Development of Automated Flotation Reagent System

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Kansanshi Mining Plc copper–gold mine, unlike other well-known copper deposits in the Zambian Copperbelt that predominantly consist of strata-bound disseminated sulphides, consists primarily of high-angle veins containing coarse-grained sulphides. The result of this ore formation is substantial variability in run-of-mine feed grades to the three designated concentrator circuits. Typical ore grades to the plant vary from 0.3% to at times as high as 3%; generally, the mean is 1.0% TCu in a day for all the three ore types: sulphide, mixed and oxide. This causes considerable upsets to plant operations. To counter this, a number of auto control systems have been installed throughout the concentrator. These include on-stream analysers, expert float controllers and reagent addition controllers. Instances of over- and under dosing of reagents prior to this installation were common. Overdosing of reagents, such as collectors, frother and sulphidizer, inevitably lead to low cost-effectiveness and poor flotation performance, while under dosing contributed to low flotation kinetics, leading to low recoveries. The Kansanshi concentrator had, by end of 2017, fully commissioned a rigorous automated dosing system. It tracks both incoming feed grades and tonnage throughput variation and therefore accounts for copper units and dosing reagents accordingly.

INTRODUCTION

Kansanshi Mining PLC (KMP) runs a concentrator that is fed by the Kansanshi copper deposit located in the North-western part of Zambia, approximately 150 km west of the Zambian Copperbelt. Unlike the deposits in the Zambian Copperbelt that consist of strata–bound, disseminated sulphides (Mendelson, 1961), the Kansanshi deposit consists primarily of high-angle veins containing coarse-grained sulphides. The deposit includes two pulses of mineralization, one at ~512 Ma and the other at ~502 Ma. Vein mineralogy and clear crosscutting relationships favour the latter suggestion (Torrealday, 2000).

All the copper minerals constituting the alteration sequence, from primary sulphides to carbonates or silicates, are present in various proportions (Table I). The alteration of primary sulphides starts with a deprivation in iron to form covellite. Further oxidation generates a deprivation in sulphur and enrichment in copper to form digenite then chalcocite (Dunn & Muzenda, 2001). The final steps of alteration, leading to the formation of copper oxide minerals, such as malachite or chrysocolla (a silicate), depend mainly on the composition of gangue or fluid. This variation in mineral classes, in addition to an angled-vein deposit, adds to the variability of run-of-mine (ROM) feed grade. Furthermore, having several different sources of material from the ROM, as Table II shows, contributes to fluctuation in feed grades, each source having its own proportionate influence. Overall influence is dependent on distances, influencing frequency of tipping, road conditions in other areas and truck sizes to the ultimate ROM feed grade.

Table I: Kansanshi Mine mineral classes.

Mineral	Mineral formula	Mineral	Mineral formula
Chalcopyrite	$CuFeS_2$	Malachite	$CuCO_3(OH)_2$
Bornite	Cu_5FeS_4	Azurite	$Cu_2(CO_3)_2.Cu(OH)_2$
Covellite	CuS	Cuprite	Cu_2O
Digenite	Cu_9S_5	Tenorite	CuO
Chalcocite	Cu_2S	Chrysocolla	$(Cu,Al)_2H_2Si_2O_5(OH)_4.nH_2O$
		Native copper	Cu

Table II: Typical Kansanshi Mine ore blend plan (showing ore sources on a single day).

Ore	Mining Areas	Combined Blend			Proportions			Respective Sources Grades		
		Tcu	ASCu	GAC	Feed %	BCM/hr	Ton/Shift	Tcu	ASCu	GAC
Oxide	SP_Ox_HG	1.51	1.00	84	30	139	2000	3.34	2.62	71
	Main 10				40	185	2667	0.94	0.6	98
	Main 12				30	139	2000	0.43	0.25	78
Mixed	Main 10	0.91	0.14	86	35	165	2567	1.05	0.22	95
	Main 6				30	141	2200	0.77	0.02	88
	HG RED				35	165	2567	0.9	0.15	75
Sulphide	Main 10	0.74	0.02		25	179	3000	1.15	0.03	
	Main 6				45	321	5400	0.6	0.02	
	Stockpile No. 6				30	214	3600	0.7	0.02	

In view of the above, it is easy to infer that plant stability is a key to improving performance generally and particularly flotation. Flotation circuits are challenging to operate consistently and stably when feed characteristics fluctuate. A stable plant is desirable for achieving consistent performance and offers stable platform for the optimization of process through continuous process improvement initiatives. It is also worth noting that automations depend on basic Proportional Integral Derivative (PID) control systems which tend to be less effective in dynamic and continually fluctuating circuits (Peacock *et al*., 2017).

