Aachen Reactors™, a proven system to realize hidden economic potentials

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Gold ore processing relies, among other criteria, on the efficient oxidation of not only the target metal, but also components inhibiting this crucial step, such as iron- and sulphur-based compounds. The associated oxygen mass requirements can be substantial and form a considerable part of the operational cost where this is the case.

The Aachen High Shear Reactor™, originally designed to enable efficient high-level oxygen mass transfer from gas to liquid phase in the treatment of refractory gold ores, has by now found many applications where substantial process optimization targets have to be met.

With many of the easy-to-process reserves depleted, the remaining gold ores often have associated problems of cyanidable gold losses, slow leach kinetics, and high reagent consumptions. The endless pursuit of higher throughput to compensate for declining gold prices in recent times has only served to exacerbate these issues.

The Maelgwyn Aachen™ technology has been developed and deployed successfully in a range of gold mining applications to address these problems and has now, in addition to its original application to refractory flotation concentrate, found significant industry uptake into normal oxide cyanidation circuits.

This paper describes the journey from laboratory test work to full commercialization of Aachen reactors. Examples of work conducted to identify the envisaged level of shear, mass of oxygen, and general process conditions to maximize the potentials for a range of different ores and applications are provided. Early-stage economic evaluations include the identified benefits, which are then offset against the inputs of power, oxygen, and rental cost. A favourable balance typically leads to a trial phase on-site with a given scope of technology deployment. Data collection to support or validate the conclusions based on laboratory work forms part of final acceptance, and examples are provided. Finally, data from selected operational sites across Africa is presented demonstrating the ability of the Aachen reactor to assist with realizing hidden potentials in reagent savings, gold recovery, or throughput increases.

Introduction

The oxygen requirement

Ever since the introduction of cyanide into gold processing, it has been understood that for the dissolution of the metal to take place, a minimum amount of oxidant, usually in the form of oxygen, is required. The well-known Elsner equation defined the basic stoichiometric needs. However, as for the cyanide lixiviant, mere equivalents will not suffice due to the multitude of side reactions potentially taking place. Otherwise, a modest oxygen level of 0.2 g/t might suffice to enable the dissolution of gold from an average ore with a grade of 5 g/t, and which has no other detrimental properties.

$$4 \text{ Au} + 8 \text{ CN}^- + \text{O}_2 + 2 \text{ H}_2\text{O} \rightarrow 4 \text{ Au(CN)}_2^- + 4 \text{ OH}^- $$  [1]

Historically, many mining operations had relatively benign ores as feed material; for resources which were either oxide ores or if sulphides were present, gold was not classified as refractory as it was not contained within the sulphide

Building a Resilient Gold Mining Industry

mineral matrix. The Witwatersrand ores, where recoveries of 96% and more are achievable with relative ease, are typical representatives of this type of feed material. Other than compressed air support to maintain modest dissolved oxygen (DO) levels and/or keep slurries in suspension, more aggressive oxidation measures were seldom required.

This has, however, changed significantly over the last few decades worldwide. Most of the more recent projects have to deal with lock-up aspects where gold is not easily accessed by the reactants, the presence of relatively large amounts of fast-reacting sulphide minerals such as pyrrhotite, or gold which is completely contained in pyrite or arsenopyrite. Alternatively, as in the case of many tailings reclaim operations, the presence of large amounts of unstable oxidation products such as ferrous iron or metastable sulphide oxidation products places a heavy demand on oxygen and cyanide consumption.

All of these aspects have redirected the focus on suitable pre-oxidation steps to help overcome the drawbacks.

It might be appropriate to reflect on the various oxidation reactions over and above the Elsner equation to appreciate the oxidant mass requirements associated with them.

Iron is often present in leach solution phases either as a function of ageing tailings material (acid mine drainage, AMD) or partial oxidation of labile sulphides in freshly mined ores. Many mining sites working from oxide through transitional ores experience a steady rise in oxygen demand owing to the requirement to decrease reagent consumption by iron species. The oxidation of ferrous iron to the ferric species represents a low-level oxygen consumer. However, as Equation [1] illustrates, an iron to oxygen ratio of 4:1 with normally prevailing low-level oxygen concentrations would not necessarily define this reaction as a high oxygen demand situation. Still, if not adequately addressed, the ferrous iron species would consume oxygen later during the leach or, potentially worse, cause a significant additional demand for cyanide through the formation of Fe(CN)$_6$$^{4-}$ (Equation [2]).

