Transaction Paper

Development of a prototype X-ray transmission washability monitor

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Synopsis

The design and efficient operation of density-based mineral processing units requires regular densimetric analysis to be carried out on the various associated process streams. The results obtained from such analyses can have wide application, including the generation of washability and partition curves, which are critical for process design, control, and simulation. This paper describes some of the collaborative efforts that Kumba Iron Ore, in partnership with Springer New Technology and Anglo Technical Solutions Research, is pursuing in developing a novel density determination technique exploiting X-ray transmission (XRT) and optical imaging. This technique is being developed with the aim to determine sample density distributions that apply to washability characterisation of ores. This technique is aimed to be an alternative to the traditional sink and float method. For certain applications sink and float has required the use of tetrabromoethane (TBE) solution—a chemical that has been classified as harmful and environmentally unfriendly. This paper therefore presents some achievements in developing this novel technique which seems to be very promising.

Keywords

iron ore, density, X-ray transmission, washability, optical imaging, size.

Introduction

Gravity concentration encompasses a broad range of mineral separation techniques that are widely applied in the mineral processing industry. Gravity concentration principally exploits the differences in specific gravities of minerals in effecting the desired separation. Wills (1992) points out that key to this process is the relative movement of the targeted components for separation in response to gravity and one or more other forces. It is further said that the latter of the two forces is often resistance to motion offered by a viscous fluid. Separators such as dense media separators (DMS), jigs, spirals, shaking tables, and Knelson and Falcon concentrators operate on the all-encompassing principal of gravity concentration.

The efficiency of most, if not all, gravity separation techniques depends largely on the densities, size distribution, and shapes of the treated particles. Of particular focus in this paper are matters pertaining to the measurement of particulate density. Density information can be applied to assess the applicability of gravity concentration at the process design stage, as it is known that the larger the density difference between the value and gangue components the easier the separation. In operation, density measurements are essential for generating washability data and also for input into predictive models that can be useful for process simulation.

The sink and float method for fractionating of particulate material into density ranges using heavy liquid such as tetrabromoethane (TBE) has been widely applied in the minerals industry, as discussed by Koroznikova *et al.* (2007) and Baniel *et al.* (1964). However, as detailed in the material safety data sheet (MDS), tetrabromethane is classified as toxic and an eye and skin irritant, and prolonged vapor inhalation can result in extreme liver damage. Chronic exposure to this chemical, as would be a possibility with unprotected analytical laboratory staff, may affect liver, kidneys and lungs. Coupled with this is the fact that TBE has been classified as environmentally unfriendly, thereby presenting industries that use this chemical with a challenge in terms of safe handling.

It is thus most desirable that industry, and in this particular case the mineral resources industry, minimizes the use of this chemical. However, to do this alternative chemicals or density characterization methods that are

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similarly cost-effective have to be sought. In response to this, Kumba Iron Ore in partnership with Springer New Technology and Anglo Technical Solutions Research has embarked on an investigation to determine a novel method to measure particle density as well as the physical separation and classification of different particles according to their measured densities. This is to be made possible through the use of optical imaging, laser and X-Ray transmission (XRT) techniques to measure particle volumes and densities. These integrated tools are housed in an analytical unit being developed called the XRT Washability Monitor (WAMON).

Operation philosophy for XRT washability monitor

Principle of operation

The monitor employs the basic idea of combining optically measured particle dimensions with radiometric mass per area measurement based on the principle of X-ray absorption. The optical measurement delivers detailed information about the shape of each particle including the width, length, and height, which in combination with the X-ray measurement provides a signal that corresponds to the density of the particle.

The measuring paths are installed on a small conveyor belt with a length of approximately 4 m. The particles to be measured are fed onto the belt using a vibratory feeder. This ensures that the particles form a single layer on the belt with minimal particle contacting. The conveyor belt's variable speed drive has a frequency converter enabling speed adjustments between 0 and 53 mm/s. The operational belt speed is optimized for data transmission and the required high resolution from CCD linescan cameras that form part of the optics.