For processing purposes, the ore types at Kansanshi are classified as Sulphide, Mixed and Oxide. All the three ore types are processed differently with each having a separate dedicated concentrator. Sulphides were treated traditionally with l frother and xanthates until 2012, when preference shifted to thionocarbamates/modified thionocarbamates based collectors which are more selective against iron. At KMP, three types of thionocarbamates (MX5149 – Cytec, C7160 – Flomin and TLQ2 – Axis House) have been used successively at different times. In the end, selection for the collector of choice was driven largely by cost and performance.

In the Oxide float circuits, target minerals are primary and secondary Sulphides with preference to allow the highly weathered minerals like malachite, chrysocolla, and copper oxide as eventual feed to the Hydromet leach plant; however, Sulphide minerals in the Oxide float circuit do not always have a surface as amiable to collectors as similar minerals present in the Sulphide circuit. This is mainly due to the surface being rimmed with a thin layer of tarnish (oxidation) (Bastin & Kottgen, 2009). As a consequence, at the beginning, a promoter (thiosulphate based) was dosed together with xanthates to enhance the flotation of weathered Sulphide minerals. During the same time when Sulphide circuit collectors were being changed from xanthate based collectors to liquid thionocarbamate based collectors, the Oxide float circuit was undergoing similar reagent regime changes – mirroring Sulphide circuit. Recently though, controlled potential sulphidization (CPS) has also been included on Oxide float circuit to considerably enhance the flotation of weathered Sulphides.

Mixed ores have been treated differently with float circuit basically having two segments with the first section dedicated to flotation of pure primary Sulphides only using simple frother/xanthate system. By contrast, the latter section is for floating oxide minerals by CPS using NaHS as a sulphidizer.

On all three circuits, reagent dosage is based on grams of reagent per ton of ore milled; however, this philosophy is not adequate in a system where feed grades are fluctuating sharply from one extreme end to the other. Therefore, it becomes beneficial to dose the reagents based on metal units. In August 2017, complete reagent automation was fully developed and became functional in the plant employing the use of on-stream analysers (OSAs), specialized reagent flow meters and reagent proportional–integral–differential (PID) controllers. Another ore characteristic that entails a change in reagent dosage rate is coarseness and fineness of incoming ore. Fine material, naturally presenting more mineral surfaces entails extra reagents consumption for the same metal units. Unfortunately, there is no system yet developed to automatically track and adjust reagents responding to this disorder. There are other units installed but not fully optimized for online particle size distribution tracking. Once fully optimized and operational, these concepts will be incorporated for next level of reagent automation to cover the aspect of particle size.

Table III shows the typical reagents that have been used in the KMP float circuits.

Table III: Reagent dosed per circuit over time.

Ore	Old reagents (Before 2012)	Intermediate change to reagents (2014–2016)	Current reagents (2016–date)
Oxide	Frother Xanthate (PAX) Promoter	Frother Thionocarbamate (MX5149 & C7160)	Frother Xanthate (SIBX) NaHS
Mixed	Frother Xanthate (PAX) NaHS	Frother Xanthate (SIBX) NaHS	Frother Xanthate (SIBX) NaHS
Sulphide	Frother Xanthate (SIBX)	Frother Thionocarbamate (MX5149 & C7160)	Frother Thionocarbamate (TLQ2)

