A critical review on the performance of the gypsum precipitation reactors on hipro® amd plants at ewrp, owrp and mwrp

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Abstract

Three Aveng Water designed HiPRO™ plants have been operating for a number of years. A key component of the process is Stage 2 and Stage 3 Precipitation reactors that allow for the additional recovery of water. The paper examines the Stage 2 gypsum reactor performance using statistical methods. The metric used was the outlet calcium sulphate saturations. The deviation of the $CaSO_4$ saturation impacts directly on the availability of the plant. Poor operation will result in RO membrane failure. The variation in the outlet was presented and a regression was done to determine the effect of certain parameters on performance. It was found that temperature variation is a major factor in the outlet saturations but the overall fit was still poor with the data available.

Keywords: ICARD | IMWA | HiPRO™ | Gypsum Reactors | Mine Water Treatment

Introduction

One of the consequences of certain mining activities is the inevitable formation of mine impacted waters. These waters are characterised by high levels of sulphate, calcium, magnesium and often alkalinity, other heavy metals and monovalent ions. The ratio of these contaminants varies from one mining area to another. The resulting effluent is a complex solution and requires treatment prior to being discharged to the environment. One such active treatment process that can be used to remedy the mine impacted waters and produce potable water is Aveng Waters HiPRO™ process. This process combines chemical precipitation with advanced membrane processes. The configuration of the plant allows for large scale treatment of mine impacted waters. Currently four major installations use this technology and were all funded and owned by the senior coal miners in the Mpumalanga province. The four plants are the eMalahleni Water Reclamation Plant (EWRP) – (Phase I and Phase II), The Optimum Water Reclamation Plant (OWRP) and the Middleburg Water Reclamation Plant (MWRP).

HiPRO™ Process

Figure 1 gives a summarised view of the HiPROTM process. Simply, the process comprises of a three stage process where water is recovered sequentially by stage-wise precipitation and thereafter desalinating with Reverse Osmosis (RO) Membranes to produce a product that is of exceptional quality. A more detailed explanation of the process can be found Hutton et al (2009)

As can be surmised, a key aspect of the process is the performance of the precipitation steps, which reduce scaling potential and allow for further recovery of water through RO membranes. Poor control of these reactors will result in rapid and irreversible scaling of the RO membranes which directly compromises production quantity and quality. Due to the nature of water being processed, the precipitation reactors on Stage 2 and Stage 3 are gypsum reactors. Owing to the importance of these units in the process the performance of these reactors will be the focus of this paper. Since the Stage 3 sections of the plant are duplication of the Stage 2, only Stage 2 information will be shown

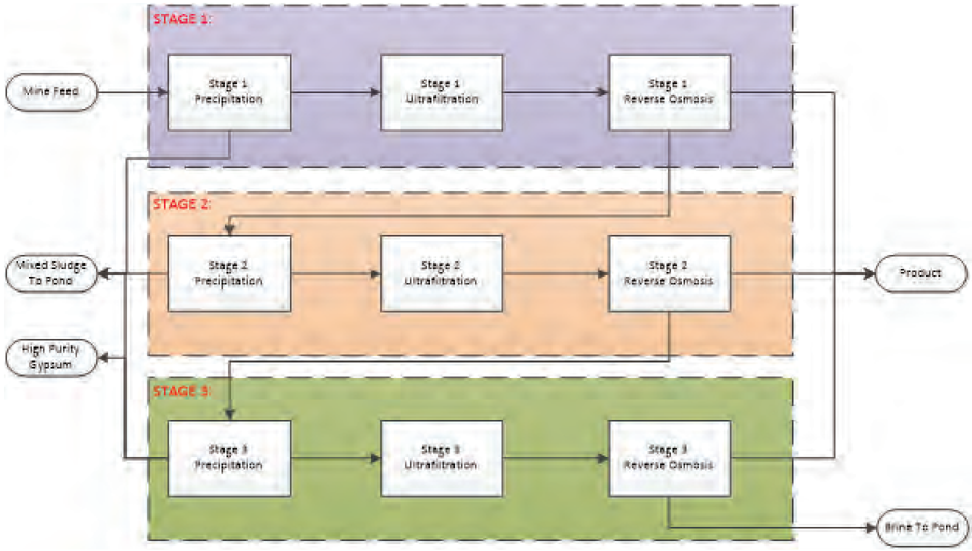

Figure 1 *Basic Process Flow of HiPRO™*

Feed Water Quality

Table 1 summarises the design capacity of each plant, the year of commissioning, the plant owner, the plant designer and the typical feed water quality (major components only) currently being processed by the plant. It can be seen that the feed water quality differs substantially between plants. It must be pointed out that currently only one of the four plants is currently processing highly acidic mine impacted water – EWRP Phase II but all except OWRP was designed to cater for a degree of acidic mine feeds.

