The journey of process improvement – Ok Tedi's vision

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ABSTRACT

Ok Tedi has been operational since 1984 and is the longest running open pit mine in PNG, producing copper, gold, and silver. In 2015, Ok Tedi conducted an internal gap analysis on the state of their existing data network and control systems to identify priority work fronts to de-risk the operation in order to achieve the business objective to safely deliver on life-of-mine production.

Various improvement projects were executed during 2015 to 2017 to mitigate the identified business risks such as upgrading of the network infrastructure and improving reliability of instrumentation and equipment on-site. However, declining ore grades and various production challenges leading into 2018 culminated in Ok Tedi experiencing low gold and copper recoveries due to unstable operation, resulting in operations reverting to manual control of the processing plant as they had lost trust in the process control system. The operating norm became one of reacting and firefighting, further compounding the situation was the lack of visibility and transparency of underperformance root cause, once again bringing to the limelight gaps identified in the 2015 review relating to insufficient digital maturity for business intelligence.

The Processing Improvement department at Ok Tedi was established in 2018 as part of the business improvement strategy. The group initiated various engagements with subject matter experts and concurrent improvement projects to address the poor performance and mitigate future business risks based on the previous gaps identified.

This paper discusses the process improvement journey Ok Tedi embarked upon in 2017 and some of the project initiatives executed by the technical services group and partnerships which ultimately resulted in recovery improvement uplifts for both copper (2.4 per cent) and gold (7.4 per cent).

INTRODUCTION

Ok Tedi Mining Limited (OTML) operates the Ok Tedi mine, situated 2000 m above sea level at Mount Fubilan in the remote Star Mountains of the Western Province of Papua New Guinea (PNG). The Ok Tedi mine is the longest running open pit copper, gold and silver mine in Papua New Guinea.

From first production in 1984 to the end of 2022, Ok Tedi has produced 5.17 Mt of copper, 15.9 Moz of gold and 36.4 Moz of silver (Ok Tedi Mining Limited, 2024).

The Ok Tedi project was to have an initial life-of-mine of 25 to 30 years. Around 2010, Ok Tedi's life-of-mine was extended to 2025 following extensive community consultation and revised mine plans. In 2021, the life-of-mine was further extended to 2032. As of 2023, the OTML board approved another extension with the current life-of-mine up to 2050.

CONCENTRATOR FLOW SHEET

The principal copper-gold ore deposit at Mount Fubilan consisted of a Leached Cap and supergene enrichment containing significant gold mineralisation, on top of the underlying porphyry copper-gold system (Jones and Maconochie, 1990).

Production of gold commenced in 1984 treating the original Leach Cap containing significant gold mineralisation. The original plant consisted of a single stage semi-autogenous grinding (SAG) mill followed by screening, with oversize treated using gravity recovery methods and the screen undersize undergoing cyanidation in a conventional carbon-in-pulp (CIP) leach plant (Newman, 1985).

The processing plant facilities have been progressively modified to suit the various available copper ore types as the mine developed, particularly around the milling, flotation, and concentrate handling areas. The first copper circuit (Train 1) was built in 1987, the same year gold bullion production ceased, with the second copper circuit (Train 2) completed in 1989 (England, Kilgour and Kanau, 1991).

A simplified schematic of the Ok Tedi copper processing flow sheet as at 2023 is illustrated in Figure 1, showing one of the two parallel and independent grinding and flotation circuits. As of the beginning of 2024, the concentrator flow sheet and process description will change going forward with the processing plant upgrades currently underway.

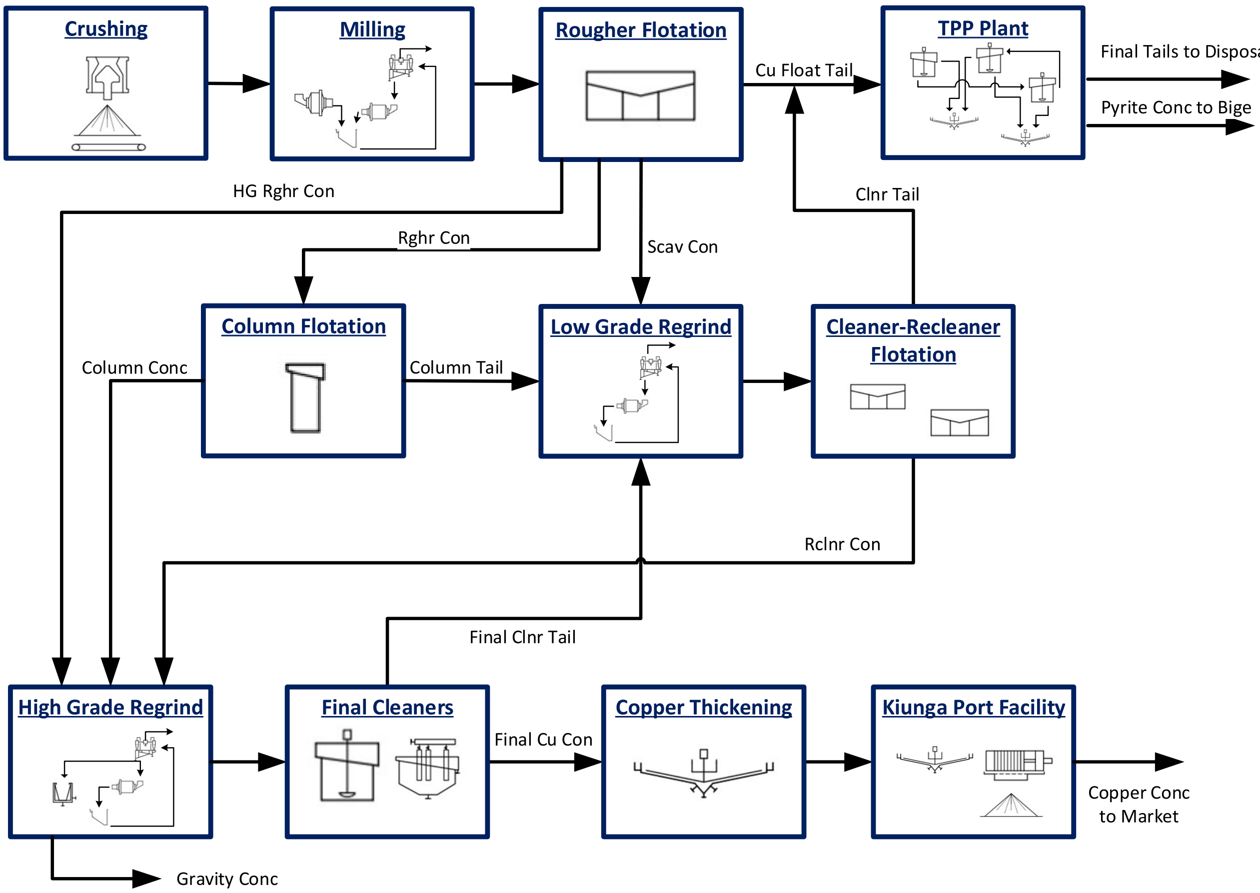

FIG 1 – Simplified block flow diagram of Ok Tedi Concentrator flow sheet as at the end of 2023.