\[
4\text{Fe}^{2+} + \text{O}_2(aq) + 6\text{H}_2\text{O} \leftrightarrow 4\text{FeOOH}(s) + 8\text{H}^+ \tag{2}
\]

\[
\text{Fe}^{2+} + 6\text{CN}^- \leftrightarrow \text{Fe(CN)}_6^{4-} \tag{3}
\]

Where the leach feed contains sulphide minerals, especially if ultrafine grinding (around 10 μm) is employed, very significant oxygen demands can result. This would of course depend on whether the sulphides contain encapsulated gold and are thus targeted for deliberate oxidation or, in the case of labile species such as pyrrhotite, there is often no choice other than oxidizing the sulphides to a very large degree to avoid excessive consumption of more expensive reagents such as cyanide or dramatic retardation of leach kinetics.

The chemistry of sulphide oxidation is not as straightforward as that applicable to solution species. The degree of oxidation depends on such variables as pH, temperature, oxygen mass supplied in a given time, and shear rate (Zhang, 2004). The correct combination of these parameters may allow a selection of outcomes ranging from oxidation-based surface passivation of sulphides to their high-level destruction.

Some of the reactions that underlie the concept are given in Equations [4] to [9].

\[
\text{FeS}_2 + 2\text{O}_2 = \text{FeSO}_4 + \text{S}^\circ \tag{4}
\]

\[
2\text{FeS}_2 + 7\text{O}_2 + 2\text{H}_2\text{O} = 2\text{FeSO}_4 + 2\text{H}_2\text{SO}_4 \tag{5}
\]

\[
4\text{FeS}_2 + 15\text{O}_2 + 14\text{H}_2\text{O} = 4\text{Fe(OH)}_3 + 16\text{H}^+ + 8\text{SO}_4^{2-} \tag{6}
\]

Pyrite oxidation may proceed to various levels depending on prevailing conditions such as pH (Equations [4] to [6]). As the reactions progress through the intermediate steps, the oxygen demand rises steeply. If a fairly high level of destruction is actually targeted, the application of shear will increase the rate of these reactions significantly.

Pyrrhotite, being a fairly labile sulphide, will require efficient treatment if present at significant levels, whether gold is contained or not. Again, the associated mass requirements for oxygen are large and neglecting the proper addressing of the issue at metallurgical process level may have dire consequences (Equation [7]).

\[
4\text{FeS}_8 + 69\text{O}_2 + 74\text{H}_2\text{O} = 28\text{Fe(OH)}_3 + 64\text{H}^+ + 32\text{SO}_4^{2-} \tag{7}
\]

Arsenopyrite, like most sulphides often associated with gold, is no exception when it comes to high-level oxidant requirements. Equation [8] illustrates the total oxidation of arsenopyrite to sulphate.

\[
2\text{FeAsS} + 7\text{O}_2 + 8\text{H}_2\text{O} = 2\text{Fe(OH)}_3 + 2\text{H}_3\text{AsO}_4 + 4\text{H}^+ + 2\text{SO}_4^{2-} \tag{8}
\]
Finally, should copper minerals be present in the ore, the mass requirements for oxygen could again be significant, whether copper dissolution is targeted or not. Copper dissolution would of course also impact on cyanidation and adsorption, and demands careful management. Equation [9] relates the overall reaction for chalcopyrite.

$$4CuFeS_2 + 17O_2 + 18H_2O = 4Cu(OH)_2 + 4Fe(OH)_3 + 16H^+ + 8SO_4^{2-}$$ [9]

Notwithstanding the dependence on the final degree of oxidation (e.g. whether a dissolving metal sulphide will react all the way to the final stable products of metal oxides and sulphate or if the reaction stagnates at the elemental sulphur level, $S_0$), the oxygen mass requirement for these reactions drastically exceeds the low-level ppm range that is traditionally sufficient to achieve full dissolution and recovery. It will be evident that most of the common sulphide minerals require a mass ratio of 0.7 to 1.0 oxygen units per unit of sulphide to complete oxidation. Thus, depending on the types and levels of sulphide present, as well as the required degree of oxidation, oxygen consumption can quickly rise to the order of several tons per day for an ore containing several per cent of sulphur in an operation treating 6000 tons of ore per day or more.

In the most drastic situations, the complete destruction of the sulphide matrix will be required to achieve economically viable levels of gold recovery. Traditionally, this has been the domain of pressure oxidation, bioleaching, or roasting, and for many large-scale projects where the increased capital cost can be absorbed over a large time span these methods are still the preferred choices. However, for projects where only partial oxidation is required or the original expectations with respect to oxygen consumption by the ore are massively exceeded at operational level later, high-shear reactors enable the efficient transfer of relatively high masses of oxygen from the gas phase into the aqueous phase of a slurry.