Stage 2 Reactor Performance at EWRP (Phase I and Phase II), MWRP and OWRP

The Stage 2 reactor performance of EWRP Phase I, MWRP and OWRP was evaluated over periods of 2 years. Due to the limited amount of data on the Phase II EWRP operation, only a small segment of information is available but this is also presented. The metric of measure of reactor performance is based on the effluent Calcium Sulphate Saturation and the practical RO cut off that can be set to allow for sustainable operation of the RO mem-

Table 1. Summary of Major Aspects of the plant installations

	EWRP Phase I	OWRP	MWRP	EWRP Phase II
Plant Owner	Anglo American Thermal Coal	Optimum Colliery	South 32	Anglo American Thermal Coal
Plant Designer	Aveng Water	Aveng Water	Aveng Water	Aveng Water
Year Commissioned	2008	2011	2015	2017/2018
Design Capacity	25 Ml/day	15 Ml/day	25 Ml/day	25 Ml/day
Feed Water -Typical				
Calcium (mg/L)	520	414	460	440
Sulphate (mg/L)	2500	3000	3400	4500
Magnesium (mg/L)	180	450	650	210
Acidity (mg/L as CC)	80	0	0	2000
Alkalinity (mg/L as CC)	10	180	180	0
pH	6	8.0	7.5	2.3
TDS (mg/L)	3500	5021.6	5000	6000

branes (no membrane scaling). Antiscalant is dosed upstream of the RO membranes and the efficacy of the product is paramount in protecting the RO membranes from scaling. The saturations reported here are that which is calculated from the antiscalant dosing software. The water quality on each Stage of the plant is measured four times daily for all major constituents namely; Calcium, Sulphate, Magnesium, pH and monovalent species. The resulting vector determines what the calcium sulphate saturation is and based on the specified practical RO cut-off, the RO can or cannot be operated. Consequence of not adhering to these cut-offs is rapid membrane failure of the membrane modules. Figure 2 shows the Stage 2 $CaSO_4$ saturations for the four plants over the periods specified in Table 2.

There are periods where the calcium sulphate exceeds the practical RO cut-off. This is especially true of the EWRP operation in the early part of the period. Although periods of instability can be seen on all trends. This can be shown explicitly by looking at the summary statistics of each plant – Table 2. Owing to the nuances of Phase II, the practical cut off differs from the other plants.

Table 2 shows clearly that the most stable reactor of the four plants is MWRP while EWRP Phase I is the most unstable – Phase II is excluded as the data set is limited due to it being early in its operation phase. The performance of EWRP was of major concern to the designers and although the plant was able to operate through these transients, it was clear that better control was needed to approach that of MWRP and OWRP. Through targeted interventions, it was possible to narrow the normal distribution and variation of the calcium saturations that have been observed. Figure 3 shows the histogram and normal distribution for MWRP and EWRP for the years 2017 and YTD 2018. It can be seen from the histogram that the normal distribution assumption of the saturations is not completely valid as there is both excess kurtosis and a negative skewness. Both indicate a high degree of upside risk to membrane operation or plant availability (if the shut off is exceeded the RO unit is taken offline) at these high saturations. The vertical line indicates the same practical shut off of the membranes as Figure 2. Similar trends are observed for the other installations. Table 2 shows the summary statistics for each installation.