Process description overview

Crushed ore is conveyed to two SAG feed stockpiles, with each stockpile feeding the corresponding processing trains. There are two independent grinding and flotation trains (differentiated as Unit1 and Unit2 for Train 1 and 2 respectively). The grinding circuit of each train utilises a SAG mill followed by two secondary ball mills to produce a flotation feed product size 80 per cent passing of 180 µm.

Each rougher-scavenger flotation train has 30 OK-38 (38 m^3) flotation cells, arranged as two parallel banks of 15 cells (differentiated as damside and roadside). Concentrates from the rougher-scavenger cells report to the regrind and cleaner circuits via different routes: the primary roughers are diverted to the high-grade regrind circuit, the scavenger concentrate reports to the low-grade regrind circuit, and the secondary rougher concentrate reports to a column cell, with the column cell concentrate reporting to the high-grade regrind circuit and column tailings flowing to the low-grade regrind circuit.

The two regrind mills in each flotation train are run in closed circuit with a corresponding cyclone cluster. Regrind cyclone overflow from the low-grade circuit reports to a two-stage cleaning circuit. The first cleaner stage consists of 16 Denver DR500 flotation cells, with the cleaner concentrate further upgraded using eight Denver DR500 flotation cells as re-cleaners.

Re-cleaner concentrate reports to the high-grade regrind circuit. The cyclone overflow from the high-grade circuit reports to a single OK-100 (100 m^3) Tank Cell for the final stage of cleaning, producing the final copper concentrate. A portion of the high-grade regrind cyclone underflow is split to a single Knelson gravity concentrator, producing a separate gold/silver concentrate.

During periods of high fluorine content, a pair of Jameson cells in rougher and cleaner duty are used to treat the concentrate from the Tank Cell as a fluorine reverse flotation circuit. The Jameson rougher concentrate is pumped to the Jameson cleaner cell, with the Jameson cleaner concentrate reports to the copper tailings stream depending on the contained copper content. Jameson cleaner tailings is recycled back to the Jameson rougher, with the Jameson rougher tailings reporting to the copper concentrate thickener as final concentrate.

The thickened copper concentrate from the Ok Tedi mill is piped 156 km to the river port at Kiunga, where the concentrate is dewatered by thickening and filtration prior to storage in a purpose-built concentrate shed until it is loaded onto river vessels.

The combined copper scavenger and first cleaner tailings are pumped to the pyrite processing (TPP) plant, where the remaining sulfur in the form of pyrite is recovered via flotation. The pyrite concentrate is transported via a dedicated 128 km slurry pipeline and stored in specially engineered storage pits. TPP tailings is thickened prior to riverine disposal.

GOING FOR GOLD

In 2015, a Processing Improvement Program was initiated in the Processing Area. Plant performance had been declining in the lead up to 2015 in the key metrics of throughput, copper, and gold recovery (Figure 2). A combination of factors contributed to the decline such as lower head grades, increasing pyrite content in the plant feed, and plant downtime and maintenance issues (Figure 3). At the time there was a significant focus around increasing throughput and any recovery related projects were in the context of ensuring recovery was maintained while throughput was increased.

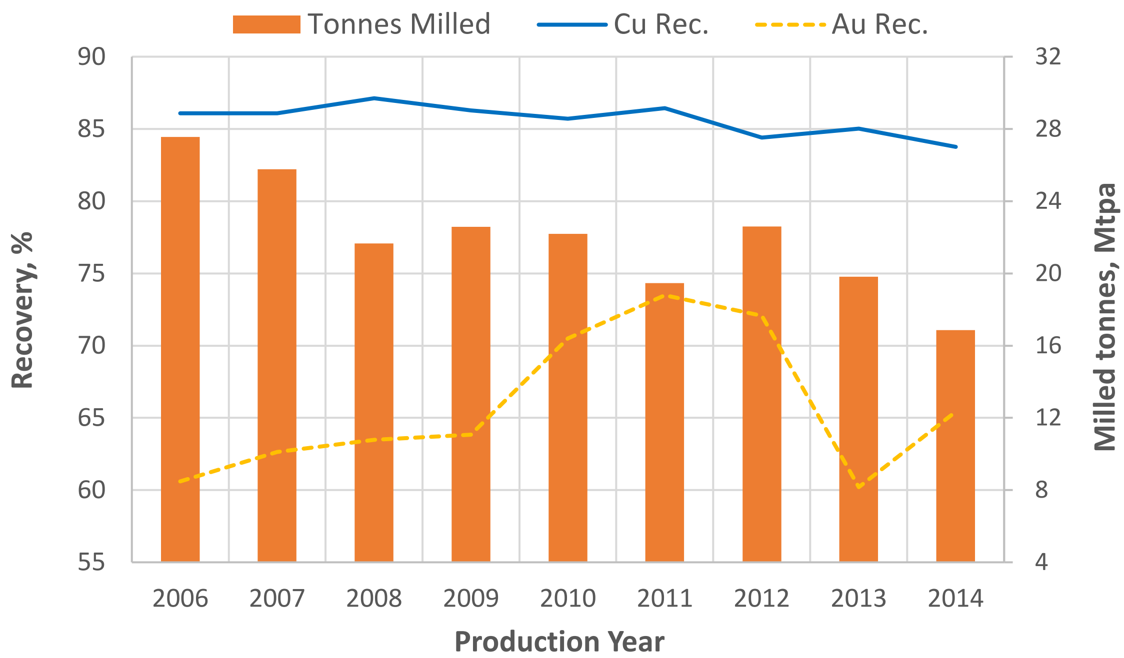

FIG 2 – Ok Tedi production snapshot between 2006 to 2014 (summary mill production report).

