Process Analytical Technologies for Representative Real Time Measurement of Conveyed Flows

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ABSTRACT

Process analytical technologies (PAT) are utilised when continuous knowledge of quality is needed in a timely manner for bulk conveyed flows of matter, usually solid mixtures of highly varying heterogeneities. Reliable, representative monitoring of material quality variability is the target of implementing an online PAT solution, but the material variability itself also has significant effects on the measurement process performance. Many sampling and analytical procedure elements need to be competently designed, managed and controlled for any specific PAT solution. Conveyed bulk flows consist of materials with characteristics influencing their ability to be appropriately and effectively sampled. The value of the final data is to a large degree determined by its purpose for the PAT system user. This article covers the demands on real time measurement system management where material quality needs to be known with high confidence to influence the technological or industrial processes involved and allow subsequent decision-making. Every process is sensitive to some degree on the nature and specifics of its input parameters. The characteristics that affect online measurement performance cannot always be characterised in a manner like laboratory measurement systems, and various assessment approaches characterise competing system vendors. This article covers some technology opportunities and challenges applicable to conveyed flows that have proven beneficial in this PAT domain as outlined in many case study examples supplied and referenced.

1. Introduction

Mining, minerals processing and many other processes often utilise conveyors in bulk material handling between discrete unit operations. These may include quarrying or mining, simple screening, more complex beneficiation stages, concentrating, recycling, smelting or refining. Process analytical technologies (PAT) can play a role in measuring the bulk material in real time to help monitoring and managing process feed, process performance, and product quality. Sampling may not be an effective solution for quality management if real time and continuous monitoring of quality variability are needed. Sampling may be difficult to implement where coarse material (up to -350mm) is conveyed at high tonnage rates and with highly variable particle size and composition. Effective control can more likely occur when appropriate process analytical technologies are selected (or developed) that provide representative, precise, and timely reliable measurements.

2. How to develop confidence in selected process analytical technologies promising representative real time measurement of conveyed flows

2.1 The Problem

Many material handling situations involve highly heterogeneous material at every particle size scale present. Material 'quality' and its variability have major effects on process performance. How can material quality be characterised representatively to enable the process to achieve a controlled quality at the scale that causes minimal disruption and optimal performance?

The solution should include process analytical technologies that are not affected by the physical characteristics of the material, i.e., quality variability e.g., segregation effects.

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To be representative PAT measurements must comply with the principles stipulated in the Theory of Sampling (TOS), which first and foremost demand that any material component is accorded an equal probability to be included in the support of the physical measurement (physical, or virtual, sample volume). Successful measurements must be shown to be independent from operational handling variability, or sufficiently account (correct for) for variabilities stemming from include e.g., mass flow, particle size distribution (PSD), moisture content, natural or imposed segregation (layering of different materials onto the same conveyor).

Many of the parameters mentioned are the results of upstream processes: 1) PSD as a function of blasting, comminution stages and materials handling, 2) mass flow as a function of how material is handled and whether surging is controlled, or a result of choke feeding, 3) moisture as a function of below ground water level mining, 4) clay content or dust management steps (water sprays), and 5) segregation. These variabilities may be imparted for example due to multiple flows of materials with different characteristics added in a sequence … causing layering, or through natural effects of vibration and movement during conveying. All such ‘detracting’ variabilities must be optimally counteracted and corrected for a successful PAT solution for one or more focused analytes.

3. Developing PAT technologies

3.1 Compositional and distributional heterogeneity

High compositional heterogeneity is arche-typical in natural geological materials (ores) and in many other bulk commodities in trade and processing technology, which are characterised by coarse particle size (e.g., shredded scrap). Such features will effectively rule out any method that only senses the surface of a conveyed flow.

Conveyed flows are quite effective at self-sorting by particle size, shape, density and parameters affecting aggregation and segregation, such as moisture, or clay content, due to vibration and movement. Fines and more dense components commonly migrate downwards, and coarse particles migrate upwards. This can occur immediately the material is placed on the conveyor belt through particle filtering and chute flow design; this results in induced vertical distributional heterogeneity.

The horizontal composition distribution can also be modified depending on distance material is conveyed, which can result in the same between-particle differences mentioned above.

In many mines the fines are considered as of consistently higher quality than the coarser fraction(s), which are often more competent, being less mineralised rock with lower grades, or vice versa depending on mineralisation style.

The conclusion of the above considerations is that penetrative technologies would be needed to provide even the first opportunity for a representative measurement regime - before even considering which parameters to measure and how to quantify composition. The specific design of the process sampling interface is critical (Esbensen & Sivalingam, 2022).

The measurement parameter of interest (aka ‘the analyte’) may be aspects of the chemistry, mineralogy or other information that sensors currently are not able to provide, such as ore textures and mineral (spatial) relationships within a particle that affect liberation and recovery processes. Currently there is no technology available to provide a full mineralogical analysis of a flow of rocks through the full depth of conveyed material in real time. This has resulted in application of off-line technologies such as QEMSEM to characterise the material using ‘selected’ samples (sample selection better be representative). Consequently, existing techniques that penetrate and measure elemental content are the main solution adopted for compositional analysis. The challenge has been to prove they provide representative analysis by preventing biased measurement of any components of the flow. Prompt Gamma Neutron Activation Analysis (PGNAA) and Pulsed Fast and Thermal Neutron Activation (PFTNA) have been the preferred technologies to consider for elemental analysis. Magnetic Resonance (MR) can be considered when only one mineral of interest is required to be measured (this is of course one that is able to be sensed with an appropriate technique).

The suitability and performance of penetrative measurement techniques to characterise the composition of conveyed material can be assessed in various ways. It should be noted that, unlike laboratory technologies that measure samples prepared carefully and consistently through a specified process, conveyed flow is highly dynamic and many variables can affect analyser (process analytical technology) performance.

FACTBOX - Specific analytical neutron activation issues

PGNAA/PFTNA and related neutron or thermal activation techniques are dependent on a number of random processes which include the number and energies of neutrons emitted from a "source" per second, the proportion of neutrons captured by elemental nuclei, generation of gamma energies emitted from "excited nuclei", measurement of the emitted gamma energies by the detector or detectors in the analyser, and the conversion of the collected spectral response through some calibration process to represent elemental proportions. Analyser calibrations use reference spectral elemental libraries to break down the measured spectral response into its components. An analyser is calibrated for the elements known to occur in a material that can be successfully measured, i.e., have a good response to the technique and are likely to be present at measurable concentrations. The analyser calibration can be customised to the expected composition ranges for each element of interest to improve measurement precisions. Each element has a fingerprint, or multi-peak response with peaks over a range of gamma energies at consistent proportions to each other. The consideration of the full spectral response for an element will improve the ability to determine its proportion in the combined response rather than using only its primary or secondary energy peaks. Elements respond differently and therefore some elements are more challenging to measure than others while some do not respond to the technique at all. Elements are continually being added to spectral libraries, and some analysers have unique capabilities, e.g., direct gold measurement, due to their configuration, components and/or calibration software. Theoretical gamma responses are available for most elements but possible recognition by a specific analyser model will vary. Some analysers can detect elements well that others struggle to measure, e.g. aluminium, magnesium, phosphorus, carbon, etc.