OLD REAGENT DOSING REGIME

The most advanced automated reagent dosing system at KMP a few years after commissioning was that of CPS using NaHS on the Mixed circuit. It involved use of oxidation–reduction potential (ORP) probes that continuously measured the hydrogen ion activity (Eh) in the pulp. When adding the sulphidizing agent to the pulp (for example, NaHS), its dissociation will give the species H_2S, HS^-, S^{2-}, depending on the pH. The ORP probes measured the excess HS^- ions in mV. The ORP probe communicates with a programmable logic controller (PLC), which, depending on the set-point, closes or opens the valve on the reagent line to allow flow that keeps the Eh value within ± 20 mV of the set point. Initially, before installation of flow meters on these lines, the system wholly depended on comparison of actual Eh and set-point Eh. However, flow meters were later installed and have helped operators in noticing when the ORP probe is out of calibration or if indeed there is actual blockage in the reagent line. This is usually when the flow rate indicator is way out of acceptable established ranges. The installation of flow meters also helped establish the frequency with which the probes lose sensitivity and at what rate they should be calibrated. Consequently, a programme has been put in place to calibrate the probes weekly.

Flotation-Depressing Effect of NaHS

It is also important to note the unwanted effect of excess NaHS. Excess sulphide ions depress the xanthate flotation and therefore have to be oxidized (the froth begins to be mineralized only at a potential higher than −400 mV). This leads to the formation of other reducing agents, such as thiosulphate, that are not necessarily indifferent in the flotation process (Castro *et al.*, 1974). After commissioning of the Mixed ore circuit incorporating CPS in 2009 and the few years that followed, hourly checks of sulphide ion activity (E_s) values were done as a way of ensuring that the NaHS dosage was within optimum range and as a check of the E_h probes that tended to fall off calibration

and be less accurate. The optimum potential (E_s) (which is a measure of the S^{2-} concentration), measured by an ion-specific electrode, is about −500 mV for the sulphidization of malachite (Jones & Woodcock, 1978); however, the optimum found by Ferron & Manu (1994) was −300 mV.

As stated above, the E_s probe (which is a selective ion sulphide combination probe) was used in the hourly checks because it is more accurate and less susceptible to fall off calibration; however, it is not robust enough to be installed in the plants for online real-time control purposes. Figure 1 shows a strong but slightly less linear relationship between E_s values and E_h values for control. The limitation with this arrangement was heavy reliance on operator intervention to physically measure E_s values. This method was prone and vulnerable to human errors and inherent lapses, especially because the exercise was laborious and repetitive. Furthermore, the pulp after being collected in a sample cutter is inclined to age within minutes before actual measurement using the external E_s probe is done. Similarly, some NaHS (S^{2-}) ions are oxidized quickly and therefore the real measured values are not truly representative. In addition, the checks were done hourly, but, as pointed out earlier, conditions can and do change many times within the period of an hour.

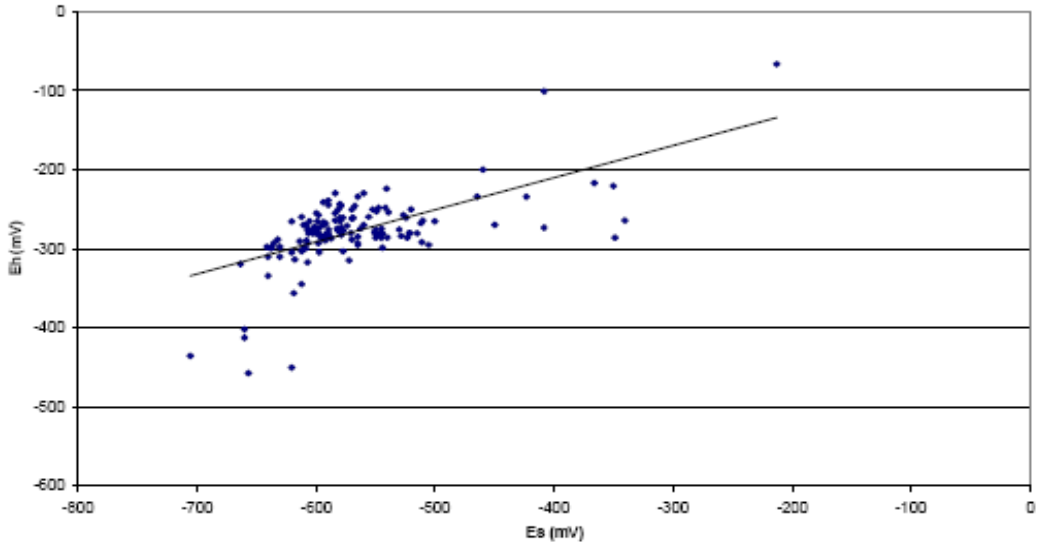

Figure 1: Relationship between E_s and E_h.