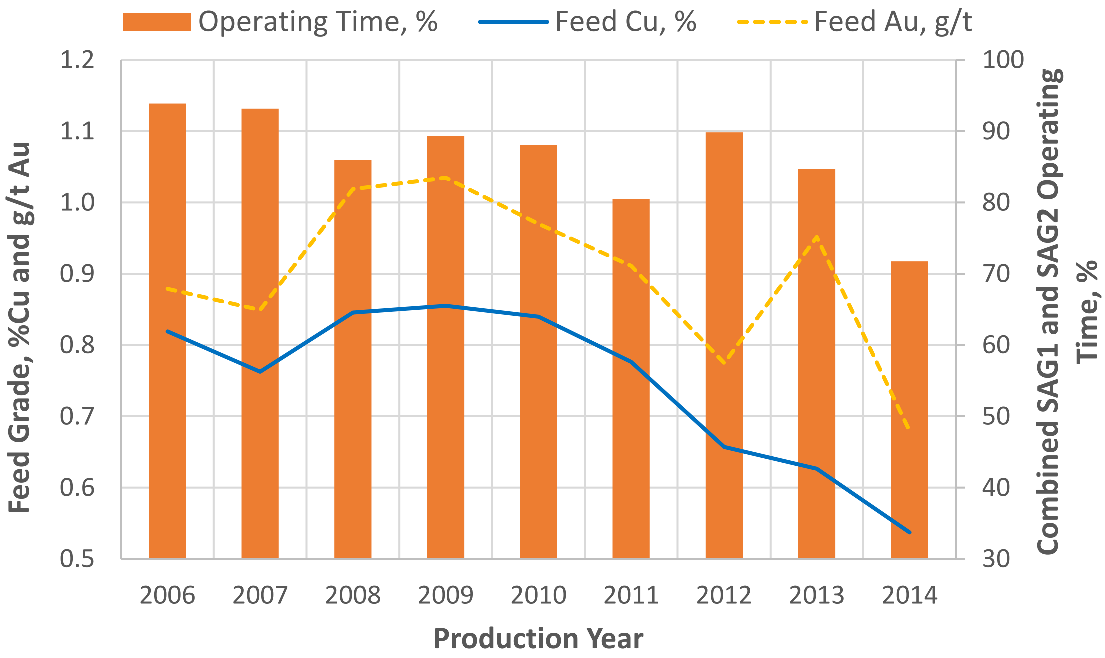

FIG 3 – SAG operating time and feed copper and gold grades between 2006 to 2014 (summary mill production report).

Compounding the metallurgical and fixed plant challenges, a gap analysis of the mill process control system and network infrastructure in 2015 highlighted the significant business risk posed to sustainably achieve the new life-of-mine production targets. Automated control of the Ok Tedi concentrator and TPP was via a hybrid of programmable logic controllers (PLC), Expert systems, and a distributed control system (DCS), of which it was found almost 40 per cent of the existing automation was bypassed or redundant. The ABB Bailey DCS contained legacy equipment and components that were no longer supported by the original equipment manufacturer (OEM).

In 2016, a strategic business plan was developed for Ok Tedi based around life-of-mine production using rigorous modelling and sensitivity analyses incorporating updated resource and reserve models, cut-off grade models, various mining plans, along with metallurgical and commercial models.

The key findings from the exercise in 2016 highlighted that under multiple mining scenarios, the unprecedented total material movement quantities required, meant maximising ore delivery to the processing plant was unlikely to be a lever available to achieve the production targets. This emphasised the importance and need for increased focus on improving recovery, particularly for gold.

As a result, the Gold Recovery Improvement Plan was initiated in 2016, exploring avenues to increase gold recovery within the context of the existing circuit and any capital upgrades required for plant modifications.

It was noted that achieving plant stability and consistently achieving plant operating targets will restore much of the throughput and recovery decline (Noble, 2017). This was underpinned by the need to address the current stability, operability, and reliability of the process and equipment, allowing for improved utilisation of existing assets. The identified drivers for improved gold recovery were largely based on maintenance of plant equipment or instrumentation and general plant infrastructure.

A JOURNEY OF PROCESS IMPROVEMENT

Significant progress was made by the site Process Technical Services team to spearhead the initial priority projects identified in the Gold Recovery Improvement Plan. Many of the projects were progressed or nearing completion around mid-2017 and were executed without additional external resources. Concurrently in mid-2017, an independent review of the site metallurgical performance was carried out by JKTech in addition to facilitating various plant surveys of the grinding and flotation area. The findings from JKTech identified additional high impact projects that would advance Ok Tedi's goal of improving overall plant performance.

To enable consolidation and prioritisation of the Process Technical Services Projects, Gold Recovery Improvement Plan Actions as reported by Noble (2017), and JKTech's recommendations into an effective implementation plan, the Process Improvements Team was established in 2018. This culminated in a total of 81 impact projects to address the issue of sub-optimal gold and subsequently copper recovery, with most of the projects focused on improving stability and reducing process variability.

There were considerable efforts by the site teams and other contracted subject matter experts involved between 2017 to 2020 towards the overarching goal of improving gold recovery. The main topics discussed in this paper centre around the process control and automation work fronts that drove the improvements to process stability.

THE ILLUSION OF (MANUAL) CONTROL

Mipac was engaged in April 2018 to conduct a process control review for Ok Tedi. The improvement opportunities identified in the review centred around physical automation projects to drive process stability, as well as improvements to process monitoring and key performance indicators (KPI) tracking by leveraging the plant historian data (AVEVA PI System). Several automation projects were identified, with the below selected improvements discussed in the following sections as they significantly contributed to reducing process variability for the operation:

1. Primary cyclone control.
2. Flotation level control.

Initially, there were various challenges with reliability of plant equipment and instrumentation which stalled the implementation of any revised control strategies. Various instruments required calibration or replacing before any automation works could commence. A small task force was established by the site Process Improvements team in Q3 of 2018 to commence with maintenance of the failing equipment, instrumentation, and processing plant infrastructure, enabling automation works to kick off by the end of January 2019.

Variability is my middle name

The Ok Tedi orebody consists of many different lithological types as reported in Smith, Horacek, and Sheppard (2007). The various geological units found within the deposit as of 2015 are categorised as follows for mine planning and production forecasting: Siltstone, Siltstone – Taranaki, Siltstone – Other, Limestone (Waste), Monzonite Porphyry, Monzodiorite, Endoskarn, Skarn, Pyrite Skarn, Oxide Skarn.

Kanau and Katom (1997) discussed the varying ore hardness work indices based on the different ore types. As a result of the inherent variability, each SAG mill can treat anywhere between 700 and 3000 t/h (McCaffery, Katom and Craven, 2002). As such, managing the hardness of the ore and the subsequent mill throughput rates that requires daily planning and management.

Stabilising the grinding circuit with a variable feed has been an iterative process from a process optimisation perspective, and significant works and developments have been evaluated in this space particularly around SAG mill control (Kanau and Katom, 1997; McCaffery, Katom and Craven, 2002; Savage, Rodriguez and Metzner, 2013), prior to the installation of variable speed drives in 2019.