The source type and size determine the number and energy of neutrons emitted. Californium-252 (Cf-252) is the dominant source used in PGNAA analysers. Cf-252 produces neutrons with 2.1 MeV energies, which are ideal for this technique. The neutrons are easily thermalised or moderated to make capture by atoms in the conveyed flow more efficient. In this process, high-energy neutrons are slowed down through elastic collisions with a neutron moderator, such as graphite. 50 micrograms of Cf-252 produces about 115 million neutrons per second, about 2,000 times more neutrons than the same amount of Americium-Beryllium (AmBe). Self-shielding occurs when neutrons and gamma rays are absorbed by the material rather than penetrating further into the material and this effect is normally modelled through Monte Carlo simulations so it can be accounted for in the analyser calibration process. This is why higher activity sources are often more appropriate for thicker conveyed beds and why a single pass configuration is used rather than a backscatter process: In a single pass, the source is on one side and the detector array on the other. In a backscatter configuration the source and detectors are on the same side of the material to be measured and consequently may bias measurement to the portion of material closest to the source and detectors which generates a larger proportion of the measured signal. Detectors cannot determine where in the material profile the signals have originated so correcting for such bias is problematic.

Smaller sources have lower activity and emit fewer neutrons. Neutron generators emit neutrons at much higher energies (14.1 MeV) that may reduce the fraction able to be captured by elements as most may pass through the material "uncaptured". The number and type of detectors affect the efficiency of the gamma measurement and resolution of gamma energies into the number of channels being recorded. Digital Multi-Channel Analyser (DMCA) count rate capacity determines how many counts are recorded and accumulated in the combined spectral response over a measured timeframe.

Pulse pile-up occurs when more gamma rays are generated and penetrate a detector crystal than can be counted, so the solution has been to use more detector-DMCA combinations using smaller detector crystals rather than larger detector crystals and fewer DMCAs. The conversion and calibration software plays a major role in the optimal derivation of the final data. If the spectral response is optimised and the highest resolution is available, then elemental characterisation can be improved, and the analyser accuracy and precision can be optimised. The process relies on atoms in the material having approximately equal probability of being "sensed" and therefore the design of the analyser system, the relative position of sources to detectors, and of course the degree of shielding to maintain a safe area around the analyser while operating are important considerations.

Static calibration does not assess the responsiveness of a technology in recognising changes in material composition or compensating for changes in the mass being measured. The mass flow input from a belt weigher is used to tonnage weight spectral responses to ensure elemental proportionality is correct during a measured increment (using a time-based accumulation of spectral response).

Not all vendors are focussed on best measurement capability for various reasons, just like some sampling systems fail to comply with all TOS' requirements. It is not always about building the best performing system as clearly some systems are built to a price point for meeting a particular marketing strategy (i.e., where customers compelled to accept the cheapest tendered price are targeted), while others may be designed without safety as a primary consideration, i.e., safety is left to the client to manage – large exclusion zones, access restrictions, are only safe when turned off, etc. The 'best' performing system may not even be the most expensive. The buyer must develop sufficient knowledge to be able to perform adequate due diligence to select the best solution for them. There are no standards available to assess and directly compare measurement performance and each vendor quotes on a different precision, accuracy or repeatability basis for different analytical measurement periods. Each vendor may also specify that a set of performance estimates is valid at or above a certain belt load (e.g., 60 kg/m) and measurement time. Lower belt loads generate fewer gamma responses, and the configuration of a system will determine the minimum required for confidence in the results. Some systems can measure reliably at belt loads as low as 10 kg/m.

Ideally the analyser will provide certain performances for the desired application given the conveyed flow characteristics: mass flow rate and variability, composition range required to be measured relative to the purpose of the data produced, any required off-line time for calibration or maintenance, operating cost, etc. Measurement time affects the size of the measured increment and whether data can be used effectively to manage overall quality. Very few conveyed flows have consistency in mass flow rate over time. The calibration of an analyser using only static samples of known composition (preprepared standards) can generate repeatability results to assess analytical accuracy and can compare measurements at certain concentrations to claimed accuracies, but these may not cover the full calibrated range or assess responsiveness of the system to normal dynamic conditions (like testing a car under ideal operating conditions and extrapolating its expected performance to reality of all-purpose driving).
Off-line static calibrations, such as when the analyser is removed from the conveyor and a standard sample placed on it, offer even less relevant calibration as the conveyor belt composition's dynamic changes (wear over time, or joins or repairs added) and those effects on overall measurement will be excluded. The calibration and performance evaluation processes of the process analytical technology should be understood in the necessary context, so limitations on performance can be used to assess suitability for each specific application.

Dynamic calibration using normal/typical material on the conveyor, in the analyser, under normal operations, enables the impact of dynamic conditions on the measurement to be comprehensively understood and accounted for, to improve analyser performance.

The presence of a suitable physical sampler (must of course be TOS-compliant) or periodically stopping a belt (during scheduled plant shut-downs for routine maintenance), to extract measured material for sub-sampling and assay allows a suitable number of comparison points to be used to validate calibration and measurement performance. This methodology has allowed better precisions than any static calibrations to be achieved over larger compositional ranges in multiple commodities where these systems have been implemented. The ultimate usefulness of all dynamic compositional measurement systems will be reflected in accuracy of the ultimate analytical results with respect to the actual physical material on the belt.

Figure 1 shows how factory test work on a small number of samples can be used to determine approximate measurement performance expectations. The PAT measurements are compared to assayed results for samples and a preliminary calibration developed for the material. This can be assessed using supplied samples without assay information (blind samples) to ensure the PAT can measure the material reliably. In many cases the suitability of the analysis results is a judgment the end user makes based on the measurement performance able to be demonstrated for a technology and its implications for the quality management process. After installation of the PAT the collection of samples from the conveyed flow that are sub-sampled and analysed can be compared to PAT measurements to ensure there is confidence in the PAT data, knowing that some variations between results will be expected due to total sampling error in determining the assay result and instrument errors in the PAT.