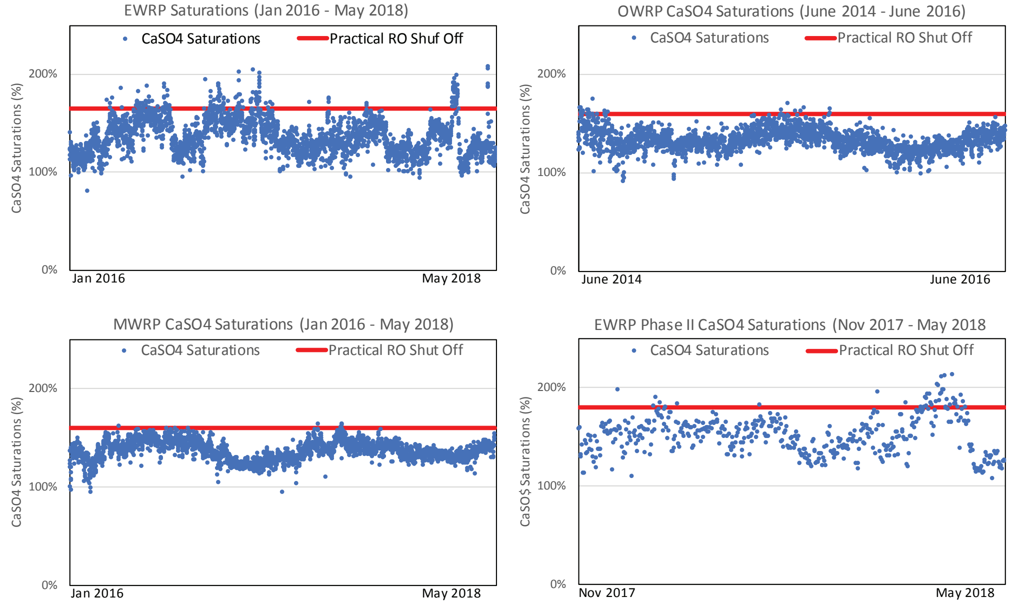

Figure 2 *Measured performance of the Stage 2 Calcium Sulphate Saturations at the four installations*

Table 2. Summary Statistics of reactor performance of the four installations.

	EWRP Phase I	OWRP	MWRP	EWRP Phase II
Time Period	Jan16-May18	June14-June16	Jan 16–May18	Nov17-May18
Average	135.45%	131.58%	136.53%	151.96%
Standard Deviation	18.4%	10.35%	9.6%	19%
No. Data Points	2918	2068	4098	482
Excess Kurtosis	0.0853	0.283	0.0607	-0.013
Skewness	0.480	-0.00185	-0.178	0.309

Any interesting nuance on Figure 3 is the changing of sign of the skewness on the MWRP sample in 2017 and followed through to 2018. This indicates more data points on the left side of the average, implying less upwards risk at MWRP through 2017 and 2018 than there was in 2016. The second implication of this is that there is a potential to shift the normal distribution left if the greater downward clustering can be intensified. The YTD 2018 information suggests that this shift has occurred but this data set is limited. Shifting the normal distribution in this manner will allow for an adjustment of the practical RO shut off and thereby a direct increase in the capacity of the plant., it is therefore critical to understand what shifts the normal distribution so that that parameter may be controlled. Ideally, one would want a leptokurtotic distribution that is characterised by a peaked mean, narrow shoulders and thin tails. A final comment on the EWRP standard deviation for 2018. Although the standard deviation has increased in 2018, this was in fact due to a single prolonged operational incident that stalled the process. The cluster of data points to the right of the shut-off indicates. A detailed root cause analysis was done