Whilst SAG controls will not be discussed in this paper, the inherent variability of the feed to Ok Tedi's concentrator provides the context for the importance of mitigating flow disturbances downstream to the cyclones post milling, and subsequently to the copper flotation circuit.

Primary cyclone control

Mill discharge from the SAG and two ball mills on each train is combined into a common sump which supplies feed to the primary cyclone packs. The configuration of the two trains is similar, the main differences are the number of cyclone packs (Train 1: three packs, Train 2: two packs) and the cyclone models. Each cyclone feed sump is fitted with three cyclone feed pumps. The configuration differences are summarised in Table 1.

TABLE 1

Primary cyclone configuration Train 1 versus Train 2.

Operating line	Cyclone cluster	Feed pump
Train 1	CS01 (8 × Krebs gMAX26-H)	PP01
	CS03 (10 × Cavex 650CVX)	PP04
	CS04 (10 × Krebs gMAX26-H)	PP05
Train 2	CS01 (10 × Cavex 650CVX)	PP01
	CS02 (10 × Cavex 650CVX)	PP02 or PP03

Cyclone feed sump level control challenges

With the backdrop of the declining performance, operating with an ageing asset, and equipment reliability challenges, the cyclone feed sump controllers (and many controllers observed during the process control review) were operated in manual. This resulted in large variations in sump level and poor cyclone density control.

Limited functioning automation in this section of the plant introduced unnecessary variability downstream, aggravating the daily firefighting which had become the operating norm. The inherent variability of the ore feed resulted in highly variable flows transferring to the sump, then to the cyclone packs, and inevitably to the copper flotation circuit.

When sump levels got to below 10 per cent, operators would intervene and make manual changes to the cyclone feed pump outputs once the cyclone feed pressure became highly variable due to pump cavitation. Discussions with site personnel in 2018 noted frequent (almost monthly) replacement of pump impellers due to damage and loss of capacity, likely compounded by if not the result of frequent and prolonged cavitation.

Operational insight based on process data was lacking with PI tags created on an ad hoc basis or configured with sub-optimal PI tag settings to track key performance metrics. For example, at the time of review the cyclone feed flow controllers were not captured within the historian, limiting capacity to assess the control loop performance.

Primary cyclone pressure control challenges

Interlinked with the variable sump levels, from the process control review there was no automatic control utilised by operators for controlling the primary cyclones to pressure. There appears to have been attempts at incorporating controls previously, as Paki (2000) had reported the necessary instrumentation was installed to automate cyclone operation in October of 2000. The existing cyclone open-close sequence within the DCS was not based on cyclone operating hours to manage even wear but on varying delay times depending on the cyclone. As a result, the sequence if active, would preferentially open and operate two out of the eight available cyclones when the pressure spiked.

Manual operation of cyclones to maintain pressure added to the cognitive load on the operators as a significant portion of their shift was firefighting and manually controlling the circuit to the variations in feed entering the mill. Consequently, operators would fail to respond to most high and low operating pressure events and the associated classification impacts (variable flotation feed sizing) transferred downstream. With manual cyclone operation, uneven cyclone wear rates were evident, further compounding the variability in cyclone overflow sizing.

Operations had reported various downtime events historically that were tied to poor pressure control. Within a three-week period during Q1 of 2019, two events occurred that resulted in a cumulative downtime of 28 hrs on Train 1 (cyclone feed line bogging) and 17 hrs on Train 2 (cyclone overflow launder sanding).

Revised cyclone control strategy

There was existing logic in the DCS that utilised the level controller output to cascade a flow rate set point to the individual cyclone feed pump flow controllers. The required flow was determined via a function block that converted the controller output in per cent to the required flow rate. However, as each of the pumps had unique level controller output to flow rate relationship, this arrangement resulted in different flow rates for each cyclone pack at the same level controller output, and the level controller process gain would change depending on which pump was operating.

Resolving the sump level control was of critical importance and enables more consistent cyclone pressure control. A schematic of the revised control strategy is presented in Figure 4.