The RMSD values represent a confidence level in the measurement and typically correlate well in a suitably designed and calibrated analyser. PAT procurement generally includes requirements for meeting expected performance criteria and an agreed evaluation process should ensure a robust assessment of the PAT.

3.2 Accuracy and precision

Terms used to quantify PAT performance are intended to be objective, however, this is relative to the processes used and different vendors recommend different approaches. “Accuracy” assumes a comparison of measurement performance to an absolute value. To do this a sample is normally synthetically created at a known composition for all important elements to be measured. The repeated measurement by the PAT produces a distribution of results with a mean and standard deviation. The standard deviation is a measure of repeatability at a known concentration. Therefore, the accuracy can be quantified as the difference between the mean measurement and the absolute known composition. Statistical processes applied to the measurement results assume that 95% of the measurements should be within two standard deviations of the mean. Accuracy issues can sometimes be addressed by applying offsets to the PAT results, assuming the difference is always constant, in one direction, however, repeatability may be more random for example because of internal PAT processes in deriving each result. Assessing PAT performance at a single composition is decidedly inferior, as it does not cover the operational range required for the PAT application.

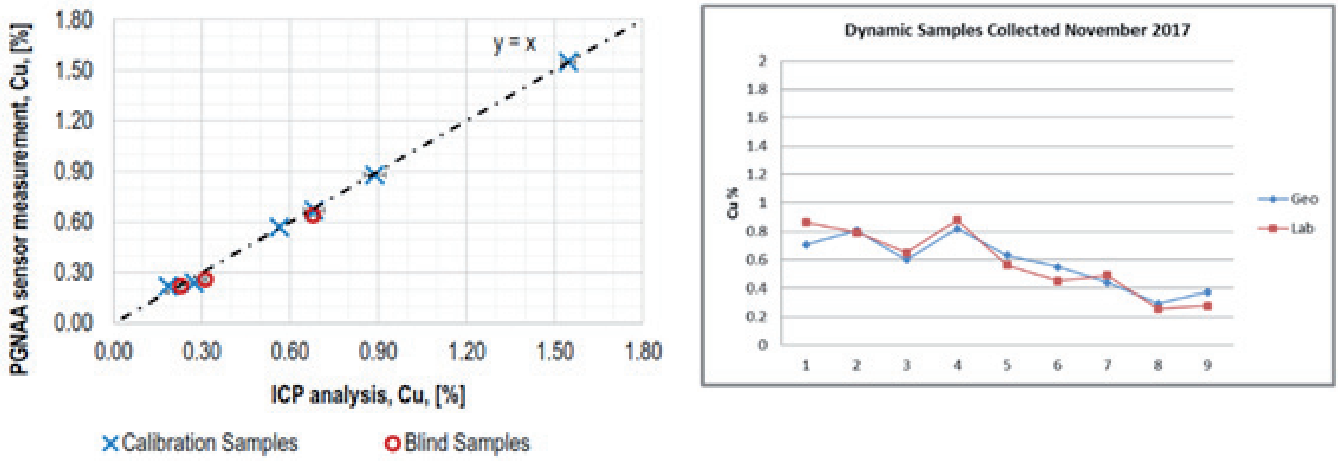


Figure 1: Left graph shows factory static measurement on 200kg samples using customer assay data to develop a preliminary calibration with an RMSD of 0.03 %Cu for copper ore for New Afton mine, Canada, and measurement of three blind samples to verify the calibration. Right side graph shows the dynamic evaluation results performed on site with an RMSD of 0.02 %Cu.

Credit: Nadolski et. al., 2018; used with permission.

Robust assessments require testing and evaluating PAT performance over the range of its intended application. Taking measurements over a range of different materials as presented in the conveyed stream allows comparison of PAT measurements to laboratory analysis based on sampling of the same analysis period for the material. While more resource intensive, this process provides a range of results for multiple estimates of the measured material quality to generate a measure of PAT precision for each element and relative to the composition range in the measured and sampled material. These precisions have been found to be a better indicator of measurement performance especially when the technology is required to guarantee the average quality of a measured batch. The ideal outcome of course is a good accuracy and a good precision in the PAT measurement. Dynamic changes can significantly affect material measurement, and the precision estimates become a better indicator of performance "robustness" where such variability is present, i.e., in most conveyed flows in the resource sector. Accuracies and precisions achieved with PATs are influenced by the amount of signal received per measurement period, resolution of the gamma energies to enable spectral interrogation, weighting of spectral response through mass flow changes, and the customisation of the calibration to the material. Releasing valid accuracy and precision evaluations are a major competitive issue between vendors.

Development of customised calibrations and expansions to element spectral libraries, to include elements additional to the standard ones needed in the "traditional" coal and cement industries where the technology has been applied, has resulted in broader applications for more commodities. The technology has been used successfully for bulk commodities such as iron ore, bauxite, manganese, chromium, phosphate rock and others (physically manifesting a relatively low heterogeneity) as well as more heterogeneous materials such as base metal ores (copper, zinc, lead, nickel), precious metals (silver and gold), platinum group elements (platinum, palladium) and specialised applications (lithium, diamonds).

Calibration is seen as the greatest challenge for obvious reasons. The process analytical technology needs to have its performance calibrated by comparing measured results to known compositions.

CASE STUDY 1: CEMENT INDUSTRY

Dynamic calibration assesses dynamic parameters and can for example be used to monitor and hence guarantee the average composition of a stockpile measured in the longitudinal transportation dimension using a specific analyser. In the cement sector, the GEOSCAN-C is the only product, and Scantech is the only company on the market, to provide composition guarantees for created limestone stockpiles. This provides high levels of confidence the analyser is performing well. For materials such as limestone, the variability is predominantly bimodal (calcium carbonate and quartz are the main compositional components) as the mineralogy is less complex than for many mineral commodities.

As an example, the known composition of a 50kg reference (or calibration) sample will be critically dependent on its full sampling history (it must be primary, secondary and tertiary sampled, sub-sampled and assayed representatively) - and this process must carefully be repeated in an identical fashion for at least thirty samples to cover the full intended measurement range.

The RMSD (root mean squared deviation) can be used as a measure of similarity between two sets of analyses of the same sample set (reference analytical values vs. corresponding process analytical results). The reference assay data is subject to sampling, sub-sampling and analytical errors whereas the calibrated PAT analyser measurement is mainly subject to instrument error (a combination of many smaller components) and errors related to the assay data used in its calibration. Assuming the analyser is calibrated well to the samples, the largest error is how well the samples represent the full flow that an analyser interrogates through its measurement technique.

