Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 7. Air rate adjustment to Peak Air Recovery (PAR) to increase mineral production by froth flotation

1. Summary of the impact (indicative maximum 100 words)

Mineral separation by froth flotation is the largest tonnage separation process in the world, and is used to recover the very small fraction (<0.5%) of valuable mineral from the mined ore. Typically, 5-15% of the valuable minerals are not recovered due to sub-optimal process settings, most important of which is the air rate. A methodology to determine the optimal air rate range to use, Peak Air Recovery (PAR), was developed by the Froth and Foam Research Group at Imperial College London.

Anglo American Platinum produces 40% of the world's platinum. They use the PAR methodology on all their flotation plants to establish to air rate control limits, tightening the operating range and improving the separation performance. Rio Tinto annually produce 300 000 tons of copper and 500 000 oz gold from their Kennecott Copper mine. They have implemented PAR as a control strategy, and statistical comparative tests have shown an increase in copper and gold recovery from this mine alone of the order of 1%, with a nominal value of approximately $30m per annum.

2. Underpinning research (indicative maximum 500 words)

Mineral separation by froth flotation is the largest tonnage separation process in the world, and is used to recover the very small fraction (<0.5%) of valuable mineral from the mined ore. The ore is finely ground (<100µm) in water and a selective surfactant added to render the valuable minerals hydrophobic. Air is bubbled through the mixture, the hydrophobic particles attach to the bubble surface, rise up and form an overflowing froth from which the valuable mineral particles are recovered. Typically, 5-15% of the valuable minerals are not recovered due to sub-optimal process settings, most important of which is the air rate.

Froth flotation collects valuable hydrophobic particles in an overflowing, bursting froth. The air that enters the bottom of the tank can leave either as bubbles in the overflowing froth or by bursting on the surface. The fraction of air overflowing as froth (i.e. not bursting) is called the air recovery, and is typically 5-25% of the total. It has long been surmised that the magnitude of the air recovery affects the separation performance; if no froth overflows, no particles are recovered.

The air rate to a flotation tank affects the air recovery as it determines the froth flow velocity and the froth bursting rate. In 2005 the Froth and Foam Research Group first reported that a maximum (or peak) air recovery is found at a particular air rate. The maximum air recovery with air rate can be interpreted qualitatively as follows; at very low air rates, the bubbles in the froth are thoroughly coated with hydrophobic, film-stabilising particles and resist bursting. However, because the froth velocity is also low, the bubbles burst before overflowing. At very high air rates, the bubbles are not fully coated with particles and therefore burst readily and which gives low air recoveries. There is an intermediate air rate at which the bursting rate is reduced by particle loading, but the froth velocity is high enough for a substantial proportion of the bubbles to overflow before bursting.

The key research finding was made between 2008 and 2009, when Dr Kathryn Hadler established the direct relationship between flotation mineral recovery and air recovery [1]. This was the result of an extensive set of industrial data collected from flotation plants in South Africa, and its subsequent analysis by Hadler. This showed for the first time that the peak in air recovery, found at a specific air rate, also corresponds to the peak in separation performance; the highest mineral recovery possible under the operating conditions. This allowed the appropriate air rate for any flotation tank to be determined in a rigorous and scientific way, simply by measuring and maximising the air recovery. The method of changing the air rate to achieve PAR, and hence the best performance, was subsequently patented by Cilliers through Imperial College [2].

The PAR methodology has been extensively tested on industrial sites, and has in all cases improved performance. Some non-confidential data has been published [3,4].

In the key research period, Dr Kathryn Hadler was a Postdoctoral Researcher in the Froth and Foam Research Group, led by Professor Cilliers in the Department of Earth Science and Engineering at Imperial College London. Both are still in the Department, and Dr Hadler is now a lecturer. In 2010 Prof Cilliers was made a Fellow of the Royal Academy of Engineering for his work in flotation.

3. References to the research (indicative maximum of six references)
* References that best indicate quality of underpinning research.

* [1] K. Hadler, J.J. Cilliers, “The relationship between the peak in air recovery and flotation bank performance”, Minerals Engineering, Vol 22, Issue 5, pp. 451-455, (2009) DOI: 10.1016/j.mineng.2008.12.004

[2] J.J. Cilliers, “Method of froth flotation control”, Patent WO2009/044149, (2009) http://www.google.co.uk/patents/WO2009044149A1?cl=en

* [3] C.D. Smith, K. Hadler, J.J. Cilliers, “Flotation bank air addition and distribution for optimal performance”, Minerals Engineering, Vol 23, pp. 1023-1029, (2010) DOI: 10.1016/j.mineng.2010.05.003

* [4] K. Hadler, C.D. Smith, J.J. Cilliers, “Recovery vs. mass pull: The link to air recovery”, Minerals Engineering, Vol 23, pp. 994-1002, (2010) DOI: 10.1016/j.mineng.2010.04.007

4. Details of the impact (indicative maximum 750 words)

Anglo American Platinum and Rio Tinto supported financially the Froth and Foam Research Group to increase the understanding of the fundamentals of flotation and the importance of froth in mineral separation. This research had two key deliverables; first, to measure flowing froth properties using image analysis; in particular bubble size and velocity, and second to develop a CFD model of flowing froths. As part of the research collaboration, regular meetings were held in the UK and South Africa to discuss the results and their practical implications.