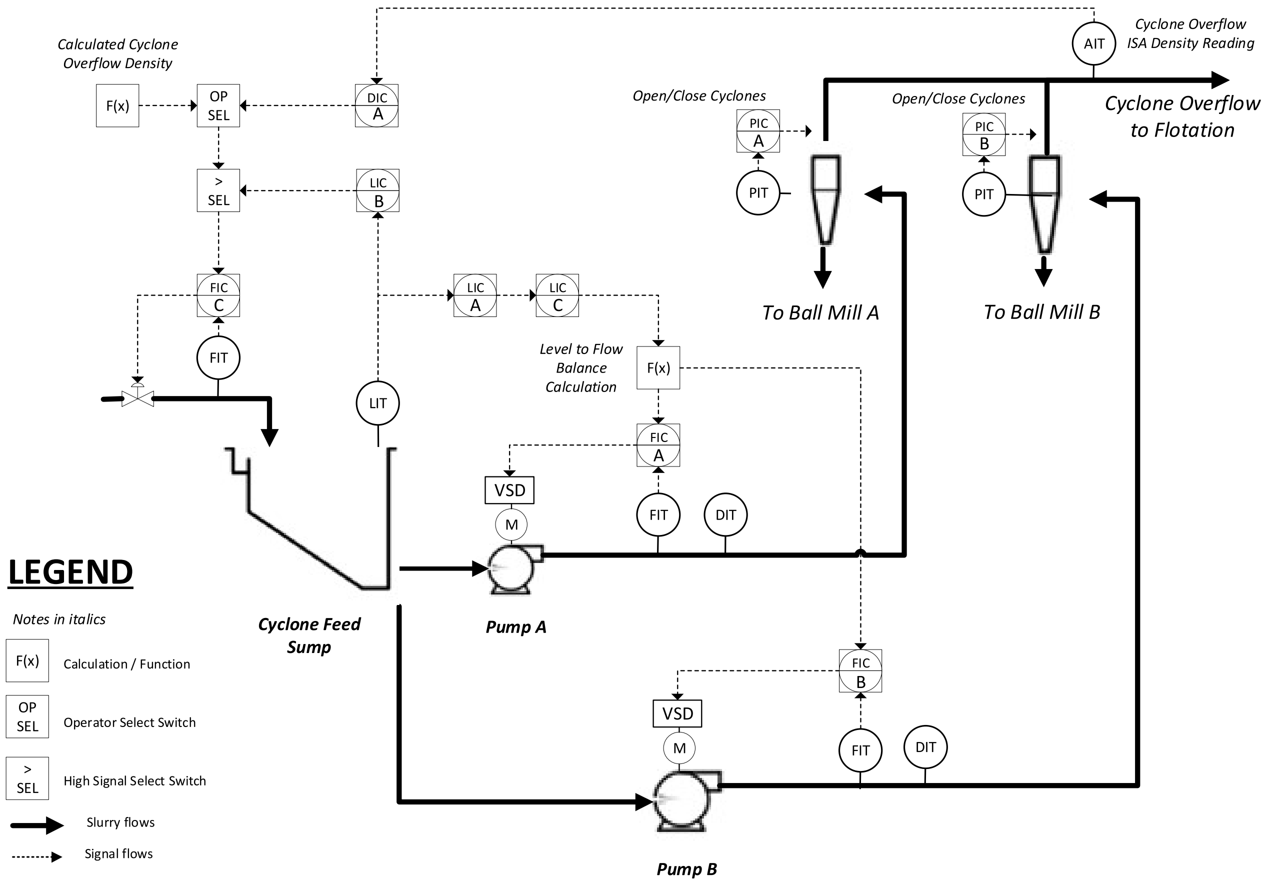

FIG 4 – Revised cyclone feed sump control strategy.

The primary control objective is to utilise the volume of the cyclone feed sumps as surge capacity to smooth out variations inflow downstream to flotation, without overflowing the cyclone feed hopper or allowing it to run empty. The primary level controller (LIC-A) is thus configured for averaging level control to maintain the sump level within an operating range (20 to 80 per cent) as opposed to tight level control (maintaining level to a set point target).

The LIC-A controller output then cascades to the balancing flow controller (LIC-C). The objective of the LIC-C controller is to balance flow distribution to the available cyclone feed pumps (FIC-A, FIC-B) and distribute the load between the cyclone packs.

The inclusion of a low-level controller (LIC-B) provides a temporary buffer from low sump level events by increasing the process water addition to the cyclone feed sumps if the level drops to a point where pump cavitation risk is likely.

Coupling this controller with the cyclone overflow density controller (DIC-A), both controller outputs (LIC-B, DIC-A) are passed through a selector switch which transfers the highest controller output to the process water flow controller (FIC-C) ie LIC-B should only drive the process water flow when a low sump level event is occurring, with the density control loop (DIC-A) as the main controller driving the process water flow.

Presented in Figure 5 is the distribution of the sump level bands for both trains comparing manual to automatic control (LIC-A controller status in AUTO = OFF or ON). The period of comparison is the start of Q1 of 2017 to the end of Q4 of 2021, with the proposed controls commissioned in Q4 of 2018. The data sets are extracted from the PI historian assessing total duration the measured sump level is LOW (<20 per cent), HIGH (>80 per cent), or within Target (20 to 80 per cent) range on a per production day basis. The data has been filtered for periods where the respective trains SAG mill is running with throughput greater than 500 t/h to broadly represent normal operating conditions.

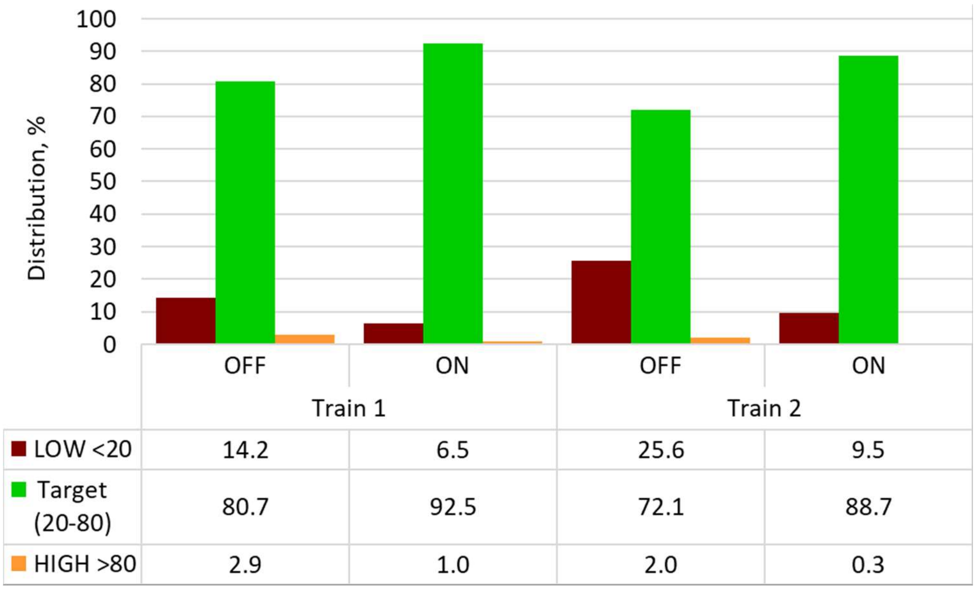

FIG 5 – Cyclone feed sump operating range distributions Q1–2017 to Q4–2021.

As noted, the primary objective of the revised controls is to maintain the sump levels within an operating range. Presented in Table 2 are the summary statistical outputs evaluating the frequency of sump levels within the target range, the results indicate with over 99 per cent confidence there is an 11.8 and 16.6 per cent improvement when the LIC-A level controller is utilised for Train 1 and Train 2 respectively. Increasing the frequency of operating withing the target band and minimising low and high sump level events have implications on operability and optimisation: reducing the low sump level events minimises the potential for cavitation of the feed pumps, and reducing the high-high sump level events means removing this as a constraint for limiting mill throughput to manage overflowing sumps.

TABLE 2

Summary statistics comparing cyclone feed sump level distributions within target range.

Parameter	**SAG1**		**SAG2**	
	OFF	**ON**	**OFF**	**ON**
Mean	80.7	92.5	72.1	88.7
Standard deviation	28.8	18.3	30.2	23.5
Data points	1597	220	1595	254
Degrees of freedom	1815		1847	
Standard error	27.7		29.4	
p-value (1-tail t-test)	4.48E-09		1.05E-16	
t-score	-5.9		-8.4	
Confidence interval	8.92E-09		2.09E-16	
Difference in means	11.8		16.6	

Flotation level control

Automated control of the flotation cell levels at Ok Tedi was achieved with the FloatStar system, and as a backup the ABB Bailey DCS system. Operator utilisation of FloatStar Level Stabiliser package was good, and performance was adequate in relation to controlling flotation levels. A potential risk raised in the review conducted by Mipac in 2018 centred around the robustness of the system, as it was operated from a standalone computer with no redundancy, and site had noted system failures had occurred previously.

Calling for backup

Come January 2019, the FloatStar server failed and was unable to be restarted. Level control reverted to the DCS based control using simple proportional-integral-differential (PID) blocks for feedback control, with some updates to the tuning parameters to minimise the observed level oscillations. Flotation cell level control was sub-optimal during the period with FloatStar offline, as the specific PID blocks configured in the DCS did not have the functionality of incorporating feedforward control, a critical component in pre-empting upstream disturbances that can significantly impact flotation cell level control.