Dynamic calibration can be improved by diligent sample preparation to minimise sub-sampling errors. The normal site primary sampling protocols are followed by crushing, splitting, pulverising and sub-sampling to the site's standard process or international standards for that type of material or commodity. Dynamic calibration is therefore much more difficult with highly heterogenous ore (such as precious metals with high coarse gold content).

FACTBOX - Validation of sampling vs. analytical error effects

Experience (Scantech) has shown that the sampling error comprises about half the RMSD magnitude (when samples are taken from a period of conveyed flow for comparison to analyser measurement for the same material). Sampling errors have been determined using a duplicate samples approach, and the analytical errors originate from the use of multiple laboratories and different assay techniques for various elements. A typical sampling error evaluation process incorporates operators taking multiple samples from a section of conveyed flow over hours, days or even weeks. Each sample is split and one half sent to one commercial laboratory and the other half to another laboratory. Results are compared to evaluate analytical error. Sub-sampling error is evaluated by splitting samples further and sending these sub-samples to each laboratory. The multiple analyses of the same samples can be assessed using the three instrument Grubbs estimation method (Grubbs, 1948) and when applied to available data often demonstrates the analyser provides a better precision then either of the two laboratories. This issue has been partially addressed using prepared standards with known composition and statically measured by the analyser. As discussed previously, this does not allow for calibration to dynamic conditions seen in the conveyed flow, which may likely have much larger effects on how well the analyser data represents the conveyed material composition. This is a standard process sampling and analysis aspect within the Theory of Sampling (TOS).

For this calibration process it is proposed to utilise a non-destructive analytical technique, such as photon assay (where suitable for the required analytes), so that the full sample size (typically this is equivalent to one metre of belt load) analysed statically in the analyser is removed and crushed to minus 3mm and split into 500gram sub-samples where each sub-sample is assayed by photon analysis and a tonnage weighted average derived for the original sample (Dominy et. al., 2024). Sufficient comparison points (samples) are used to develop what is expected to be the best available calibration for such material.

Ore blending has improved the consistency of process feed quality, reduced plant upsets and improved process performance. Feedback of conveyed material quality to mining operations has improved ore reconciliation and mine scheduling performance. Feed forward of the digital data has enabled process plant operators to modify feed rates, blends and reagent settings to optimise plant capacity and performance. High performance process analytical technologies enable responses in real time allowing for lag time in process changes to take effect.

CASE STUDY 2: GOLD ORE

Despite the high errors involved in sampling gold ores, the GEOSCAN GOLD has been able to demonstrate gold measurement to as low as 0.2ppm and measurement RMSD of 0.25ppm over ranges of up to 5ppm gold. These verification processes have involved meticulous preparation of samples for sub-sampling and assay. At least half of the precision value, estimated using the RMSD, is still expected to be sampling and analytical error, even when 30 or more assay comparison points are used. TOS indicates that most of the total sampling error originates when the primary samples are extracted from the lot. Difficulty in reducing the magnitude of that error suggests that the comparison of PAT measured results to those of correctly selected, prepared and assayed samples may be the best for of comparison for calibration improvement purposes.

CASE STUDY 3: IRON ORE AND BASE METALS

Assmang Khumani, South Africa (Matthews & Du Toit, 2011). Assmang utilises elemental and moisture analysers to measure:

- Mined ore for diversion: approximately 33% of final production bypasses full beneficiation saving around USD 5M per year in unnecessary operating costs. Only material needing beneficiation is diverted to the jig circuits. Ore characterisation studies recognised the potential for this and allowed a smaller plant to be constructed saving significant CAPEX.
- Ore feed to jigs and product from jigs: upgrade factors for different ore types can be well controlled to optimise recovery.
- Product quality to stockpiles: quality of each stockpile is known, so stocks can be monitored in real time.
- Loadout quality from stockpiles to train: allows the tonnage and quality of each train load to be deducted from the relevant stockpiles to manage stocks but also enables that load to be correctly allocated to stockpiles at the port.

The measurement at over 20 locations in the plant using GEOSCAN analysers also allows Assmang to perform real time multi-elemental balance of feed materials from each mine through to product and reject flows to optimise quality management through the complete process. Benefits provided by the mined ore diversion application alone resulted in an effective payback for the equivalent of over 20 analysers across the site in a period of less than one year.

Iron Ore – FMG, WA (Balzan, Beven & Harris, 2015). Fortescue Metals Group applied elemental and moisture analysers to their operations in the Pilbara region of Western Australia to monitor mined ore quality and product quality.

Measurement data is visible by remote access on personal devices. Resource Strategy Director (J. Clout, pers. com.) while travelling in China to meet customers was monitoring product analyser measurement results and noticed low grades being detected on the conveyor feeding the product stockpile. After contacting the site, it was found the mining block had been mistakenly allocated as high-grade ore instead of waste. The cessation of conveying waste onto the product stockpile prevented hundreds of thousands of tonnes of production being out of specification. This proved equivalent to an analyser payback period of one day.

Copper – Sepon, Laos (Arena and McTiernan, 2011. Balzan et. al., 2016). Measurement of crushed ore feed to a mill and leaching circuit for copper production.

