Introduction

Modelling of mineral separation plants is extensively utilized to prepare fully delineated flowsheets that are in turn used as the basis for design for the plants. There are inherent risks associated with a number of uncertainties that necessarily require the process engineer to make certain assumptions. Some of these uncertainties are shown in Figure 1. The main variations that can alter the performance of a plant are due to feedstock parameters, and operator practices and operational preferences. The performance outcomes for the plant can then be optimal, average (or typical) or at some lower practical limit.

The optimal case is generally expected to occur if all the factors, both operator controlled and feed conditions, have minimal variation. The average case would be the ‘norm’ under good tight operating control with experienced operators, minimal feed characteristic variations, in a mature operation. The lower practical limit would generally occur during the initial stages of the plant, life i.e. during and immediately after plant commissioning. The optimal case is considered possible, however unlikely, while the average and lower scenarios are likely, albeit after some process experience is obtained for the ‘typical’ (average) scenario to become the established performance base.

For the simulation and design of a plant it is important to know the range and extent of these performance variations. The usual practice is to conduct and gather data from testwork using commercial-scale equipment with real representative orebody samples.

This paper reports a methodology, using release curves for individual stages within the flowsheet, to estimate the optimal, average and lower limit for a given plant design performance. The methodology will be demonstrated using gravity separation plants with spiral separators as the prime device.

It is important to note that this paper examines the base level of uncertainty that might be expected in the development of a project in that it examines the errors propagated in translating physical testwork data into a simulation of the proposed flowsheet.

Establishing a methodology to predict the upper and lower limits of performance

The release curve (or recovery versus mass yield to concentrate curve) is the common basis of the construction of computer-based simulation of a gravity separation plant or wet plant. The curve is derived from testwork where the particular stage feed is processed using a selected model of spiral and the separation performance determined from a series of tests where the mass take to the various product streams is varied. The general form of the curve and the salient features are shown in Figure 2.

The perfect separation curve is shown in Figure 2. It indicates the form that the release curves should be if the...
separation were ideal. Under these circumstances the recovered concentrate would be at the maximum grade available up to a mass yield equivalent to the feed grade. Thereafter the concentrate is diluted by the gangue fraction. The main features of the chart are the ‘no go’ areas where, by definition, the release curve cannot appear.

A simple approach to determining the separation performance of the material under the three scenarios discussed above would be to offset the expected curve by a fixed amount above the curve to indicate optimal performance and the same fixed amount below the expected curve for the lower practical performance. This is illustrated in Figure 3. It is clear that this method to define the performance, particularly for the optimal performance scenario, is flawed in that the performance curves show deviation into the ‘no go’ areas.

A solution to this situation would be to constrain the optimal and lower limit curves to the actual possible performance area on the chart. However, this approach would not represent an actual plant performance. For example, in the case of optimal performance the material would be expected (simulated) to follow the ‘perfect separation curve’ to approximately 85% recovery and again after approximately 50% mass yield to concentrate. For the lower limit performance, using this model, the recovery would be essentially zero up to approximately 5% mass yield to concentrate and would not increase after approximately 95% mass yield to concentrate. Neither of these scenarios represents an actual plant performance. Another approach is required.

The problems indicated in the previous paragraph and Figure 3 have led to the derivation of a procedure to define the curves that obey the fundamentals of the requirements for a properly defined release curve for each of the scenarios. By the very nature of the release curve, we know that in order to simulate actual separation performance, certain rules must be adhered to. In summary these are:

- Negative mass yield and recovery, as well as recovery and mass yield exceeding 100%, are not possible.
- Release curves showing upgrading of a particular component (in this case HM or Fe) do not fall into the lower ‘no go’ area.
- Release curves cannot be developed showing separation performance that exceeds perfect separation.

These factors therefore determine the rules and subsequent shape of the optimal and lower practical limit recovery curves that are above and below the expected curve. The points of contraction of all the possible recovery curves are located at the origin (0,0) and the maximum (100,100) points of the performance curves, as illustrated in Figure 4.

The basis of the approach used in this paper for determining the three performance scenarios is to embrace the three rules and points of contraction discussed above. The parameters used for each of the recovery curves of the different scenarios were determined statistically using the deviation of the actual data to the calculated (‘expected’) performance curve. The optimal curve data corresponds to the positive deviation while the lower curve data corresponds to the negative deviation from the ‘expected’ release curve. These scenarios were determined in order to encapsulate all the experimental data for a particular set of design feed conditions to a confidence level of 95%.