While not configured, the existing ABB Bailey DCS software had additional function blocks which could be used to enable advanced features such as cascade control and feedforward. As this was implemented in the flotation level control at the TPP a few years prior with Mipac, Ok Tedi had reviewed the option of whether to recommission the FloatStar system or replace the existing PID blocks with the Advanced PID (APID) block within the Bailey DCS library.

Both options were expected to produce similar control performance, and ultimately the decision was made by site to build-up in-house capability and update the control blocks in the DCS, alleviating the need to upgrade the hardware, software, and associated licensing with recommissioning the previous FloatStar system.

Capability Development

The revised APID blocks were commissioned in late June 2019 by Mipac assisting the site process control team. To compare the performance of the different control modes on flotation cell level control a period of approximately one-month for each of the control modes was extracted from the PI historian as 5-minute averaged calculated data, filtered for periods where the SAG throughput is greater than 500 t/h to reflect normal operation.

The following periods were used for comparison on the performance of the FloatStar Level Stabiliser package, the original Bailey DCS PID blocks, and the updated APID control blocks with feedforward.

1. FloatStar Level Stabiliser – 1/9/2018 to 1/10/2018.
2. DCS PID Blocks – 1/5/2019 to 1/6/2019.
3. DCS APID Blocks with Feedforward (APID_FF) – 22/6/19 to 10/7/2019.

The level measurement (process variable, PV) against target (set point, SP) for the three data sets is presented in Figure 6 as a time-series chart. For brevity, only the first three rougher flotation cells with level control valves for Damside and Roadside on Train 2 are presented as a snapshot of the control improvements.

Additional PI trends and KPI tracking reports were co-developed with site to enable monitoring of flotation level performance. Tracking the error in level as a KPI also highlighted various flotation cells that required maintenance and investigation due to issues such as valve stiction, or improper zeroing of instrumentation. As an example, for the U2 RS Cell 6 trend shown in Figure 6, the trends enabled more streamlined identification of a pinch valve blockage/failure that needed to be addressed.

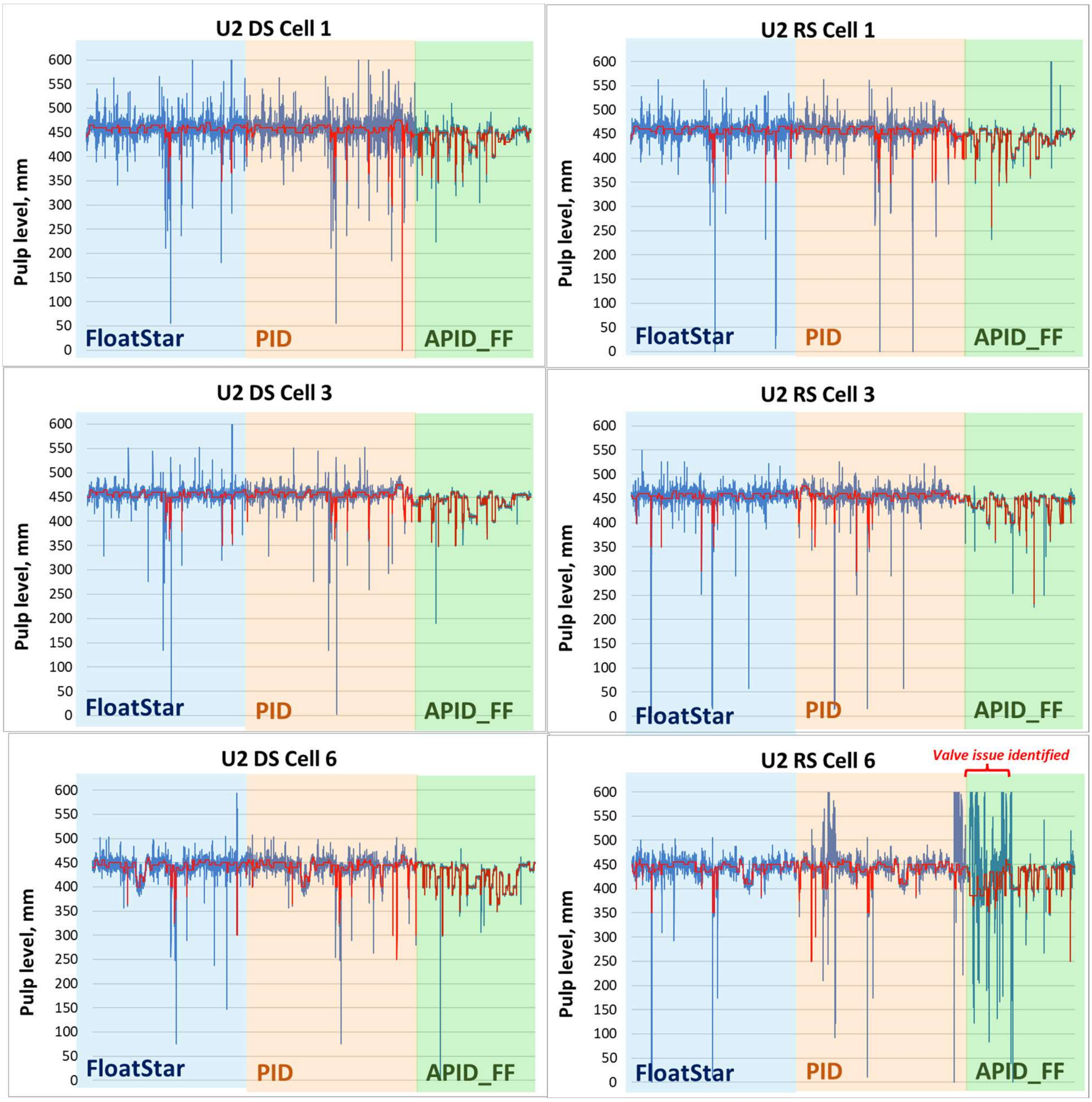

FIG 6 – Time series trends (3-month block) comparing measured level (process variable) to set point for the different control modes (FloatStar, PID, and APID_FF) on Train 2. DS = Damside, RS = Roadside.

Observing the trends of the measured level to the set point in Figure 6, it is evident the implemented APID blocks with feedforward can provide robust process control even with multiple set point changes. Overall, the new APID blocks within DCS showed superior performance to both PID and the previous FloatStar system (Figure 7). Excluding U2 RS Cell 6 due to the identified valve issue, the results demonstrate average reductions in the mean level error (PV minus SP) between 36 to 71 per cent (able to operate closer to target), and a corresponding reduction between 61 to 80 per cent in the standard deviation (tighter level control) using the APID blocks compared to the FloatStar system.