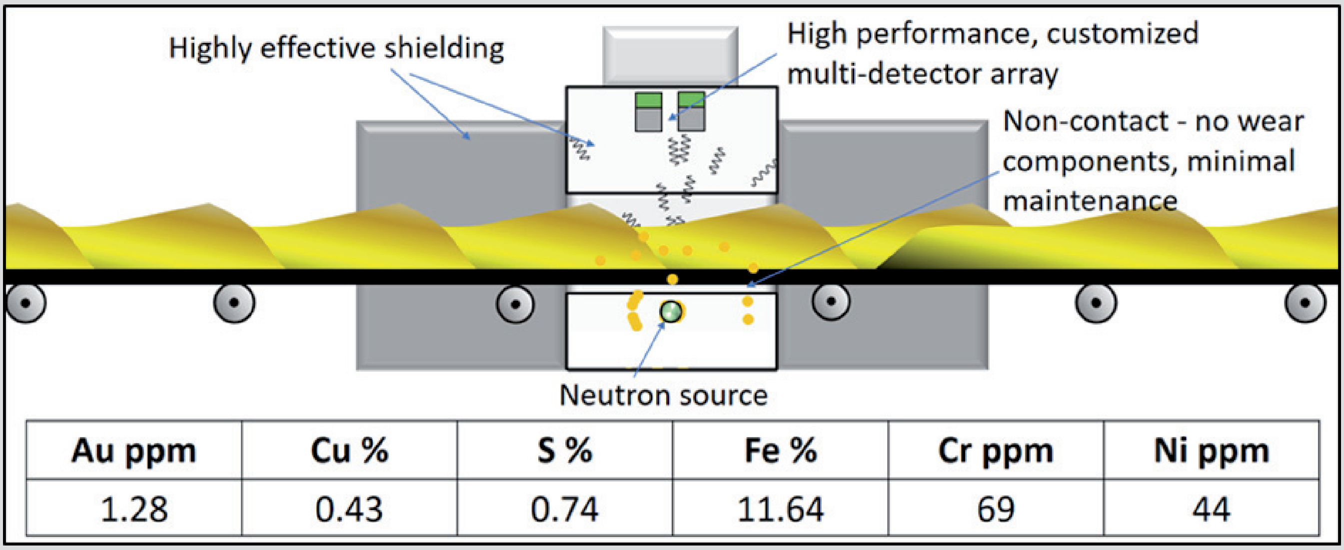
Blending ores from stockpiles is controlled each 30 minutes using feedback from an analyser located after crushing. Heterogeneity within the piles is large and sections of each pile may not reflect the expected average quality. Blending ore from piles averaging 1% copper up to 13% copper allows a consistent copper metal feed rate to the process to prevent exceeding its metal capacity and avoiding direct copper metal losses. Measurement of calcium, magnesium and manganese, correlated with acid-consuming gangue content of the ore, combined with moisture measurement data assisted in controlling acid addition to maintain target pH. The ferric leach process required pyritic material addition from a separate stockpile and its proportion in the feed was controlled using iron and sulphur measurement data from the analyser. Benefits resulted in an analyser payback period of approximately one month.

Lead-zinc – Glencore, QLD (Patel, 2014). Measurement of crushed ore feeding a heavy medium preconcentration plant (HMP).

Feed forward control enabled the optimisation of HMP density cut point control to minimise ore losses and maximise waste reject in lead-zinc ore that previously rejected a fixed 30% feed by volume, irrespective of ore quality. A significant increase in performance was achieved in plant operations.

Gold ore – Newmont, WA (Balzan et al, 2022). Measurement of crushed gold ore from underground mining feeding the Telfer process plant.

Newcrest (now part of Newmont) assisted in the development of direct gold measurement capability using GEOSCAN at Cadia and Telfer sites in Australia. Development of a spectral library for gold as an element was followed by extensive test work to validate measurement results. Since that time gold measurement has been successful at each site; the technology has been installed with measurements achieving precisions of as low as 0.2 ppm gold over calibrated ranges of nearly 5 ppm gold. This development is expected to improve further as better gold assay techniques are adopted to reduce sampling error components. See figure 2.



Au ppm	Cu %	S %	Fe %	Cr ppm	Ni ppm
1.28	0.43	0.74	11.64	69	44

Credit: Kurth, 2025; used with permission.

Figure 2: Cross-section through GEOSCAN GOLD high specification PGNAA analyser showing main components and an example of elemental results for a 30 second measurement period; for direct gold measurement over ten minutes.

3.3 Moisture measurement

Moisture content is one of the few parameters than can change during sampling and sample handling. Ambient temperature and humidity can easily affect the moisture of material while being sampled and/or analysed, particularly in hot, dry climates where many mining and processing operations are often located. Free moisture is usually assessed by weighing a sample as supplied, then drying it for a set period at 105 degrees Celsius, and reweighing when dry to determine a moisture percentage. Any moisture losses or additions between the sampling and the first weighing will contribute to the overall measurement error. Moisture can be lost through evaporation simply by disturbing the conveyed flow. Errors can be reduced by capturing a sample into a sealable container before transporting to a laboratory.

Moisture is rarely distributed evenly through a conveyed profile. Particle size distribution affects the migration of moisture: e.g., finer materials, capillary action and vibration causing water to migrate upwards (similar to tapping a bucket of wet sand), while ambient temperatures, air flow and coarser material results in dryness near the surface while moisture is retained in the finer materials towards the base of the flow cross-section.

The focus needs to be on developing representative measurement techniques to avoid any such obvious measurement bias(es). This eliminates any surface-based measurement techniques because any assumption that a conveyed flow surface, or for that matter the moisture at any vertical position within a flow, represents the average moisture in the full profile is prone to large errors, indeed suspect in the extreme. Continuous full depth measurement is possible using microwave transmission if carefully calibrated to the material and moisture range.

The full width and depth of a flow cross-section is not necessarily covered by the technique due to the lens shaped measurement volume and surface water accumulating at the edges (in the gullies where the material meets the conveyor) and may thus not be fully represented in the analysis, violating against TOS' imperative demand for a complete stream slice (Esbensen 2022).Still this technique has proven more reliable for moisture measurement than many others when effectively calibrated.

Not all materials are suitable for the application of microwave transmission moisture measurement, so sometimes alternative radiometric techniques need to be used. These tend to include collimated beams which are targeted at the deepest part of the flow, and hence they may not provide the lateral coverage to give representative results, although continuous measurement has proven to correlate well with average moisture over short, measured parcels. These approaches have been successfully applied to measurement of moisture in coke and magnetite concentrates. The application on less heterogeneous materials such as metalliferous concentrates, results in very precise moisture measurement particularly when excessive moisture (literally flowing on top of the conveyed material) is absent.

Moisture analyser calibration is a crucial element to ensure that compositional results are indeed representative. Sealable plastic bags with a known weight of dried site material allow moisture content to be adjusted over a desired range and the analyser calibrated to known contents. Mineralogy may affect the moisture measurement technique, so such effects must also be accounted for in relevant calibrations. Looking for universal solutions within the panoply of heterogeneous materials in science, technology and industry is a futile exercise – but dedicated solutions commensurate with specific material compositions and local, site-specific measurement conditions is the only way.

CASE STUDY 4: MOISTURE

In some cases, compositional changes in material that relate to different moisture properties can be determined using an external sensor and the moisture analyser informed on which of a set of pre-validated calibrations to use for a certain material. This approach has been successfully applied to iron ore in Western Australia where the elemental analyser measurements are used to communicate an ore type category (goethite-rich or hematite-rich) to the moisture analyser so the relevant calibration customised for that ore type can be applied for that material parcel. The benefits of such synergies in sensor data (sensor fusion) can apply to many applications of process analytical technologies.

Vendors compete based on science-backed method descriptions, and generous comprehensive calibration and validation information to customers.