During the CFD froth model development, *air recovery* (the fraction of air entering the cell that overflows as froth, rather than bursting) was identified as an essential boundary condition of the flow models and that it will affect flotation performance. The value for air recovery had not previously been quantified or characterised at all in industrial flotation, and was first measured by the Froth and Foam Research Group. The Group’s research proved to Anglo Platinum and Rio Tinto that *air recovery* was important and could be measured using image analysis.

Air recovery was then, between 2007 and 2009, repeatedly measured by the Froth and Foam Research Group on Anglo Platinum and Rio Tinto copper industrial flotation plants to quantify the relationship between air recovery and the air rate, the most important control variable. It was discovered and confirmed through these trials that a maximum air recovery exists as a function of air rate – the so-called *Peak Air Recovery* or PAR. The link between the air recovery, specifically PAR, and the separation performance achieved at that air rate was, however, not yet clear.

The strong correlation between the air rate, PAR and the separation performance was finally identified in 2009 by Hadler and Cilliers from industrial data they collected [1]. It showed that the air rate to the flotation cell that gives the highest air recovery (PAR), is also the air rate that gives the optimal flotation performance under the operating conditions. This relationship allows the flotation performance to be optimised by making a well-defined measurement solely of the froth flow properties, by simply measuring the air recovery at a range of air rates and finding the air rate that

yields the maximum.
Throughout this research period and development of the PAR methodology, Anglo American Platinum and Rio Tinto were research partners. They became convinced of the validity and potential of the PAR research in two ways: first, the data that were used to prove the concepts was collected on their sites and with their cooperation and technical personnel involvement. Second, the results from the novel CFD simulation software developed in parallel by the Froth and Foam research team were proven to predict accurately industrial flotation performance. Since the air recovery concept was a direct outcome of the models, and the data showed that their process responded as predicted, they became convinced of the potential of the PAR methodology for determining plant settings.

It was proposed by the Froth and Foam Research Group that the PAR methodology could be used either as a manual technique by plant operators and engineers to optimise their flotation circuits and to inform the parameters used in their control strategies, or as part of an automatic control system. The two companies each took a different approach; Anglo American Platinum the former, Rio Tinto the latter. The measurement and manipulation of air recovery to optimise flotation separation performance procedure was patented by Imperial College in 2009 [2].

Anglo American Platinum independently made significant progress towards developing an automated control system that controls the air rate based on the froth velocity and mass flowrate of solids and liquid overflowing with the froth (the “mass-pull”). They decided not to replace their “mass-pull” control strategy with the PAR methodology, but to use instead the PAR methodology as a tool that can be easily utilized on remote mineral beneficiation sites, thus enabling the optimization of operations to maximize mineral recovery. This technique was licenced from Imperial College to Anglo American Platinum. The control limits determined from PAR allows tighter control of the process and avoids sub-optimal control parameter combinations. Due to the proprietary nature of this methodology we are unable to go into details as to how exactly the new methodology has resulted in impacts, but the PAR methodology has had significant impacts on key strategic drivers such as costs, water and energy efficiency per unit metal at Anglo American Platinum.[C]

Rio Tinto has implemented the PAR methodology as the basis of the flotation control system at their Kennecott Copper operation. Statistical trials were performed in 2009 showing an increase in copper recovery of 1%, approximately equivalent to an additional 3 000 tons of copper and 5 000 oz gold produced annually. In 2009 this had a nominal annual value of approximately $30m.[B]

The Rio Tinto Annual Report (2010) states: “The [Rio Tinto] Innovation group achieved several milestones during 2010 including the following: Successful trial of an innovative flotation control system at Kennecott Utah Copper demonstrating improved recovery.”[A] The Rio Tinto industrial control system has been fully operational since 2013.

5. Sources to corroborate the impact (indicative maximum of 10 references.)

[A] The Rio Tinto Annual Report 2010 confirms successful trials.
http://www.riotinto.com/annualreport2010/performance/te_performance.html
(Archived at https://www.imperial.ac.uk/ref/webarchive/7rf on 6th September 2013)

[B] The financial value of the impact is commercially confidential.
The Chief Development Officer, Innovation, Rio Tinto, can be contacted to corroborate the impact and its value.

[C] Head of Research, Anglo American Platinum, will corroborate the impact of the PAR methodology to Anglo American Platinum.