Reagent Dosing and Checks

In the old reagent dosage set up, all reagents were pumped to respective plant header tanks for eventual redistribution to dosing points via gravity. Except for NaHS, the reagents were physically dosed by adjusting manual valves on reagent lines to get required flows. Gravity dosage also had other problems of the siphoning effect in cases where reagent was running full bowl in the line. This would always distort the required flows and invariably end up in overdose.

With the exception of NaHS, which was dosed as described, all reagents were dosed based on reagent charts derived from experimental data initially for newly introduced reagents and later refined to best plant response with reference to reviewed historical data. Experimental dosages were derived by doing float tests in the laboratory, fixing all other parameters and only varying the dosage rates of (grams of reagent per ton of ore; gpt). The dosage rate with best repeatable results was then selected and replicated in the plant. Dosage charts based on laboratory experiments were given to operators who are supposed to measure and adjust reagent flows hourly according to current instantaneous obtaining milling throughput and feed grade. As pointed out, these parameters are constantly fluctuating, depending on feed characteristics for milling rates and feed grades. At times, even sources of ROM feed within the pit are numerous and of variable characteristics and feed grade. A typical dosage chart is shown in Table IV. Over time, reagent dosage charts are regularly updated based on historical data, selecting only best performing data points. Dosage in terms of gpt is determined

based on feed grade then, by factoring in the milling throughputs, the flow rates in mL/min are calculated.

Table IV: Typical reagent dosing chart.

SULPHIDE circuit - Collector (MX5149) - Flow Rate (cc/min)																
Feed grade		<0.3 - 0.5			0.5 - 0.75			0.75 - 1			1 - 1.5			>1.5		
g/t		4			5			6			7			9		
Dosage point		Dosage Point 1	Dosage Point 2	Total	Dosage Point 1	Dosage Point 2	Total	Dosage Point 1	Dosage Point 2	Total	Dosage Point 1	Dosage Point 2	Total	Dosage Point 1	Dosage Point 2	Total
Mill throughput - dry tonnes (tph)	1,500	70	30	100	88	38	125	105	45	150	123	53	175	158	68	225
	1,550	72	31	103	90	39	129	109	47	155	127	54	181	163	70	233
	1,600	75	32	107	93	40	133	112	48	160	131	56	187	168	72	240
	1,650	77	33	110	96	41	138	116	50	165	135	58	193	173	74	248
	1,700	79	34	113	99	43	142	119	51	170	139	60	198	179	77	255
	1,750	82	35	117	102	44	146	123	53	175	143	61	204	184	79	263
	1,800	84	36	120	105	45	150	126	54	180	147	63	210	189	81	270
	1,850	86	37	123	108	46	154	130	56	185	151	65	216	194	83	278
	1,900	89	38	127	111	48	158	133	57	190	155	67	222	200	86	285
	1,950	91	39	130	114	49	163	137	59	195	159	68	228	205	88	293
	2,000	93	40	133	117	50	167	140	60	200	163	70	233	210	90	300

The best recovery days from historical data are selected. Feed grade is then plotted against collector dosage, and the equation of the best-fit line is obtained to be the guiding equation with the variable x being the feed grade.