Optical measurement

Optical distance measurement in the range of 10–100 cm is mostly carried out using lasers. This technique has been available for more than ten years and is widely applied in the paper industry, steel casting, military, robotics, and many other industries including automotive and academia. The basic principle for optical measurement is illustrated in Figure 1. A laser projects a well-focused dot onto a surface, and the laser image is then projected via a lens onto a detector. This can be a CCD line or a position sensing device to measure the distance through the lens. The lens, which is focused on a single point, needs to be mounted at an angle to the surface where the laser beam is projected. The position of the projected laser point on the detector depends on the distance of the detected object to the detector and on the distance between laser and sensor.

Using the one-dimensional approach would give only very little information about each particle on a conveyor belt. In the best case the length and a height profile at one single line of the particle could be obtained. In the worst case no particle can be seen at all because it is not exactly centered. If the particle is scanned a second time and the orientation does not exactly match the previous one, the measurement would show a totally different result.

This principle has been exploited for the WAMON optics by easily expanding the laser point to a laser line and replacing the single detector by a CCD camera. By so doing it has been made possible to generate a complete profiling of an entire particle in terms of height, length, and width. The connection of the camera to a computer with specialized software allows processing of the optical images to determine particle volume, a key parameter in determining particle density. A similar approach was described by Darboux and Huang (2003) in the use of laser scanning to measure soil surface microtopography.

Optical camera angle optimization

Using a standard camera is an economical and easy way to realize the required particle dimension measurements. No special low-level camera programming is required and the options for debugging and implementing software changes are powerful. Various specialized imaging toolkits are available as well as interfaces.

In order to overcome data transmission issues Ethernet-connected cameras are used. Ethernet provides a usable bandwidth of 1000 Mbit/s and thus offers double the frame rate of a USB camera. Therefore the use of Ethernet as interface allows running a fast particle analysis without being limited by the available hardware.

In theory the best resolution will be achieved if the camera angle to the belt approaches zero (shown in Figure 2). This maximizes the distance the camera monitors between the projection of the laser without a particle and with a particle of a given height. However, in this configuration the back of the particle (from the camera's perspective)

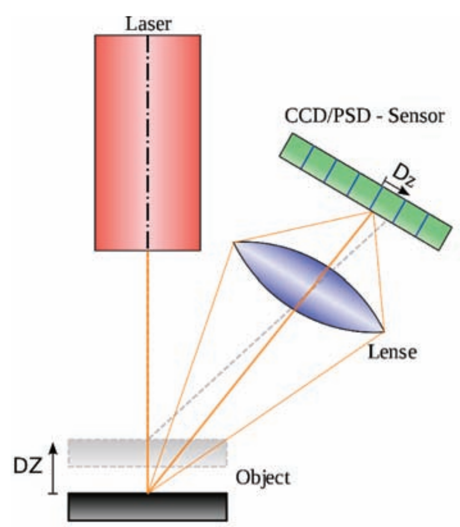

Figure 1—Principle of laser triangulation

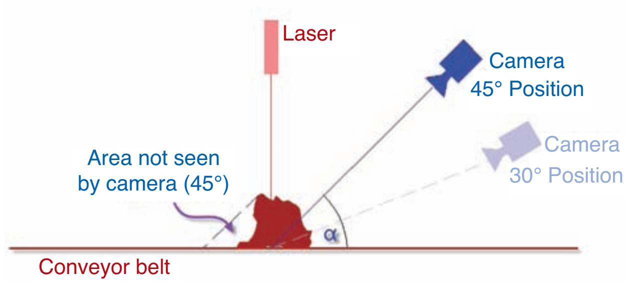

Figure 2—Laser and camera alignment

cannot be seen at all. The larger the angle alpha becomes the lower the maximum possible resolution achieved with a given camera. Alpha is also the angle of the maximum (negative) slope of the particle where the measurement can be made.

The camera angle on the WAMON was set-up to around 30°, which was chosen as a reasonable trade-off between resolution and maximum slope. In order to determine also the opposite side of the particle a second camera is installed symmetrically on the belt. With this setup an optical resolution of 0.14 mm (length/width/height) can be achieved.

Figure 3 shows the optical setup, detailing the line laser and the two cameras, while Figure 4 indicates the details of the setup.

X-ray measuring path

The fundamental principles of the application of X-rays for the determination of densities of materials are described by Zou *et al.* (2008). They state that X-rays have the ability to penetrate matter and interact with atomic species. The material under investigation is irradiated with X-rays of known incident energy and the attenuated intensity is accounted for by coherent scattering, incoherent scattering, and photoelelectric absorption. The absorption law as given in Equation [1] shows the relationship between amount of X-ray absorption or transmission and the material density and thickness.

$$I=I_o e^{-\mu\rho d} \qquad [1]$$

where

I_o = incident radiation

I = transmitted radiation

d = absorption path length/distance

μ = absorption coefficient

ρ = product density.