In practice, although it would be desirable to have a detailed overview of gold deportment in relation to mineralogy for a given feed material, the information available is usually of a more general nature. Thus assumptions have to be made for the original test work approach and end results based on somewhat empirical observations.

In summary, all of these reactions, whether targeted intentionally or not, will lead to oxygen demands measurable in tons, rather than kilograms, per day. Generally speaking, the finer the grind, the faster the reaction rates and oxygen addition requirements per unit time.

**Reaction rates and the shear element**

Whether it is the sulphide matrix or the actual gold (Au⁰) being oxidized, the dissolution rate is to a large degree diffusion-controlled across the film boundary layer between the solid surface and the bulk solution phase (Nicol, Fleming, and Paul, 1987).

As such, the reactants (oxygen, cyanide) will have to migrate towards the solid surface, and the products (auro dicyanide, sulphide reaction products) move away from it (Figure 1). The thickness of this film boundary layer is inversely proportional to shear. Thus agitation, or more generally kinetic energy input, is one of the drivers towards limiting the boundary layer and thereby enabling faster reaction rates.

The Aachen™ high-shear reactor design incorporated shear from the onset, based on the need for efficient gas transfer from the gas to the liquid phase. In addition, the high-shear environment has beneficial impacts on the solution/solid interface reactions and adds a boost to reaction rates which are considerably slower under normal conditions of a low-shear environment.
To arrive at comparable results, several test sequences are normally performed on a specific sample. Test work at Maelgwyn Mineral Services Africa laboratories aimed at rationalizing the use of shear usually also incorporates, apart from the routine base-case leaches, a comparative test where oxygen is sparged using a fritted thimble porosity G3 device to support pre-oxidation at DO levels around 20 ppm. The prevailing shear environment would be defined by the agitation rate during the peroxidation, which is set at moderate stirring rates in a reactor or typical bottle-roll velocities.

The Aachen-related data results from tests performed using the laboratory pilot rig (Figure 2) at pre-oxidation level, simulating a one tank residence time coupled with the appropriate shear.

The data obtainable from the shear and modest pressure (4 bar) differentiates significantly from the no-shear tests and would potentially be influenced by several factors at the same time, such as relatively minor additional gold dissolution from sulphides through mild oxidation, simple particle surface polishing, or increased shear-induced reaction rates.

Table I illustrates the differences obtained at laboratory level, comparing the base case tests replicating plant conditions with oxygen sparging and modest Aachen/shear-based test variations.

It will be noted that while the oxygen sparging based low-shear pre-oxidation is able to improve the recovery at modest levels, the Aachen-based pre-oxidation contributes yet higher potential benefits. The potentials to save cyanide through pre-oxidation exist but are not realizable in all cases.

The data provided relates to a range of ore types. The first three represent sulphide ores containing a significant portion of arsenopyrite, and the last one represents flotation tails from a copper/gold operation.
Table I. Selection of laboratory-generated leach data indicating the influence of oxygen with and without shear