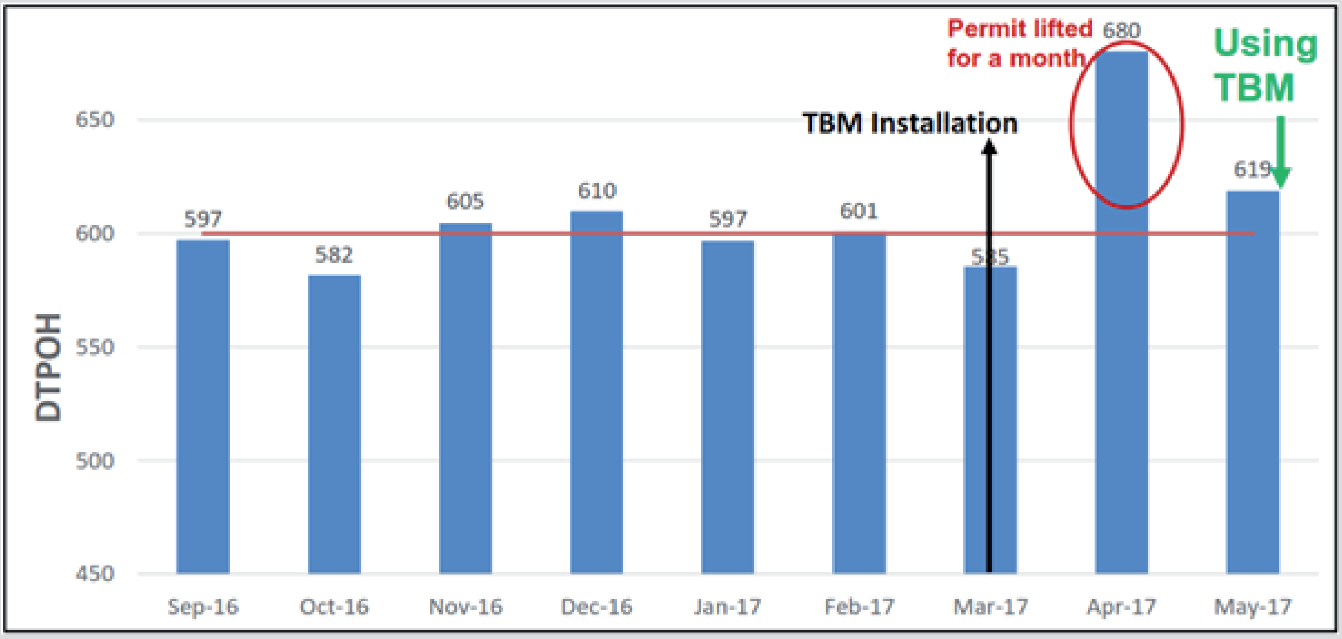
Moisture measurement is critical for dry tonnage determination for metal accounting and ore reconciliation at mines. It is used to monitor TML (transportable moisture limit) in shipping and trucking of bulk cargoes, as well as dust management for conveyed materials. Moisture measurement in dewatering operations can be used to optimise filter or dryer cycle times and throughput to ensure target moisture levels are achieved in bulk product.

In each case there needs to be a high confidence in the moisture data for proper process control responses to be effective in achieving the desired benefit.

CASE STUDY 5: NGM

Cortez Gold Mine (Bozbay & Moyo, 2019) as part of a continuous improvement process.

- The site had a regulatory limit on monthly throughput rate in dry tonnes.
- A conservative moisture factor was used to estimate dry tonnes so that it was kept below the limit, but moisture was not routinely measured with any confidence.
- This represented a huge opportunity for a site producing well over one million ounces of gold per year.
- Due diligence involved multiple vendors, some of which were found to be unable to effectively calibrate their moisture analysers at other sites.
- Scantech ReadiMoist TBM 210 was chosen and within a month of commissioning and calibration the site was able to increase the feed tonnage and stay below the regulatory limit (Figure 3).
- Real time moisture analysis contributed to a three percent increase in annual feed tonnage and gold production, valued at that time at USD 75M per year.



Credit: Bozbay and Moyo, 2019; used with permission.

Figure 3: Improvement of 19 DTOH (dry tons per operating hour) following moisture analyser installation at Barrick Gold Cortez operations in Nevada without exceeding permit limit.

3.4 Particle size distribution

There is no technology currently on the market that measures particle size distribution (PSD) of conveyed material through the full conveyed flow. Particles covering the surface area visible to cameras (or lasers) are normally measured and a relationship with the PSD derived from a sieve analysis of a full cross-sectional segment of the flow is used to extrapolate the measured PSD to that of the full volume for several belt cuts. This type of proxy calibration process has proven reliable in many cases.

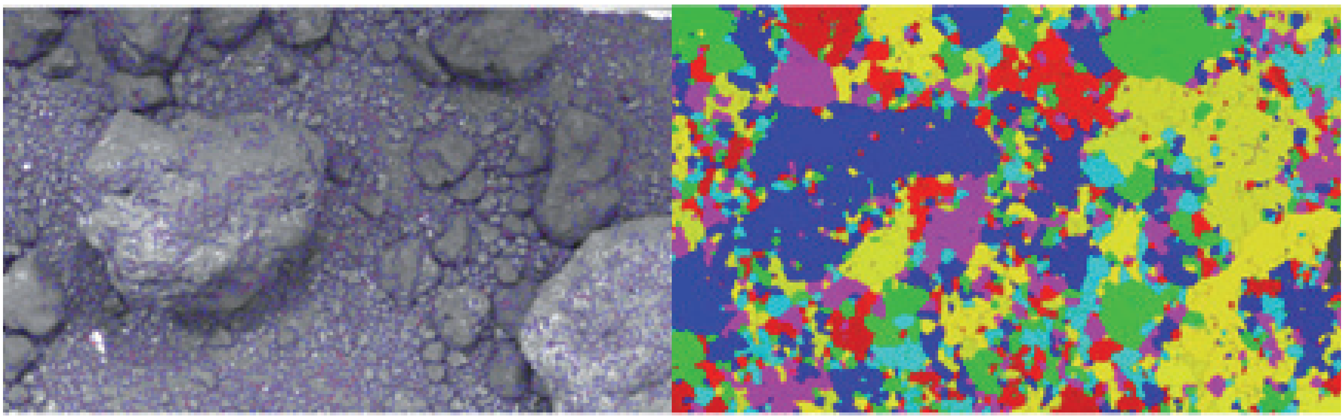
Any number of cameras applied to the flow, even for the falling stream, may not cover the full flow volume, hence achieving a representative PSD analysis remains a challenge. This is not to say there are no benefits in the use of existing technologies.

