decisions regarding unloading, based on compliance with predefined quality criteria. Non-conforming deliveries are subject to resampling and further evaluation.

Figure 10 shows the process flow whilst figures 11 to 12 give an impression of the installation. The data evaluation for this recent project is also in progress.

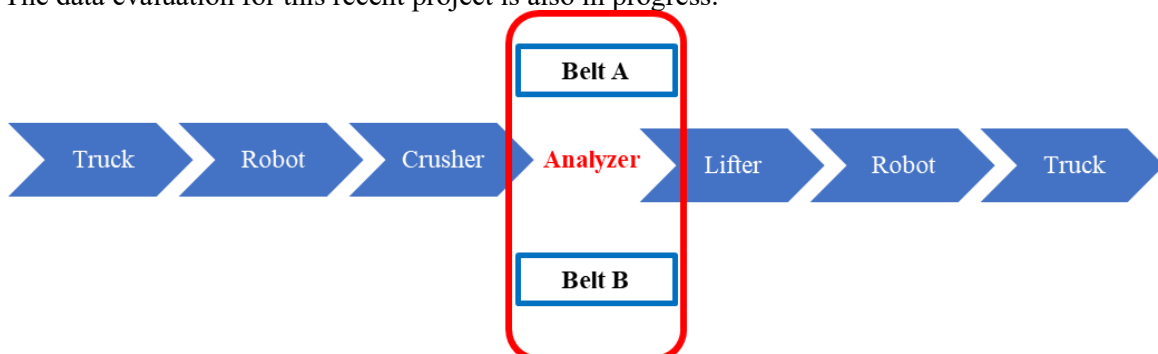


Figure 10. Process flow for Chalco refinery “A” coal analyzer.



Figure 11. Left: installation schematic, Right: installation after implementation.

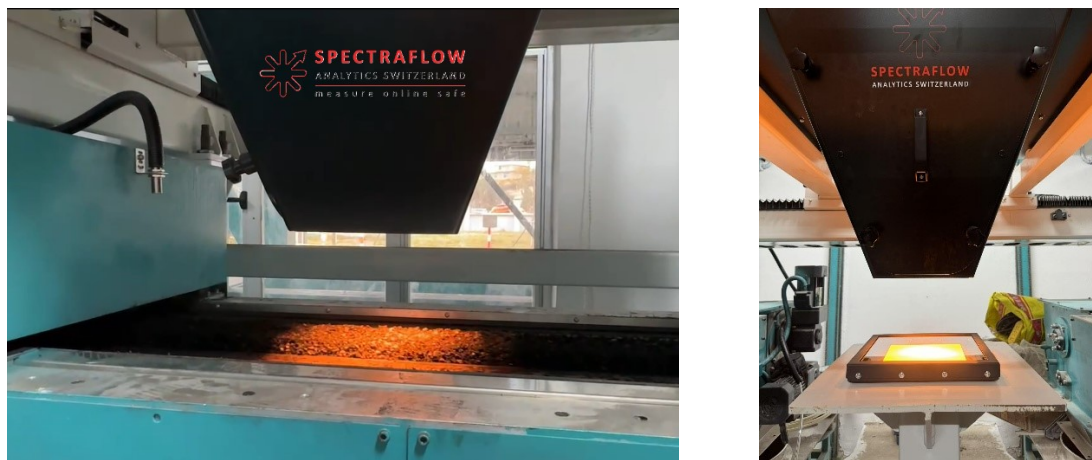


Figure 12. Left: analyser in operation, Right: analyser during referencing.

## 4.5 Upcoming Projects

### 4.5.1 Maaden, Saudi Arabia

Maaden has placed a purchase order for three NIR analysers to improve bauxite blending control at the Al Baitha mine and process control at Ras Al Khair refinery. Due to significant variability in the bauxite sourced from Maaden's local mine, the objective is to enhance feed consistency and process stability at the refinery through precise real-time blending at the mine and monitoring of the materials. The analysers will be deployed at strategic locations to support this objective.

### 4.5.2 Optimized Use of Imported Bauxite Ore

Many clients face the challenge of inconsistent quality in domestically sourced bauxite. To mitigate this, higher-quality imported ore is blended to optimize feed composition, maximizing available alumina content while minimizing reactive silica and other impurities. The primary challenge is determining the optimal blending ratio to balance cost and process efficiency.