Case studies

Two case studies, one for fine iron ore processing and another for a mineral sands deposit, were examined to determine the uncertainties in the modelling of the individual spiral separation circuits.

Iron ore beneficiation

In the first case study, beneficiation testwork was performed on a 12-ton sample of iron ore fines with the aim of determining a flowsheet capable of producing a final product with an Fe grade of greater than 60% from a feed stock containing approximately 58%. Although the final flowsheet contained several processing stages other than spiral separation, including wet screening, hydraulic

Figure 2. Generalized release curve

Figure 3. Fixed offset performance curves

Figure 4. Practical offset performance curves
classification, wet high intensity magnetic separation and coarse and fine jigs, only the performance of the spiral circuit is the subject of investigation in this paper.

The proposed spiral circuit consisted of three stages. Each stage generated a final concentrate with the middling and tailing streams from the rougher being processed separately through their respective stages, as shown diagrammatically in Figure 5.

The measured feed grade to the spiral circuit was 58.6% Fe, representing approximately 27% of the total head feed by weight. As is appropriate for the majority of iron ore wash waterless spiral separator applications, the model HG10S spiral separator was used in the proposed flowsheet for all the spiral stages.

The testwork was conducted using a pilot-plant facility. The general feed conditions, consistent with the test material type, to have a nominal 30 to 35% solids by weight and with a spiral loading of approximately two tons per hour per start. A ‘start’ in this context represents a single trough.

Processing iron ore data presents a challenge to the mineral processing design engineer. The traditional release curve analysis, which has been utilized for mineral sand, is extremely insensitive to subtle variations in Fe distribution with the release curve lying close to the lower ‘no go’ line— as illustrated in Figure 6. Expanding the axes does little for the interpretation of the curves, so in this case the release curves are fitted with reference to the grade versus mass yield data, as shown in Figure 7.

Similarly, release parameters were generated for the mid scavenger and tail scavenger stages of the proposed flowsheet. These are shown in Figure 8 and 9.

As stated previously, the expected scenario encompasses release curves generated directly from the testwork data, whereas the optimal and lower release curves are derived from data-sets that are derived from the plus (optimal) and minus (lower) deviation of these data from the expected curve at a 95% confidence level.

The spiral concentrates from each stage of the separation were combined to produce the final spiral product. Using the stage by stage release parameters for each of the scenarios the separation performance of the circuit can be predicted. The feed grade used in all the simulations was normalized for design purposes to 58% Fe and the circuit feed rate was 300 tons per hour. For the purpose of determining the annual production rate 7,000 operating
hours was used. The stage by stage mass yields to the various streams were altered to achieve a constant final concentrate grade of 60.3% Fe. The derived performance data for each of the scenarios are summarized in Table I.

The difference in performance from one scenario to the next is significant, with the product mass yield varying from 51.2 to 59.0% and the Fe recovery from 53.2 to 61.4% respectively for the lower performance to the optimal performance cases. The additional annualized product generated using the ‘lower’ scenario as the base case is shown in the table. This indicates the very significant benefit that can be obtained by targeting an operating strategy that maintains the recovery or mass yield at the optimal values.

**Mineral sands beneficiation**

The second case study involved the beneficiation of a 3% heavy mineral ROM grade mineral sand material. The final developed flowsheet consisted of six stages of spiral separators, including a rougher (model MG6.3 spiral separator), middlings retreat (model MG6.3 spiral separator), cleaner (model HG10 spiral separator), up current classifier (UCC) overflow (model MG6.3 spiral separator), UCC underflow cleaner (model VHG spiral separator) and UCC underflow middlings scavenger (model VHG spiral separator), and two stages of classification (hydraulic and a vibrating screen). Figure 10 shows a block diagram of the processing circuit.

The circuit was designed to generate four products for upgrading:

- **HMC**—the prime concentrate containing the majority of the valuable heavy minerals, namely, ilmenite, rutile, zircon, etc.
- **LHM Con 1**—a sillimanite rich stream
- **LHM Con 2**—a garnet rich stream
- **LHM Con 3**—a second garnet rich stream containing coarse garnet.