It is this theory that is exploited in the X-Ray Transmission Washability Monitor for the determination of material densities.

The X-ray measuring path on the WAMON consists of two X-ray tubes with a maximum voltage of 65 kV and a line detector with a width of 260 mm. The resolution of the detector is 0.8 mm (width), while the length resolution is determined by the belt speed. A resolution of 0.33 mm in length can be achieved.

The X-ray tubes are placed side-by-side above the centre of the belt in order to obtain high radiation intensity with a small distances between source and detector. The X-ray tubes are shielded by a lead-lined enclosure in order to keep the radiation to the outside within tolerable limits. Figure 4 illustrates the layout of position of X-ray tubes covered by a lead-lined box on a conveyor belt.

Equipment software

The WAMON is operated on a software package called RACCOON, which has been developed especially for this device. This software is complex, as it has to fulfil the following tasks:

- *Control of the hardware*—this is done by communication with a programmable logic controller (plc) built into an electrical cabinet as well as with the sensors
- *Data acquisition*—the camera images have to be acquired, time fixed, and correlated with the X-ray images when the particles arrive at the X-ray sensor
- *Image processing*—particles have to be identified; sizes, areas and volumes have to be calculated, and each corresponding mass/area has to be calculated
- *Evaluation and data processing*—calculated values have to be stored and reports produced
- Calibration will follow in order to optimize the unit to suit customer's requirements, since every customer's needs are unique.

Typically, particle size distribution is based on sieve analyses. This technique is well established and applied in laboratories. However, the size of a particle is not fully described by the mesh size of a sieve:

- Sieve meshes may have different shapes (circular, hexagonal, square)
- Particles may not necessarily be of cubic or spherical shape
- Elongated oversized particles may wrongly report to mesh undersize.

Using a model that describes the particle volume using length, width, and height values, it can be stated that the sieve analysis characterizes the particle size by the second largest (or second smallest) of these measurements. Although this method is viable for a sieve analysis in the laboratory, particle sizing by volume as applied by the WAMON is an alternative well-known sizing technique.

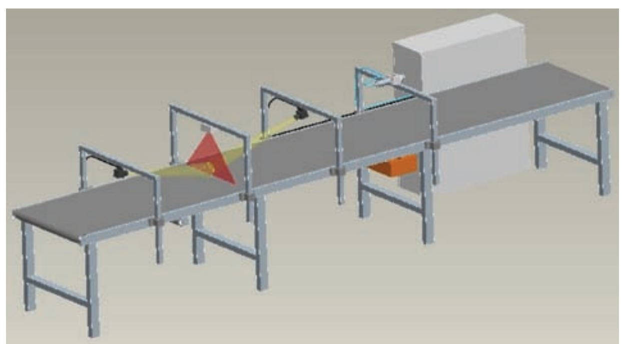

Figure 3—Schematic layout of optical cameras on conveyor belt

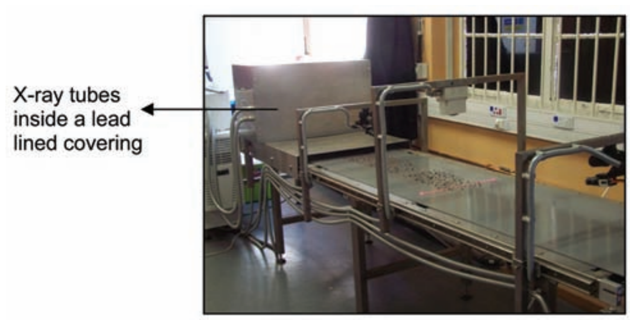

Figure 4—XRT monitor setup showing position of X-ray tubes

Measurement procedure

The software offers three measurement modes as characterized by different particles size ranges. The distinction is made in order to provide the ideal measuring conditions for each particle class. Mainly the X-ray parameters are different. If larger particles have to be measured then the voltage used with the tube is higher than for small particles in order to attain sufficient penetration.