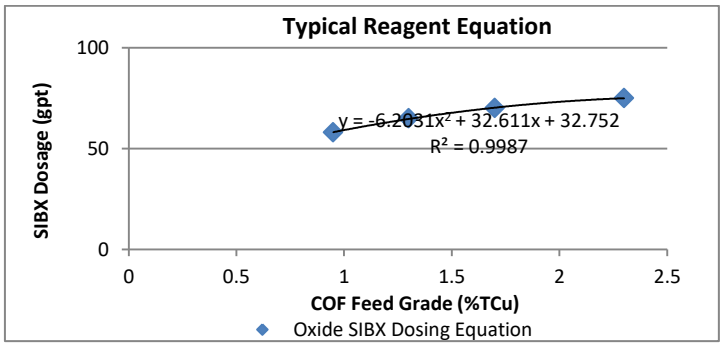

Figure 2: Collector curve with equation of line.

Equation of the best-fit line after plotting dosage against head grade (HG):

$$Y = -6.20x^2 + 32.61x + 32.75. \quad [1.0]$$

$$\text{Dosage (gpt)} = -6.20 \times (\text{HG})^2 + 32.61 \times (\text{HG}) + 32.75. \quad [1.1]$$

$$\text{Flow rate (mL/min)} = [\text{Dosage (g/t)} \times \text{Throughput (t/h)}]/[\text{Strength (g/mL)} \times 60 \text{ min}]. \quad [1.2]$$

Effects of Reagent Over- and Underdosing

The liquid-based collectors, being highly concentrated, are therefore minute flow reagents and fairly averse to over- and under dosing. For example, Figures 3 and 4 depict an experiment done for a thionocarbamate-based collector (TLQ2). Higher dosages were not depressing, but affected the froth, which sometimes overloads and the bubbles burst, causing lost recovery. However, on the plant the operators would notice and react with increasing mass pulls. Therefore, in the plant, recovery is maintained but the concentrate grade and quality deteriorates. This effect is aggravated with non-selective xanthate-based collectors.

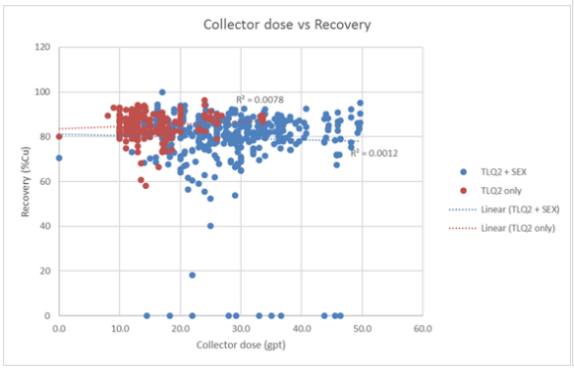

Figure 3: Recovery as a function of collector dosage.

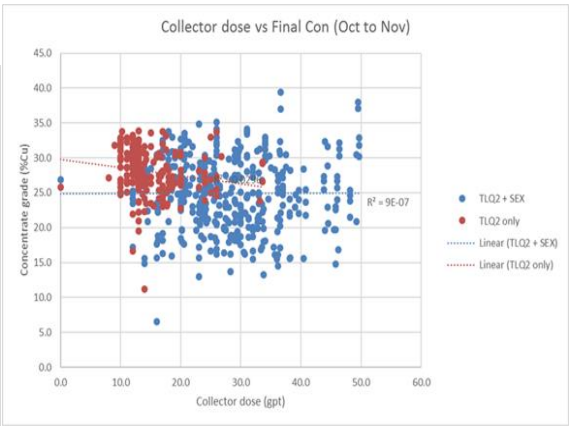

Figure 4: Final concentrate grade as a function of collector dosage.

NEW REAGENT DOSING REGIME

To maintain more efficient reagent dosing, KMP developed a robust automated reagent system on each circuit that was less reliant on human interventions. The above-described old reagent dosing method had inherent problems, mostly arising from human errors and too-frequently changing parameters were difficult to cope with. New dosing regimes guaranteed efficient running of KMP float circuits and maintaining low cost of reagents.

Mixed Ore Circuit

Sequence of actions taken to automate the reagent addition in the circuit:

- Change all reagent (frother, NaHS and SIBX) header tanks and pump systems;
- Dose from the new header tank using pumps to a pressurized ring main;
- Installed compatible flow meters on NaHS lines;
- Installed valves and flow meters at each dosing point for SIBX and frother;
- Linked valve control to PLC.