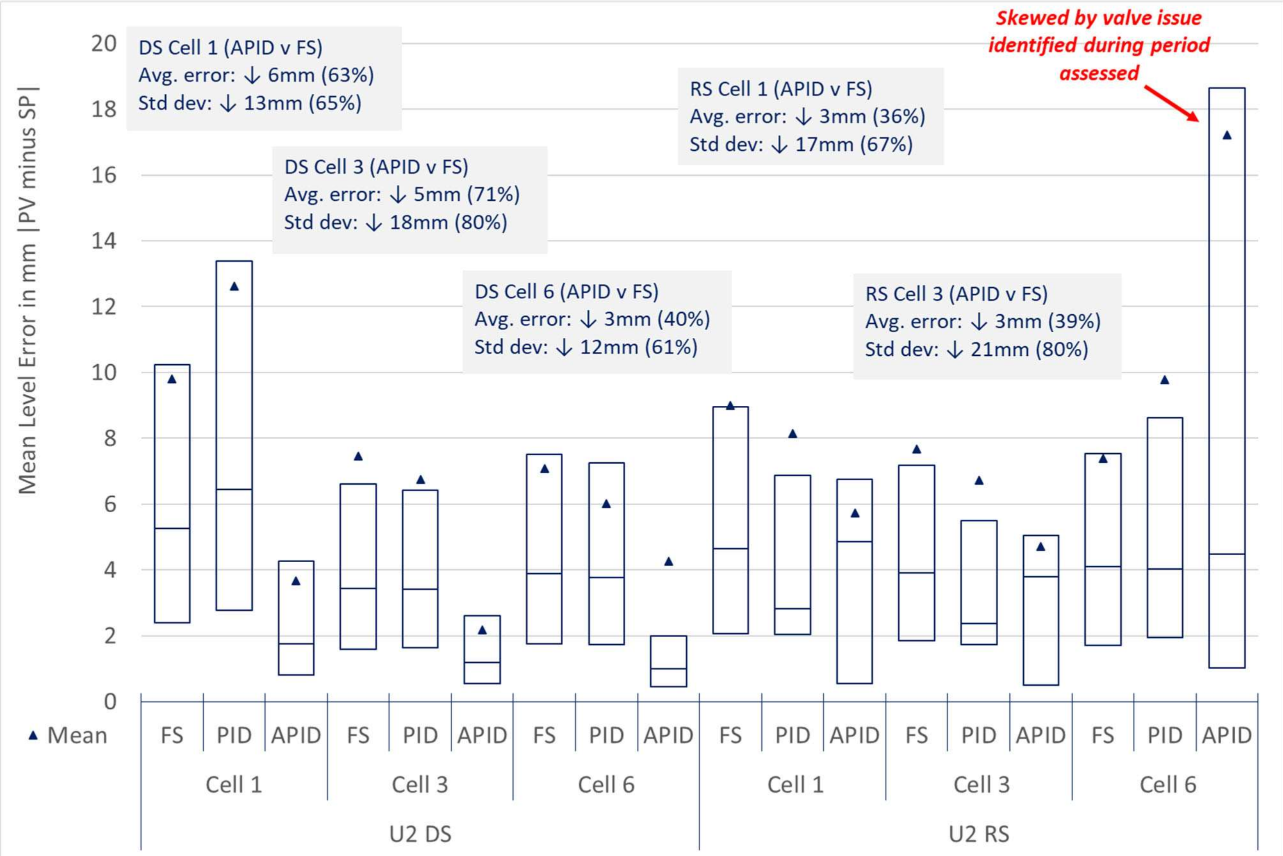

FIG 7 – Box-plot of error distribution (PV-SP) for the first three rougher cell level controls comparing FloatStar, PID, and APID_FF on Train 2. DS = Damside, RS = Roadside.

In principle, the control philosophy and strategy used for the APID blocks with feedforward and the FloatStar Level Stabiliser are similar, and the performance was expected to be comparable. The likely cause of the observed difference is lack of routine maintenance and retuning of the FloatStar system, which was believed to have last occurred in 2016 based on discussions with site personnel.

With the long operating history of Ok Tedi, process responses change over time and controller tuning needs to adapt with the change in process dynamics. Updating and implementing the APID solution reinforced one of the benefits to Ok Tedi of completing the control within the DCS system: developing in-house capability and enabling site personnel to maintain and improve the control.

RESILIENCE MAKES THE DREAM WORK

Addressing the gaps in the data systems to provide production insight and prioritising projects that addressed plant stability and process variability were key enablers for successful execution of the concurrent improvement projects undertaken by the Processing Improvements team and Process Technical Services teams. Implementation of the 81 impact projects from the Gold Recovery Improvements action plan (Noble, 2017) and JKTech's independent review were accelerated in 2018, with 82 per cent of the projects having been completed or in progress at the end of 2019 (Brown, 2020).

The successful completion and execution of the Gold Recovery Improvement plant initiatives has had a quantifiable effect on the overall plant performance at Ok Tedi. Results from the analysis using the daily production data extracted from MinVu are presented below. Illustrated by Figure 8 is the box plots showing the distribution of gold and copper recoveries by quarter between 2017 to end of 2021, with summary statistics comparing performance in 2017 to 2021 provided in Tables 3a and 3b for gold and copper respectively.