After choosing the measurement mode and starting the instrument the conveyor belt and the sensors will automatically start followed by the preloaded vibratory feeder. The particles are fed across the vibratory feeder pan onto the conveyor belt and transported through the different measuring paths. The shape of particles illuminated by laser as shown in Figure 5 can be viewed on a user interface screen as soon as the particle is detected by the cameras. The height profile of the particles is presented in a particle map through the user interface software. Low height is shown in red and with increasing height the colour changes following the sequence of colors in the spectrum. Figure 6 shows such a particle map with one selected particle shown in detail. The software uses images from the cameras to superimpose the X-ray analyses for a specific particle to determine the mass of the particle.

Commissioning

The prototype WAMON platform was delivered to KIO by Springer New Technologies in the first half of June 2010. Commissioning commenced in August, during which the following challenges were encountered.

X-ray tubes

One of the X-ray tubes was totally damaged, as a result of overheating. The X-ray tubes are equipped with a water cooling jacket and the jackets are connected to the water supply. However, the supply had been operated with a manual valve that was accidentally left closed or not opened correctly during operation.

Following the replacement of the damaged X-ray tube, remedial action had to be taken to prevent recurrence. The cooling water system had to be equipped with an electromechanical valve which is connected to the instrument PLC and automatically opens when the main power is switched on. Additionally, a temperature sensor controls the tube temperature and powers down the X-ray tubes if the temperature exceeds the set operational level. The suppliers recommend that an additional atomized water control system be installed as a precautionary measure.

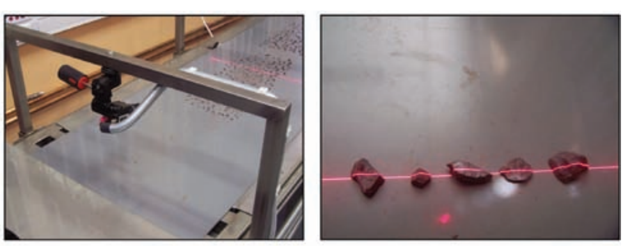

Figure 5—X-ray monitor showing particles along laser beam

X-ray tube orientation

The two X-ray tubes on the WAMON are placed side-by-side in order to cover the whole range of the detector with ideal X-ray intensity. In the original setup the X-ray beams were aligned so as not to overlap in the centre. In this configuration, as long as a particle was irradiated only by a single X-ray tube then the images of the particles were correct. If a particle happened to lie in region of overlap it would no longer be correctly imaged. Figure 7 shows that preventing the overlap results in a reasonable portion of the particle positioned in the middle not being irradiated. This would result in the shortening of the particle image, consequently resulting in an error in the evaluation of its width.

To overcome the problem, the left X-ray tube was turned by 20° clockwise and the right one counterclockwise by the same angle. This, coupled with placing the tubes closer together, resulted in the X-ray beams approaching more