In some cases, stockpiles allow for pre-blending of ores with varying quality, as exemplified by Maaden. However, many sites lack the infrastructure for large-scale blending and stockpiling initiatives. The bauxite is simply stored in predefined areas, and they rely on front-loader operations feeding directly to crusher. This situation raises critical operational questions:

- What is the current quality of the domestic material fed to the process?
- How much imported high-quality ore is required to maintain feed consistency?

Installation of an NIR online analyser on the feed belt to the mills provides continuous compositional data to the Distributed Control System (DCS) or Advanced Process Control (APC) platform. Calculated rolling averages over defined time or tonnage intervals enable operators to detect changes in feed quality and dynamically adjust blending ratios accordingly.

The benefits of this system are threefold:

- **Quality parameters:** Knowledge of the composition of the currently fed material
- **Feedback control:** Dedicated feed of the high-quality material only when required, facilitating improved in bauxite blending of refinery stockpiles
- **Feedforward control:** Informed adjustments to the Bayer process to improve overall efficiency.

#### 4.6 Additional Applications for Advanced Process Control (APC)

Beyond stockpile management and mill feed optimization, NIR technology can support APC strategies at various downstream refinery stages:

- By accurately measuring low concentrations of NaOH, the analyser can monitor the trihydrate feed to the calciners, allowing for early detection of off spec alumina product.
- Measurement of the final alumina product parameters, including Al<sub>2</sub>O<sub>3</sub> content, impurities (including trihydrate), Loss on Ignition (LOI), and moisture, facilitates calciner control (e.g., temperature, residence time, fuel rate) and provides early warning of precipitation operational issues, such as agglomeration seeding control.
- With sensitivity to mineralogy, NIR can measure the CaO content of burnt lime which is added to the process
- Measurement of bauxite residue filter cake / tailings: moisture and mineralogy of the cake give a feedback to the alumina recovery and information on the filtrate composition e.g. for further use.

### 5. Installations in Smelter Applications

NIR technology is also deployed in aluminium smelters to support process monitoring and control:

- Three installations monitor sodium (Na), calcium (Ca), iron (Fe), silica (Si), and sulphur (SO<sub>3</sub>) concentrations in crushed return butts (refer to ICSOBA 2023 proceedings [2]).
- Additional (not yet implemented) applications include analysis of:
  - Crushed bath material
  - Calcined petroleum coke (CPC)
  - Primary and secondary alumina oxide feedstocks.

### 6. Conclusions

The integration of Near Infrared (NIR) spectroscopy as an online analytical technique within alumina refineries represents a significant advancement in process monitoring and control. By enabling real-time, accurate measurement of key parameters such as available alumina, reactive silica, moisture, and minerals as well as organic impurities in bauxite feed, or critical coal quality attributes, NIR technology provides operators with enhanced visibility and actionable data that traditional laboratory methods cannot deliver with comparable speed or representativity.

The ability of NIR analysers to distinguish organic as well as inorganic (mineral) phases, rather than relying solely on mineral elemental composition, improves refinery process control. The data collected can be used to facilitate more precise adjustments to caustic soda dosing caused by

variations in bauxite reactive silica input, optimizing digestion efficiency (alumina recovery), improve bauxite stockpile blending to minimize wide variation in the alumina, silica feed to the refinery and reducing operational risks such as digestion piping wear caused by high quartz input in bauxite feed and DSP scaling of pipe caused by perturbations in reactive silica in bauxite feed. Furthermore, the high-frequency data generation supports Advanced Process Control strategies, including feedback and feedforward loops, which improve material blending, reduce off-spec product generation, and increase overall process stability.

Case studies from leading global alumina producers, including installations in Australia and China, demonstrate the long-term stability, robustness, and operational benefits of NIR online analysis implemented by SpectraFlow Analytics. As refineries continue to face challenges related to feed variability, complex blending requirements, and energy efficiency, the adoption of NIR technology within integrated control systems will be pivotal to achieving enhanced process performance and sustainable production.

In summary, NIR online analysers constitute a valuable tool for modern alumina refineries seeking to advance digitalization, improve process intelligence, and achieve superior control over critical material streams, ultimately contributing to more efficient, flexible, and environmentally responsible operations.

## 7. References

1. Petra Mühlen, Near infra-red based online mineral phase analysis of bauxite, *Proceedings of 36<sup>th</sup> International ICSOBA Conference*, Belem, Brazil, 29 October–1 November 2018, *TRAVAUX* 47, 139–154
2. Edouard G. M. Mofor et. al, Practical use of online chemical analyser for spent anodes quality control, *Proceedings of the 41st International ICSOBA Conference*, Dubai, 5–9 November 2023, *TRAVAUX* 52, 1069–1079