Most systems on the market have cameras with capability limitations that result in a minimum particle size that is much larger than a client may wish to detect and hence any material recognised as being finer than 15mm, for example, may be classified as “fines”.

The camera resolution may also limit the belt speed at which measurement of particles becomes less distinguishable. The application of these sensors may be focussed on the coarser size fractions or detection of "oversize" material to prevent damage to equipment downstream of the measurement location. Hence, the technology may prove fit for purpose for that specific aspect alone. Other benefits of these sensors include their capacity to measure conveyed volume and belt speed sufficiently well to calculate a mass flow to greater reliability than a belt weigher. The sensed PSD can inform the bulk density value used in the mass flow calculation for a given material type. The main error will be through assumptions on a "usual, average" bulk density based on typical fragmentation and specific gravity of the various components. The dangers involved are obvious!

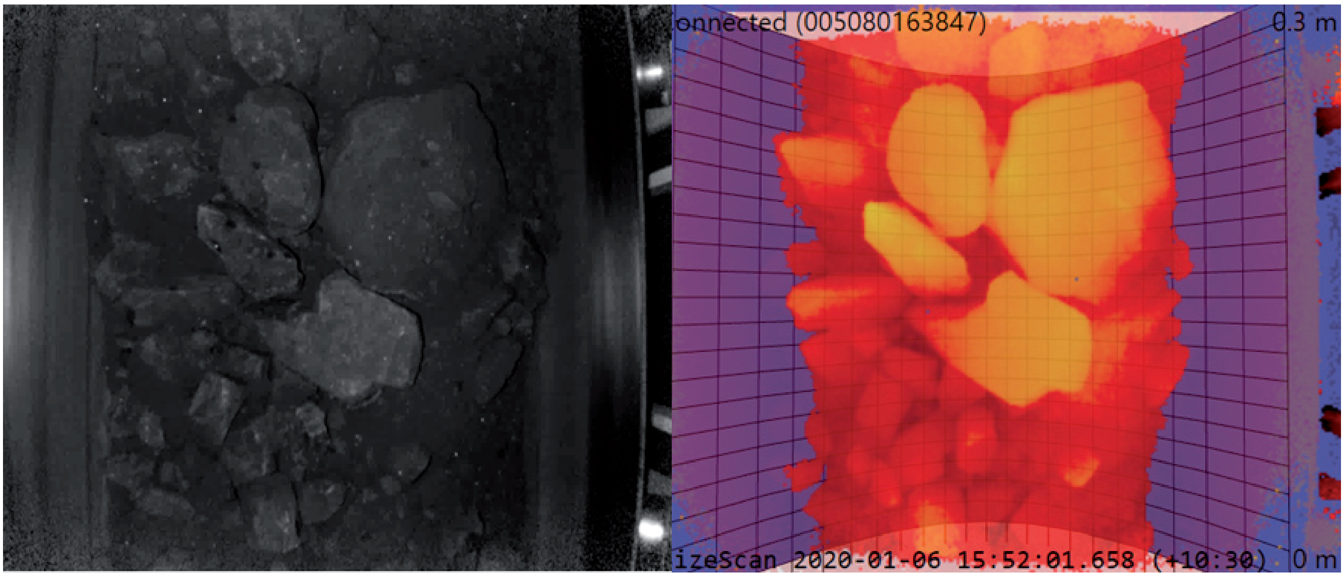
There is a wide opportunity for vendors to compete on the basis of comprehensive sampling -, analytical method - and site-specific knowledge and experience.

The SizeScan is a 3D infrared camera-based PSD analyser using advanced algorithms and was previously known as AGFeed (for Autonomous Grinding mill Feed analysis). It was developed by COREM in Canada (an industry funded research group based in Quebec City) (Faucher et. al., 2015). It was developed due to limitations associated with segmentation software applied to 2D camera images which miscalculated PSD in flows with largely bimodal size distributions because areas of fines with little colour contrasts were considered to be a single large particle and facets in large particle surfaces were misinterpreted as smaller particles (Figure 4). Image processing improvements allowed the images to show elevation associated with surface changes that better characterised particle size (Figure 5).



Credit: Arnaud and Gagnon, 2015; used with permission.

Figure 4: Photo of a segment of conveyed flow clearly showing multiple large rocks and a segmentation software representation of the same image showing incorrect determination of particle size.



Credit: Scantech; used with permission.

Figure 5: Photo of a conveyed flow image and SizeScan analysis clearly showing large rocks and correct determination of particle size despite minimal colour contrast being present in such materials as coke, anthracite and magnetite ores.

3.5 Validation of PAT solutions

All process analytical technology systems and solution are critically dependent on proper calibration and validation. The best way to assess performance is to extract representative samples in full compliance with TOS protocols and comparing the associated laboratory analysis to the PAT analyser data for a period of flow using a minimum of 30 comparison points (an industry developed standard number of reference points); Esbensen (2024). There is today no excuse for not complying with TOS - since 2024 the world has access to a fully comprehensive universal standard for sampling, DS 3077:2024, stipulating all principles and unit operation needed for defensible representative sampling (Danish Standards, 2024). 'Stopped belt' sampling and analysis permits the analysis of a short interval of flow, for example one metre, to be PAT analysed statically and then moved along so it can be removed from the flow for further sub-sampling and assaying (Figure 6). This has been successfully applied where mechanical samplers are not available. A sufficient number of samples needs to be taken for this to be effective in calibration verification.

The most effective measurement of a sample's quality in highly heterogeneous commodities, such as gold ores, may require the removed sample to be assayed in full, such as through a non-destructive offline analysis process, e.g., by photon assay. All of the removed sample of coarse ore can be photon assayed to provide an analysis of the one metre of conveyed flow. This is expected to be the method of choice that minimises sampling, sub-sampling and analytical errors for gold ores.

Other solutions are needed where the samples cannot be taken that are representative of the flow quality. In some cases, there is a need to calibrate analysers statically using samples with known composition which are often finely ground and homogenised. While not preferred, it may be a practical solution that can be used but most emphatically only if/when diligently validated. The analyser measurement of conveyed material should account for the conveyor composition through background measurements on clean, empty belts to remove background signal during normal flow measurement etc. The inability to account for other components of the conveyor belt, such as steel cords or chlorinated content, may, and does, result in poor analyser performances. Robust analyser design and calibration techniques have enabled these conveyor characteristics to be determined and accounted for in calibrations.