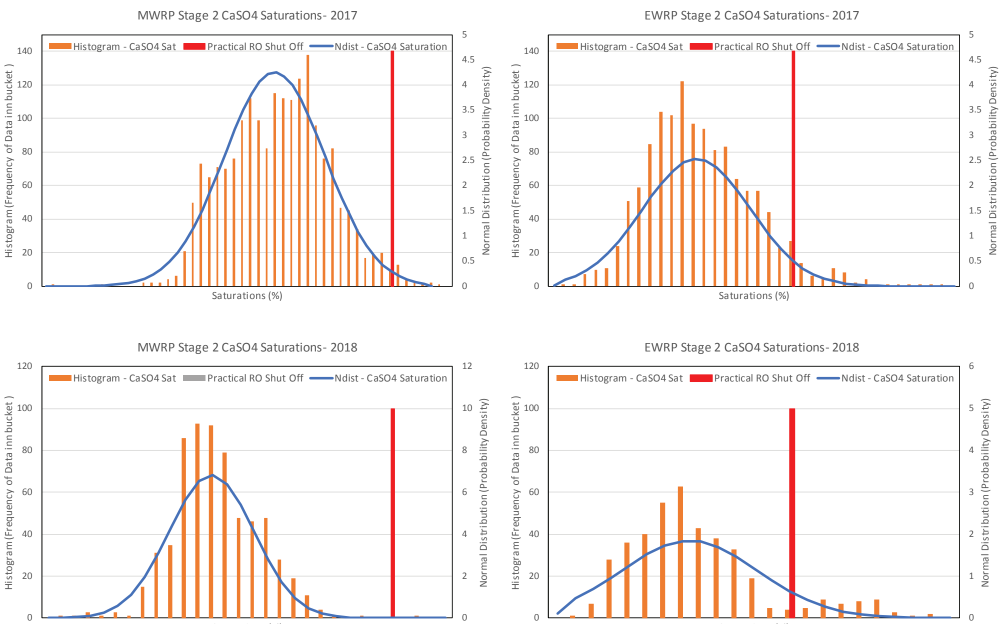

Figure 3 Histogram and Normal Distribution for EWRP Phase I and MWRP 2017-May 2018

and it was found that this related to a change on the plant. The implication of engineering change management is incredibly important in operating a plant of this nature. Baring this incident, the normal distributions have in fact narrowed through 2018.

Stage 2 Reactor Performance – Quantitative Effects

As discussed above, the factors that affect the performance of the gypsum reactors on each of the plants need to be clearly understood. Since this is a precipitation reactor, it obvious that endogenous factors such as feed water quality to the reactor and seeding material are important for controlling the outlet conditions. However, there are other exogenous factors such as temperature which may also be significant. Two separate regressions were run on the information. The first using the controllable variables and the second compensating for temperature. The entire data sample was used for the regression on each plant. The phase II EWRP has been excluded owing to the limited data sample available.

Control Variable Impact

There are a number of variables controlled within the plant but only three are going to be used here, namely the percentage solids of the reactor/clarifier complex and the feed water quality to the reactor. The latter will be represented as the calcium sulphate saturations of the previous stage. It is expected that the solids control will have a substantial effect on the performance. The solids measurement can be regressed against the measured saturations according to:

$$CaSO_4\_Sat = A + B*Reactor\_Solids\% + C*Clarifer\_Solids\% + D*Stage\_1\_CaSO_4\_Sat\%$$

The measure of fit from these variables can be seen by the adjusted R2 value. All three plants show a similar fit with respect to the explanatory variables used. What is surprising is how poor the fit is. An interesting nuance is that the EWRP phase I reactor solids measurement is not statistically significant but this does not mean it is practically insignificant.

Temperature Effect

A regression was performed on the entire sample for each plant to compensate for the impact of water temperature on the $CaSO_4$ saturation. Table 4 Shows the results of the regression. EWRP Phase I and II was not shown owing to the limited amount of seasonal data available. The expectation would be that one would see a reduction in $CaSO_4$ Saturation as the solubility of $CaSO_4$ decreases with decreasing temperature. However, theoretically this will be a function of how dominant the temperature component is in the rate of reaction equation and the sign. The determination of the rate equations for this system is out of the scope of this paper. The following Equation formed the basis of the regression.

$$CaSO_4\_Sat = A + B*Reactor\_Solids\% + C*Clarifier\_Solids\% + D*Stage\_1\_CaSO_4\_Sat\% + E*Temp$$

It can be seen from Table 5 that the calculated R2 (the measure of fit) is similar across both plants. In addition, coefficient A,B and E are highly significant, are of the same order and have the same sign. The dominance

Table 3. *Regression output control variables of the four installations.*

	EWRP Phase I		OWRP		MWRP	
Coefficients	Coeff	P-Value	Coeff	P-Value	Coeff	P-Value
A	1.567	5.7E-52	1.233	5.5E-97	0.964	9.7E-86
B	-0.256	0.639	-1.356	1.2E-06	-0.996	4.4E-24
C	-2.89	7.0E-16	-1.255	2.8E-17	0.760	3.9E-08
D	0.288	5.8E-09	0.459	2.0E-40	0.301	1.1E-19
Adjusted R^2	0.207		0.189		0.127	

Table 4. Regression output addition of temperature of the four installations.