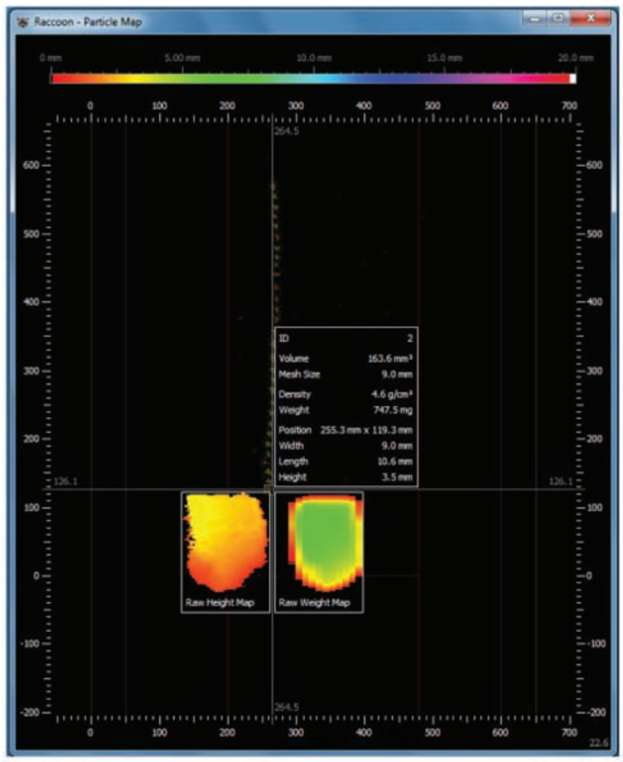

Figure 6—A particle map showing one selected particle in detail

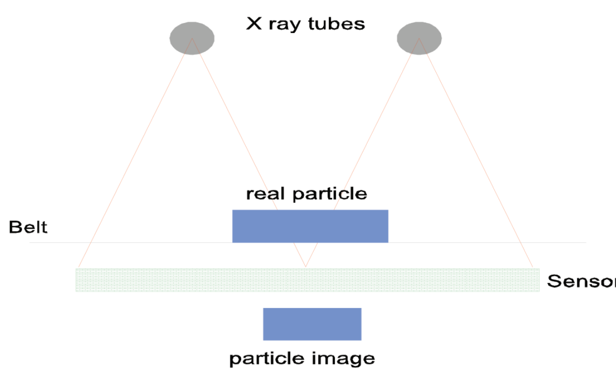

Figure 7—Initial X ray tube setup

closely to perpendicular in the centre of the belt. Hence the area of overlap, although still present, has been significantly reduced.

Belt speed

The belt is driven by a 3-phase drive that can be operated at varying frequencies, which was made possible by using a Mitsubishi frequency converter. The frequency can be set digitally in centihertz (cHz), which allows for an accurate adjustment of the belt speed.

Constant belt speed is vital for the test work purposes. For example: the distance of the optical measurement and the X-ray sensor is approximately 1500 mm. The equipment is designed to measure particles with smallest size of approximately 1 mm, thus translating to 0.066% of the distance. If the distance used to compute the match of both measurements using X-rays and camera image is out by 1 mm then it can be off by 0.066%. This would result in the X-ray measurement being inaccurate and missing the particle. Thus to avoid any mismatching it is recommended that the belt speed remains constant.

To overcome the problem special software was developed which adapts the matching parameters continuously to the actual belt speed. This is very resource-consuming, demanding substantial computational power to ensure perfect matching all the time.

Feeder

A challenge was experienced in feeding the material onto conveyor belt in monolayers. The problem was remedied by a reduction of the vibratory frequency for optimum feeder arrangement. Therefore several trials were conducted, from which an alternative adjustable feeder has been specified and recommended.

Sunlight reflections

A problem that was not foreseen in Germany where the WAMON was developed was the strong sunlight and its reflections on walls and furniture. The ultraviolet light reflections are absorbed by the cameras, thus making the analysis inaccurate.

Several measures were taken to solve this problem:

- ➤ A filter which blocks all light except red light was added to the camera lens
- ➤ A polarization filter that blocks reflections was added to the camera lens
- ➤ The intensity of the laser beam was increased
- ➤ Windows were darkened.

Test work results

The samples that would be used to calibrate and validate the X-ray washability monitor were classified according to specific density fractions using an Ericson cone and a minerals density separator (MDS), and further characterization was carried out using pycnometer and Archimedes method. Sample density results indicated density differences to be within 5% accuracy levels when using pycnometry and Archimedes density methods.

Several tests were conducted as part of commissioning to determine the response of the WAMON to measurements on internal reference materials (IRMs). The results indicated that the monitor was able to measure the particle volume and atomic density as shown in Figure 8.

Following the commissioning of the WAMON, calibration was carried out and the next step in the development was the validation exercise. It was recognized in the scope that the WAMON is currently optimized for a top size of 8 mm. Even though designed to be automatically fed using a vibratory feeder, the validation was to be conducted by placing the material on a stationary conveyor prior to running the sample through the unit. To date preliminary validation testing has been carried out in which repeatability and reproducibility have been evaluated using IRMs. Some of the results pertaining to the validation exercise are presented here in normalized format, as the absolute values remain confidential. Reference will be made to IRM samples L and F which were received already prepared each into several density fractions using two different techniques. Figure 9 shows an example of the detailed results from reproducibility tests carried out on one of the IRM samples.

Table I shows the summarized results from all the reproducibility tests carried out as part of the validation exercise. These results are also graphically presented in Figures 10 and 11, which show the correlations achieved between IRM densities and the density measurements from the WAMON. Generally, very low standard deviation values were achieved on the replicate density measurements per test, indicating satisfactory reproducibility.

Conclusion

The commissioning and validation of the X-ray monitor was successfully carried out and the team learned from the challenges encountered. The commissioning also showed that the concept of density determination by the WAMON is achievable.