CASE STUDY 6: PSD

PSD analysis in a lithium operation in Western Australia ensure any oversize material, which normally migrates to the surface through the conveying action, visible to the camera, is detected prior to material entering a high-pressure grinding roll (HPGR) comminution stage. The HPGR can be damaged if material exceeding a certain size enters the system. It should be noted that a moisture analyser is also used as high moisture material can be detected which may cause clumping and blockage in the HPGR. Both systems provide operational protection from damage and or blockages.

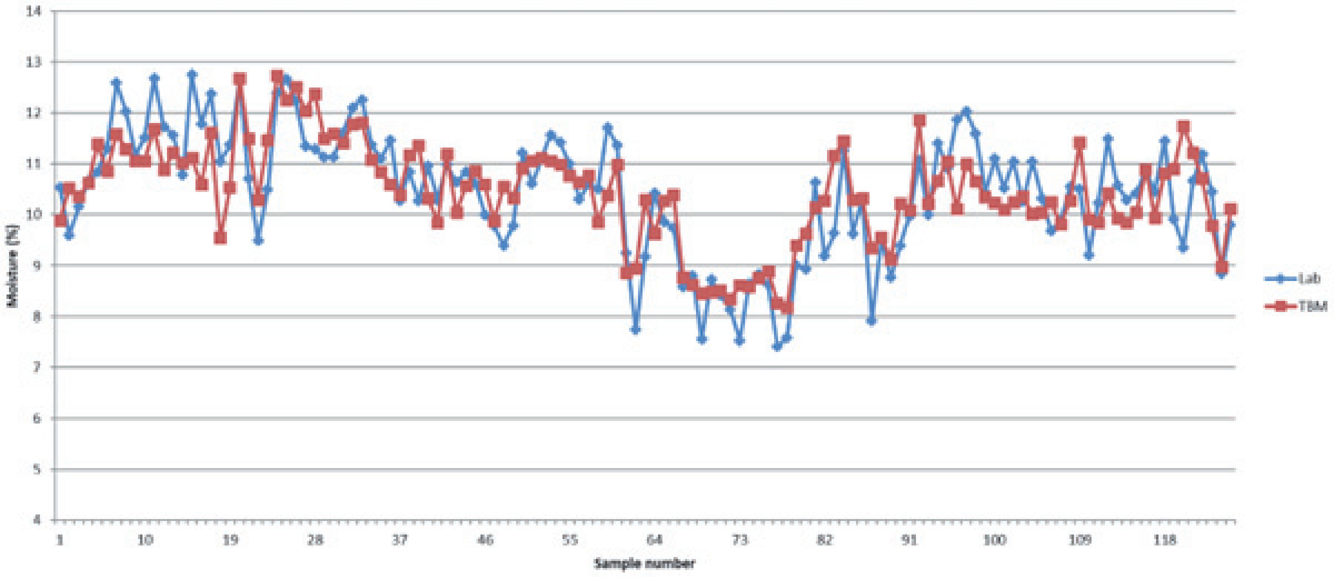
Scantech has demonstrated the ability to distinguish elements such as sodium and potassium in potash ore where chlorine is often present at concentrations in excess of 30 percent. There is here a great opportunity for creative technological improvements.

Experience with various analyser technologies suggests that sampling is least effective for moisture analyser performance evaluation as moisture content can change during a sampling and handling processes and that change (error) cannot be accurately determined. Many operating sites only perform a mass balance infrequently and once a moisture content is determined it is continuously applied as the average moisture factor. No consideration is given to seasonal changes, or dust management applications of water. Moisture content is generally found to be more variable than typically assumed or expected. In figure 7 the moisture measurements are for one-minute averages of flow, and the laboratory results are for samples taken during these same respective measurement periods. The PAT data is an average of a much larger amount of material than that included in the samples intended to represent the same flow.

Elemental composition and PSD are affected to a much smaller degree during any proper (TOS-compliant) sampling processes. Offline sieve analysis is used for calibrating the full volume of a segment of flow to the surface-measured signature for PSD analysers. The type of PSD analysis technology will dictate the frequency of required calibration. The SizeScan system requires only a single calibration after installation.

Credit: Scantech; used with permission.

Figure 6: Example of stopped belt sampling to remove a stream cut from a conveyed flow as fully as possible to compare with PAT measurement data from the same segment to reference laboratory assay results.



Credit: Scantech; used with permission.

Figure 7: Moisture measurement results for hematite iron ore from a microwave transmission-based moisture analyser and laboratory analysis of sampled material showing higher variability in laboratory results.

4. Summary

Process analytical technologies (PAT) are utilised when continuous knowledge of quality is needed in a timely manner for conveyed or flowing streams of matter, usually solid mixtures of significantly very varying heterogeneities. Reliable (indeed representative) monitoring the magnitude and periodicity of material quality variability is the necessary attribute for implementing an online PAT solution - but the material variability itself also has significant effects on the measurement process performance, which must be reduced, controlled or eliminated. Many sampling and analytical components need to be competently designed, managed and controlled for any specific PAT solution.

Specifically, conveyed flows are made up of materials with many characteristics adversely influencing their ability to be appropriately and effectively sampled, although this article argues that the main limitations are engineering and cost.

The value of the final sample assay data is to a large degree determined by its purpose for the PAT system user. This article covered the needs of real time measurement system management where material quality needs to be known with high confidence to influence the technological or industrial process/processing involved. Every process is sensitive to some degree on the nature and specifics of its own input parameters. The characteristics that affect online measurement process performance cannot always be characterised in a manner similar to that for laboratory measurement systems, and this is where various assessment approaches characterise competing system vendors. This article covered the main technology opportunities and challenges applicable to conveyed flows that have proven beneficial in the PAT domain as outlined in many case study examples supplied and referenced.

FACTBOX - Commercial documentation

The application of high specification PGNAA for many elements able to be used as proxies for parameters that cannot be directly measured (e.g., Lithium or Platinum) has resulted in over 140 installations of the GEOSCAN-M or GEOSCAN GOLD in the minerals sector for over a dozen trading commodities. The technology has also found applications in other sectors, such as recycling, where materials may be even more challenging to sample (such as shredded scrap metal, e-waste, non-ferrous scrap). It has been applied successfully to many applications where representative sampling is costly and technically challenging and where calibration solutions have involved extraordinary effort. The effort has proven worthwhile as paybacks on these applications has been as short as a few weeks in several industries. The real time data provided from such systems and the confidence developed by the users has allowed the technology to find many new beneficial applications. The ability to measure representatively over shorter time increments has generated bulk diversion opportunities to remove waste from ore to upgrade plant feed quality, improve plant utilisation, increase metal recoveries and prevent unnecessary processing of material for no value, consuming resources and generating fine tailings.

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