	OWRP		MWRP	
Coefficients	Coeff	P-Value	Coeff	P-Value
A	1.495	7.7E-215	1.662	1.7E-292
B	-1.015	3.9E-07	-0.090	0.208
C	0.091	0.414	-0.159	0.111
D	0.282	1.6E-29	0.129	4.3E-08
E	-0.019	3.9E-203	-0.020	7.2E-257
Adjusted R2	0.584		0.5683	

of the temperature in the fit is clear with it increasing the fit substantially. The implication is that a large proportion of the reactor outlet CaSO4 saturations are statistically not dependent on the controllable variables presented. The second implication is that the rate equation is negatively affected by temperature i.e. the reaction rates slows with decreasing temperature and the rate equation dominates the equilibrium solubility in this system or conversely, the residence time within the system is not sufficient to allow the system to get to complete equilibrium. The lower the temperature the further away from equilibrium. However, it must be noted that it would be impractical to build a reactor system that has unreasonably long residence times as it will cause a substantial ballooning of capital costs. The residence time selection by the designers was a compromise to get as close to equilibrium as possible while minimising reactor size.

In addition, the coefficients "B" and "C" are not statistically significant for MWRP. However, this does not prove the practical significance of the solids control on the performance of the reactors. In fact operational experience has shown that should the solids percentage not be operated in the correct range, there is a substantial and immediate shift in the saturations. This causes particular problems during initial commissioning of the plant. However, since these are operational plants and strict control of the solids is required, the standard deviation of solids control may be too narrow to show the response to incorrect solids positioning. To illicit this point, the standard deviation for the three systems stands at 1.32%, 0.97% and 2.2% respectively.

Conclusions

The performance information from the four operational HiPRO™ plants has been shown and analysed from a statistical point of view. The findings show that the EWRP Installations have a substantial greater deviation in saturations than that of OWRP and MWRP.

The impact of feed water quality and sol-

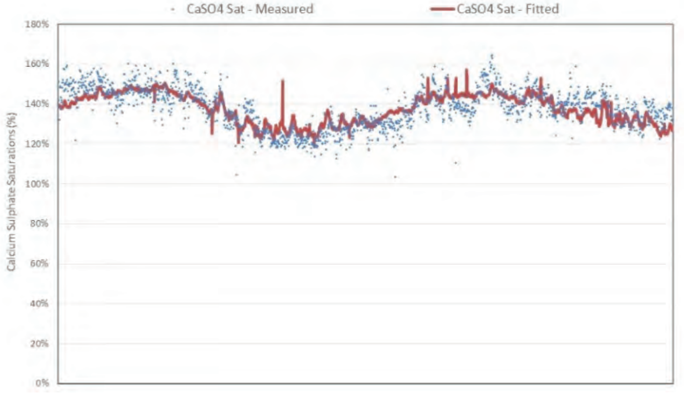

Figure 4: The Fit of CaSO4 Saturations compensating for temperature for MWRP

ids control statistically only counts for ≈20% of the deviation in the measured calcium sulphate saturations. This is a smaller contribution than what one may expect for a precipitation reaction. This is in contrast to the substantial effect that the feed water temperature has on the regression, where the temperature increases the fit to ≈58% on both cases investigated. The implication of such a change is that the rate of reaction equation slows with decreasing temperature and the residence times chosen for the design of the plant is not sufficient to get to equilibrium. However, the residence time selection is clearly sufficient as al four plants have operated sustainably over a long period.

The solids percentage was not statistically significant for the combined regressions. However, it does not practically make sense for this to be the case. This may highlight a limitation in only using statistical analysis in evaluating the factors that effect the reactors or highlight that the current measure of solids control is not sensitive enough to show the expected effect.

Further investigations are required following this paper which may include other explanatory variables within the process system as well as a determination of the cointegration between these explanatory variables to be able to develop a theoretical model that is better able to predict the performance of the calcium sulphate reactors.

References

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