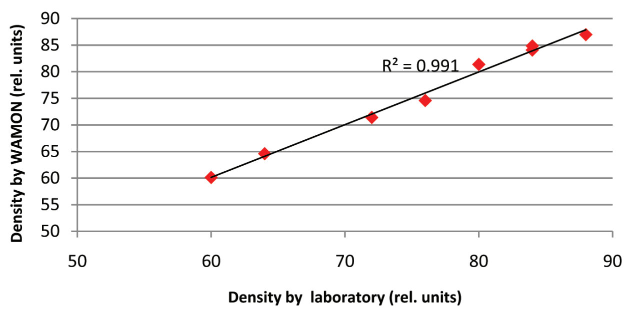

Figure 8—X-ray monitor trial-normalized results

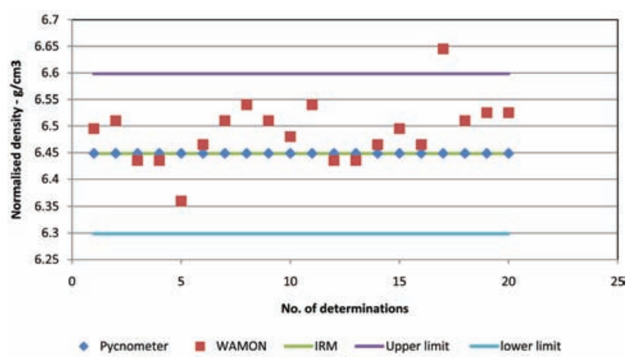

Figure 9—Normalized validation results for L5

Table I

Validation results

Sampled ID	Normalized density (g/cm3)		
	IRM	WAMON reading	SD on WAMON readings
L1	7.392	7.190	0.089
L2	7.340	7.350	0.054
L3	7.170	7.150	0.125
L4	6.887	6.292	0.035
L5	6.485	6.489	0.058
L6	5.636	5.736	0.072
L7	4.538	4.490	0.017
F1	4.256	4.042	0.023
F2	4.849	4.850	0.023
F3	5.211	5.205	0.030
F4	5.387	5.850	0.054
F5	5.951	6.001	0.109
F6	6.449	6.489	0.058
F7	6.848	6.765	0.060
F8	7.403	7.169	0.045

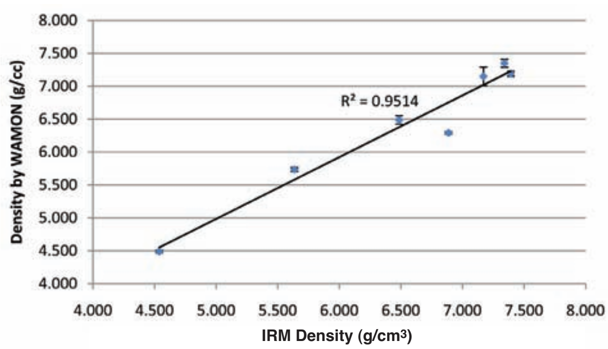

Figure 10—The validation results using L-samples plotted to 95% confidence limits

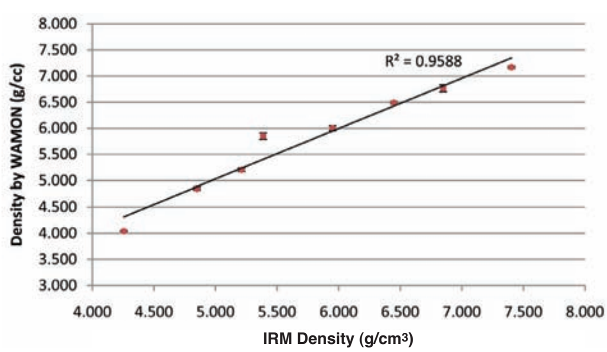

Figure 11—The validation results using F-samples plotted to 95% confidence limits

It was demonstrated during the validation exercise that the WAMON is highly capable of producing reproducible results. However, the WAMON for now remains an instrument in development as improvements are being implemented as part of ongoing planned staged developments. These include the planned incorporation of an automated particle sorting capability and sample chemical analysis by X-ray fluorescence. The implementation of this monitor is aimed at computing washability curves in matter of minutes, thereby producing real-time analysis.

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