Oxide Ore Circuit

Sequence of actions taken to automate the reagent addition in the circuit:

- Installed pumps pumping from reagent storage tanks to individual dosing points;
- Installed compatible flow meters on NaHS, frother and collector lines;
- Linked dosing pumps to PLC.

Sulphide

Sequence of actions taken to automate the reagent addition in the circuit:

- Header tank system was maintained;
- On each reagent header tank, dual-redundancy pumps were installed that pump to a pressured manifold with the pressure relief line recirculate to header tank;
- From the manifold, various lines were abstracted to dose to required dosing points;
- Installed compatible flow meters and valves on each line to a specified dosing point;
- Linked valve control to PLC.

On-Stream Analysers

OSAs have been part of the KMP plant configuration since inception albeit with poor utilization in the initial stages. Most concerns relating to poor utilization were line blockages, flawed sample streams feeding system to the x-ray machines and varying sample cutters in the samplers. In order to significantly reduce line sand out incidences, 90◦ bends were replaced with radial turns. Additionally, the abstraction nozzles were modified to ensure slurry line velocities in smaller OSA lines were maintained. Major streams on the floats are run through these Courier OSA machines to read real

time assays that get displayed on Supervisory Control and Data Acquisition (SCADA). For a long time, operators only used the OSA figures on SCADA to proactively view the trend (whether upward or downward) and act timeously. Actions taken when anything odd is noticed in the trends varied between increasing/decreasing air flows into float cells, changing mass pulls, adjusting frother depths. Other interventions included manually adjusting reagents.

REAGENT CONTROL PHILOSOPHIES

Mixed Reagents

The Mixed float circuit has three reagents; namely, NaHS, SIBX and frother, all running off the pressured ring main. Figure 5 shows a schematic drawing of a typical reagent dosage system on the Mixed float circuit.

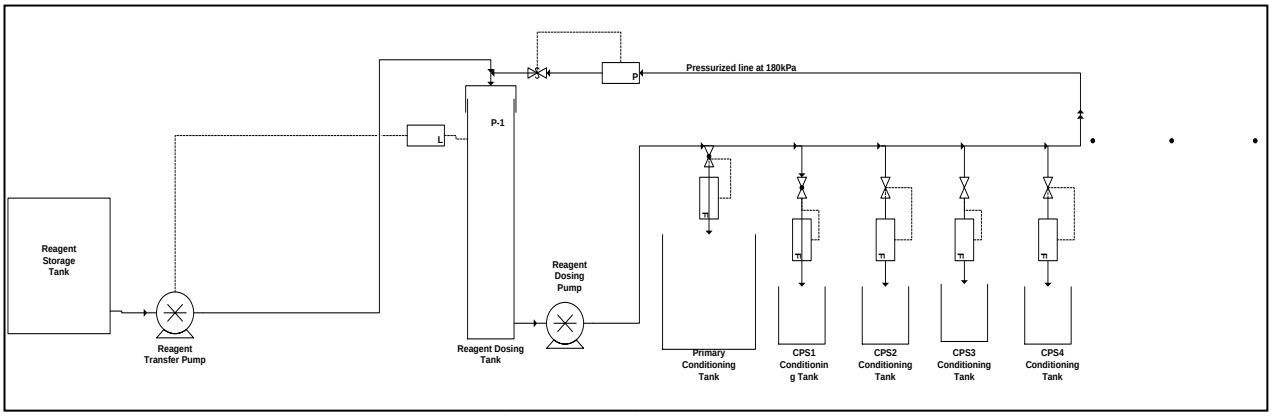

Figure 5: Schematic of Mixed ore flotation circuit dosing system.