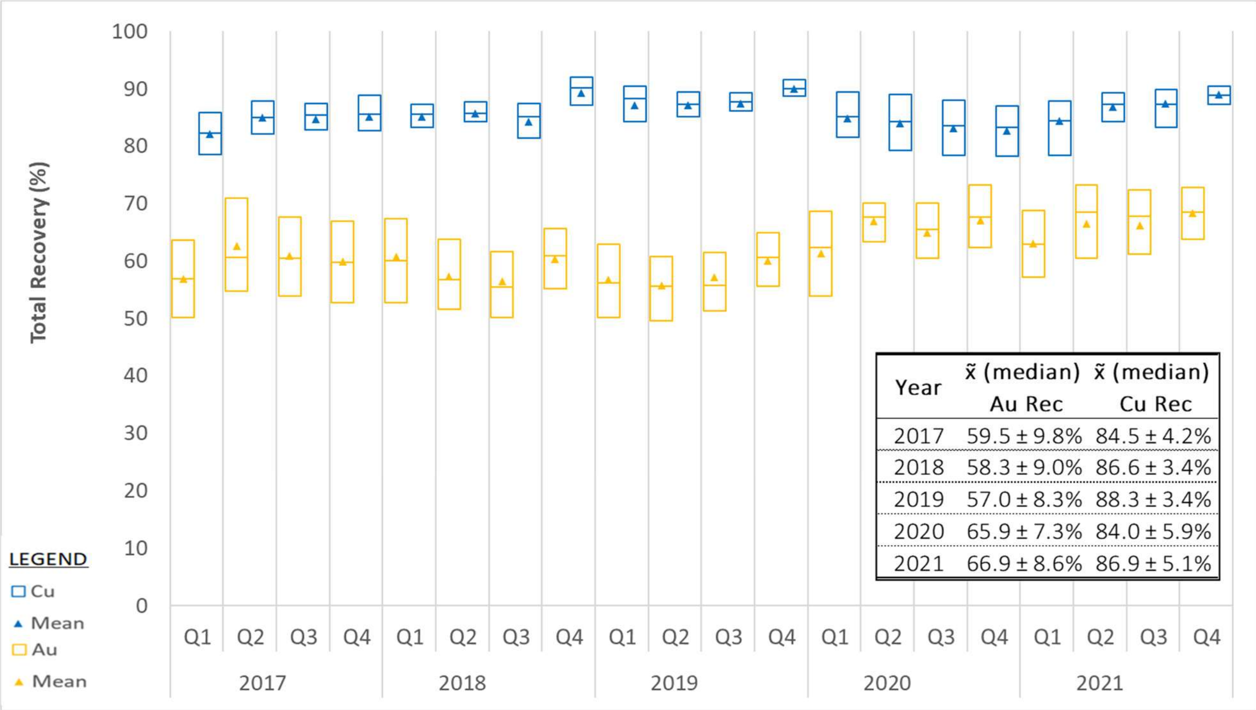

FIG 8 – Total gold and copper recovery between Q1–2017 to Q4–2021.

TABLE 3A

Summary statistics comparing gold performance metrics in 2017 to 2021.

Parameter	Au Rec (%)		Au in Feed (g/t)		Au in Final Float Con (g/t)	
	2017	**2021**	**2017**	**2021**	**2017**	**2021**
Q1 – median	56.9	62.8	0.64	0.64	13.7	23.6
Q2 – median	60.6	68.5	0.70	0.58	17.9	22.2
Q3 – median	60.5	67.8	0.62	0.43	16.8	22.7
Q4 – median	59.8	68.5	0.70	0.45	18.7	20.4
Mean of Q1-Q4	59.5	66.9	0.67	0.52	16.8	22.2
Standard deviation	9.8	8.6	0.17	0.19	3.40	4.87
Data points	348	334	360	342	313	337
Degrees of freedom	680		700		648	
Standard Error	9.24		0.18		4.23	
p-value (1-tail t-test)	1.9E-03		2.1E-02		2.8E-03	
t-value	-10.50		10.64		-16.33	
Confidence Interval	1.3E-03		2.8E-04		9.4E-04	
Difference in means	7.4		-0.14		5.4	

TABLE 3B

Summary statistics comparing copper performance metrics in 2017 to 2021.

Parameter	Cu Rec (%)		Cu in Feed (%)		Cu in Final Float Con (%)	
	2017	**2021**	**2017**	**2021**	**2017**	**2021**
Q1 – median	82.3	84.4	0.66	0.43	25.0	24.6
Q2 – median	84.9	87.2	0.65	0.40	24.4	25.2
Q3 – median	85.3	87.3	0.59	0.32	24.6	24.9
Q4 – median	85.6	88.8	0.57	0.42	24.0	24.8
Mean of Q1-Q4	84.5	86.9	0.61	0.39	24.5	24.9
Standard deviation	4.2	5.1	0.13	0.39	1.9	2.3
Data points	357	143	360	342	360	338
Degrees of freedom	498		700		696	
Standard Error	4.45		0.29		2.10	
p-value (1-tail t-test)	4.6E-02		2.8E-04		8.1E-02	
t-value	-5.44		10.12		-2.41	
Confidence Interval	2.0E-02		6.1E-06		1.3E-02	
Difference in means	2.4		-0.22		0.4	

Comparing the median recoveries for the 2017 calendar year to the 2021 calendar year gold recovery has improved by 7.4 per cent (with 99 per cent confidence) from 59.5 ± 9.8 to 66.9 ± 8.6 per cent, with copper recovery improving by 2.4 per cent (with 95 per cent confidence) from 84.5 ± 4.2 to 86.9 ± 5.1 per cent.

For both copper and gold in the rougher feed, the data indicates there has been a significant decrease in grades in 2021 compared to 2017 (continuing the declining ore feed trend). Gold content in rougher feed having decreased by 0.14 g/t (from 0.67 g/t to 0.52 g/t with 98 per cent confidence), and copper in feed decreasing by 0.22 per cent (from 0.61 to 0.39 per cent with 99 per cent confidence).

Furthermore, the gold and copper reporting to the final flotation concentrate has increased in 2021 compared to 2017. Gold content to final flotation concentrate increased by 5.4 g/t (from 16.8 to 22.2 g/t with 99 per cent confidence) and copper grade increasing by 0.4 per cent (from 24.5 to 24.9 per cent with 92 per cent confidence).

Based on the extracted production data, the observed improvements to the copper and gold recoveries appear independent of head grade as well as final concentrate grades. The data and outcomes presented have been validated independently by JKTech for the purposes of this paper.

CONCLUSIONS

Improved automation drives process stability, reduces operating risk and is key to enabling sustainable increases to production. As part of the evolving journey of process improvement undertaken by Ok Tedi in 2015, there has been a concerted effort to address the foundational gaps of the ageing asset to sustainably meet the life-of-mine production targets. Reverting to first principles metallurgy with a focus on improved plant and instrument reliability were significant enablers to meeting production targets in the context of increasing ore hardness, declining feed grades, and assets approaching end of life. The strategic drive and efforts towards the common goal by the site teams and contractors culminated in significant increases to gold and copper recoveries by 7.4 per cent and 2.4 per cent respectively.

ACKNOWLEDGEMENTS

The authors wish to thank the management of Ok Tedi Mining Limited for permission to present this paper, Mipac Pty Ltd and JKTech in their collaboration and assistance in the analysis of the presented outcomes in this paper, and to the Process Technical Services Metallurgy team and Process Improvement teams on the significant contribution and collaboration demonstrated to accomplish the projects that advanced the reported improvements to overall plant performance.

Further, the authors would like to express their appreciation and gratitude to the support from the external vendors and contractors throughout the process improvement journey (Alasdair Noble, JKTech, Mipac, Flottec, Magotteaux, Consep, SGS, MinVu).

Finally, special mention to Martin Randall and Anthony Porter for championing and implementing the various process control changes during the period recounted.

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