As before, each stage of separation was tested and release data generated using commercial equipment in a test laboratory. This procedure gave the parameters for stage by stage separation performance of this particular material and the end use separators. In this case, since significant upgrading was achieved between the stages. The simulations were conducted on the basis of the distribution release curves; these are shown in Figures 11, 12, 13, 14, and 15.

For the purposes of this discussion the HMC product will be the focus with the low value LHM products not considered.

The circuit model was first balanced using the ‘expected’ performance data generating products of the required quality. The mass splits at the various stages were adjusted in order to achieve a similar HMC grade for each of the scenarios. These resultant data is tabulated in Table II. It is noted that for the lower performance case the final HMC output grade of 98.5% HM was not achieved, further penalizing the performance resulting from this scenario.

From the data of Table II it can be seen that the production of some 280 000 tons of additional HMC at the required grade from the laboratory testwork and process plant simulation where ‘optimum’ conditions prevail compared to where ‘lower’ conditions prevail. Table II shows the additional product generated with each of the strategies relative to a base case of lowest performance for

<table>
<thead>
<tr>
<th>Solids rate (t/h)</th>
<th>Yield (% of feed)</th>
<th>Grade (% Fe)</th>
<th>Fe recovery from feed</th>
<th>Additional product cf. ‘lower’ case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>300</td>
<td>100.0</td>
<td>58.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Lower</td>
<td>154</td>
<td>51.2</td>
<td>60.3</td>
<td>53.2</td>
</tr>
<tr>
<td>Expected</td>
<td>168</td>
<td>55.9</td>
<td>60.3</td>
<td>58.1</td>
</tr>
<tr>
<td>Optimal</td>
<td>177</td>
<td>59.0</td>
<td>60.3</td>
<td>61.4</td>
</tr>
</tbody>
</table>

**Figure 10. Flowsheet for mineral sands beneficiation**

**Figure 11. Rougher release curve**

**Table I**

Comparison of iron ore beneficiation for the three likely scenarios
the plant design for a year of production. Again it is seen that significant additional production can be realized at the same feed rate from a plant by ensuring that the plant runs at its optimum capability.

**Conclusion**

This paper has presented a methodology for the establishment of an economically feasible separation plant and the associated uncertainty due to orebody characteristics and the operation approach of the plant. The formula to estimate the uncertainties in the production capacity has incorporated the key characteristics of the separation performance curves. The curves must always pass through the origin and the 100% recovery and 100% mass yield. If one uses this information, more realistic error estimates and hence production impacts can be achieved from testwork and simulation for plant design.

For both the case studies used, the increase in recovery performance has resulted in significantly greater production for capital investment in the separation plant. In practice, the additional benefit would most likely occur without or with a minimal increase in energy (power) or water consumption.

Within the life of a project it can be expected that the plant will operate around the lower performance level during and immediately proceeding commissioning. As with all operations, it is only with operational experience that the plant can be fine tuned and optimized to a point where production approaches optimal performance, and it is not unusual for this to happen after 12 months or more of operation. Once optimal performance has been achieved, continued close plant performance monitoring and adjustment is necessary to maintain this level of performance.

**Acknowledgement**

Assistance with assembly of test results and establishing the statistical procedure used in the analyses from Mary Ng of Mineral Technologies is acknowledged.

**Table II**

Comparison of the HMC output for mineral sands beneficiation under the three performance scenarios

<table>
<thead>
<tr>
<th></th>
<th>Solids rate (t/h)</th>
<th>Yield (%) with respect to feed</th>
<th>Grade (%Fe)</th>
<th>HM Recovery with respect to feed</th>
<th>Additional Product cf. 'Lower' case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>357</td>
<td>100.0</td>
<td>32.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>40.5</td>
<td>11.3</td>
<td>97.7</td>
<td>34.6</td>
<td>0</td>
</tr>
<tr>
<td>Expected</td>
<td>54.3</td>
<td>15.2</td>
<td>98.5</td>
<td>46.8</td>
<td>96,965</td>
</tr>
<tr>
<td>Optimal</td>
<td>80.2</td>
<td>22.5</td>
<td>98.5</td>
<td>69.1</td>
<td>278,368</td>
</tr>
</tbody>
</table>