With reference to Figure 5:

- Pressure in the ring main is maintained around 180 kPa and is fitted with a pressure controller logic that manipulates the relief valve to maintain uniform pressure and ensure that the line is always pressurized.
- Reagent transfer pump runs on an ON/OFF basis regulated by the level in the reagent dosing tank. When the level drops, the pump starts to fill the tank and stops automatically when level is high.
- The respective valves into the reagent conditioning tanks are controlled by flows read on flow meters on each respective line flow meter. The flow set point is determined by the written programme in the PLC. Dosage in gpt is governed by Equation 2 written to it and previously derived from historical data, incoming feed grade instantaneously read in real time from OSA and inserted into PLC.
- The flow rates in mL/min are calculated from milled tonnage throughput based on previously determined dosage (gpt). That is the total flow required through the circuit.
- For NaHS and SIBX, all five points receive flows in pre-set proportions known as splits. For SIBX, splits are typically as shown in Figure 6.

Oxide Reagents

The Oxide float circuit, like Mixed circuit lately, has the same three reagents, which are NaHS, SIBX and frother; however, these do not run off the pressured ring main but each dosing point has a dedicated positive displacement pump. The reagent flows are determined from incoming metal units and tonnage throughput, but flow rates are regulated by the PLC manipulating pump speeds and not valves (as on the Mixed float circuit). Apart from the ring main, every other principle remains the same.

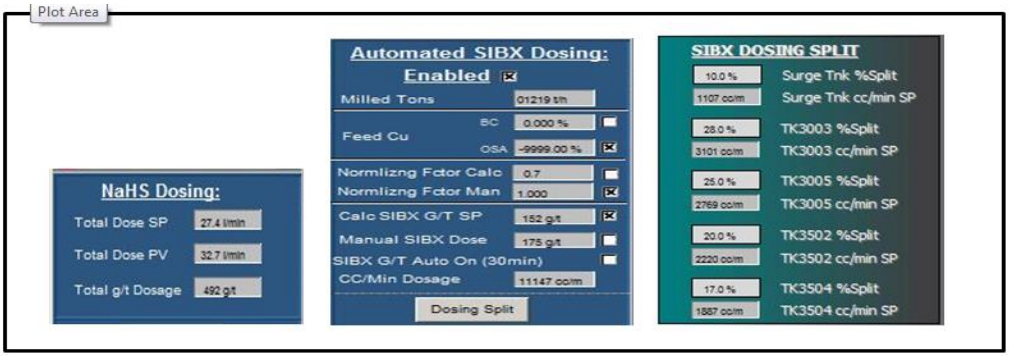

Figure 6: Snap shots of SCADA showing how reagent splits are distributed in Mixed ore circuit.

Sulphide Reagents

On the Sulphide float, the principal reagents are frother and TLQ2 (liquid-based thionocarbamate collector), both being pumped off the header tank to a manifold that comprises a valve and flow meter system into a specific dosage point. It has similar split system as shown in Figure 6.

Frother dosage in gpt is decided by the operator after visually assessing the bubble formation and float performance; however, on Sulphide, there is a fully developed froth camera system and an expert-controlled frother addition system is being developed. On intuitive observation, it was noticed that, almost invariably, collector dosage in Sulphide is in a 1:1 ratio with frother. Therefore, an expert controller is being set up that, for every collector dosage determined from head grade and throughput, a band of ± 20% of collector dosage set point will govern the frother dosage band. The controller is then set to increase or reduce frother dosage within the band, depending on the froth velocity.

CONSTRAINTS ENCOUNTERED

Consistent with the flow of this reagent automation development, variation in head grade and ore characteristics are not isolated, so even reagent types have been varied to match ever-changing trends. Reagents were changed a few times, causing instances of having incompatible reagents to installed flow meters. Care has to be taken to ensure the reagent being applied is compatible and less corrosive to the equipment internals, in which case, may distort readings and ultimately controls. Particularly, magnetic flow meters, which are more robust to the plant conditions, depend on conductivity; however, some reagents have low conductivity and do not respond to this effect. Therefore, on some reagent lines, flow meters were changed to the next-most robust instruments, which use the principle of ultrasound. Having so many gadgets connected to the reagent system also introduced extra weak points in the system, leading to reagent leakages.

REAGENT AUTOMATION BENEFITS

Continually controlled reagent additions have ensured fewer instances of unnecessary overdosing and reagent wastage. This means that cost efficiency in terms of reagent dosing has improved. Tables V, VI and VII show reagent consumption reductions since the change to full automation.

There has also been an advantage to recoveries as most of these overly sensitive reagents when overdosed tend to depress the froth, as roughly illustrated in Figures 3 and 4. Besides, recovery gains are also there due to reduced instances of under dosing. Extent of recovery and concentrate grade improvements has not yet been established due to many other interventions that happened during the same period. However, detailed analysis is still on-going.

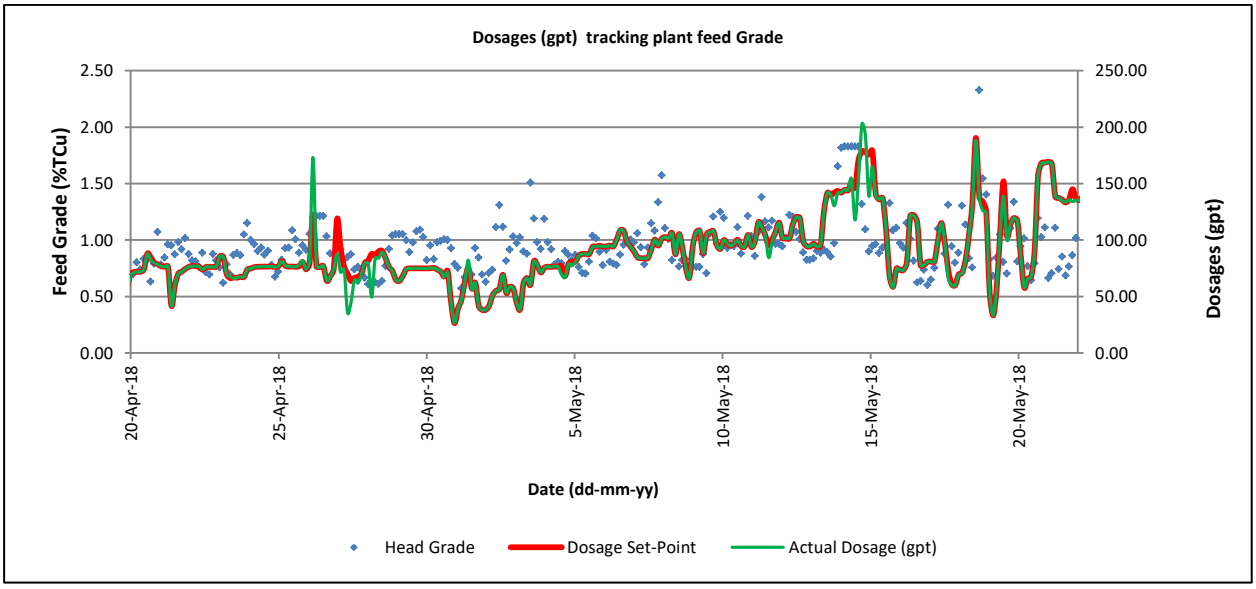

Figure 7: Graphs depicting reagents running close set points determined by head grade and throughput.

Table V: Mixed ore flotation circuit measurable key performance indicators before and after automation.

Mixed reagents	Consumption rates (gpt)	
	Before automation	After automation
Frother	20	14
SIBX	175	126
NaHS	864	805

Table VI: Oxide ore flotation circuit measurable key performance indicators before and after automation.

Mixed reagents	Consumption rates (gpt)	
	Before automation	After automation
Frother	22	15
SIBX	80	75
NaHS	550	450

Table VII: Sulphide ore flotation circuit measurable key performance indicators before and after automation.

Mixed reagents	Consumption rates (gpt)	
	Before automation	After automation
Frother	10	8
TLQ2	10	8

CONCLUSION

The previous reagent dosing system had inherent demerits like under dosing, over dosing and at times not dosing at all. Other shortcomings included bordered on health as operators physically needed to be in close contact albeit using gloves and respirators; however, this successful development and implementation of a robust automated reagent system, all reagent dosing problems previously faced have been eliminated and operators' frequent contact with reagents minimized. Primarily, consistency in dosing only required flows of reagents have ensured plant stability and yet to be quantified recovery final concentrate gains. This is in addition to effective cost controls.

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