<table>
<thead>
<tr>
<th>Ore type</th>
<th>Au grade</th>
<th>NaCN addition</th>
<th>NaCN consumed</th>
<th>Au residual</th>
<th>Au dissolution</th>
<th>Type of test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/t</td>
<td>g/t</td>
<td>g/t</td>
<td>g/t</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>BTRP BIOX residue</td>
<td>2.82</td>
<td>3000</td>
<td>2880</td>
<td>1.83</td>
<td>35.0</td>
<td>Operational base case</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2910</td>
<td>1.71</td>
<td>50.6</td>
<td>O₂ sparge-based pre-ox</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2650</td>
<td>1.28</td>
<td>54.5</td>
<td>2-pass Aachen pre-ox</td>
</tr>
<tr>
<td>BTRP flotn tails</td>
<td>0.90</td>
<td>3000</td>
<td>2830</td>
<td>0.36</td>
<td>60.0</td>
<td>Operational base case</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2860</td>
<td>0.29</td>
<td>67.8</td>
<td>O₂ sparge-based pre-ox</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2308</td>
<td>0.28</td>
<td>68.9</td>
<td>2-pass Aachen pre-ox</td>
</tr>
<tr>
<td>Mali (West Africa) tailing retreat</td>
<td>0.56</td>
<td>600</td>
<td>450</td>
<td>0.39</td>
<td>30.4</td>
<td>Operational base case</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>530</td>
<td>0.37</td>
<td>33.9</td>
<td>O₂ sparge based pre-ox</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>450</td>
<td>0.24</td>
<td>57.1</td>
<td>2-pass AAL pre-ox</td>
</tr>
<tr>
<td>Mali (West Africa) ROM - CIL</td>
<td>12.60</td>
<td>475</td>
<td>444</td>
<td>4.32</td>
<td>65.7</td>
<td>Operational base case</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>429</td>
<td>4.14</td>
<td>67.1</td>
<td>O₂ sparge-based pre-ox</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>459</td>
<td>2.17</td>
<td>82.8</td>
<td>2-pass AAL pre-ox</td>
</tr>
<tr>
<td>Mauritania (West Africa) Cu/Au mine</td>
<td>1.98 (Cu 1.07%)</td>
<td>2000</td>
<td>1780</td>
<td>1.45</td>
<td>26.8</td>
<td>5 ppm DO leach</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1790</td>
<td>0.68</td>
<td>65.7</td>
<td>15-20 ppm DO leach</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1810</td>
<td>0.53</td>
<td>73.2</td>
<td>5-pass AAL pre-ox</td>
</tr>
</tbody>
</table>

The pass concept

The Aachen reactors rely on internal recirculation to contribute to oxygen transfer and shear exposure. Slurry is pumped from near the bottom of a CIL tank through the Aachen reactor and the back into the tank. The degree of exposure is expressed in ‘passes’, –a pump rate through the reactor equal to one hour’s plant throughput being a single pass. Feeding a multiple of this rate through one or more reactors thus leads to a correlating multiple pass rate. For example, if a plant indicates a nominal throughput of 600 m³/h, leach slurry that is pumped through reactors at 1200 m³/h would be defined as two passes.

The reactors are manufactured in differing sizes, which allows for tailor-made applications. The main units finding application at present are the:
- REA 400 unit, accommodating a slurry flow of approximately 300–350 m³/h
- REA 450 unit, accommodating a slurry flow of around 600–750 m³/h.

The oxygen diffusion capacity for these reactors covers a range of 30–200 kg/h.

Experimental

The experimental approach at laboratory level is aimed at generating data that characterizes the resulting dissolution, recovery, reagent consumptions, and leach kinetics under the following conditions:
- Current plant or project baseline conditions (e.g. currently defined optimal set of parameters)
- Elevated oxygen support environment (but absence of shear)
- High-oxygen environment created and supported by differing shear exposure.

The two case studies presented illustrate what can be achieved when applying the Maelgwyn technology in a tailings reclaim environment. It will be appreciated that several of the previously mentioned reaction possibilities may play a role in shaping the outcome. Additionally, the shear-based particle polish is likely to contribute to the positive outcomes, but attributing results to specific factors is often difficult due to analytical constraints. Thus, a measure of empirical outcomes evaluation was accepted at this stage.

Laboratory set-up and related test work

The laboratory-scale tests were conducted using a combination of a pilot-scale Aachen rig followed by standard bottle-roll leaches. All the critical parameters were kept aligned with the plant operational conditions.
Figure 2 illustrates the laboratory test rig for the Aachen based oxidative pre-treatment. The rig incorporates the Aachen pilot device, the Warman 1½-1 slurry pump and associated motor, and the holding tank.

Several pre-oxidation test work modules were conducted on gold-bearing ore samples supplied by companies listed in Table II.

Table II. Operations participating in laboratory trials and field applications of the shear reactor

<table>
<thead>
<tr>
<th>Company</th>
<th>Gold plant</th>
<th>Nature of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan African Resources</td>
<td>Barberton Tailings Retreatment Project (BTRP)</td>
<td>Tailings reclamation plant</td>
</tr>
<tr>
<td>Sibanye</td>
<td>Cooke Surface Operations (CSO)</td>
<td>Tailings reclamation plant</td>
</tr>
</tbody>
</table>

The head grade analyses of the BTRP and Cooke samples are shown in Table III:

Table III. Head grade analysis of laboratory testwork samples

<table>
<thead>
<tr>
<th>Material source</th>
<th>Au (g/t)</th>
<th>S¹ (%)</th>
<th>S² (%)</th>
<th>Fe (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTRP – BIOX tails</td>
<td>2.82</td>
<td>0.99</td>
<td>0.91</td>
<td>4.23</td>
</tr>
<tr>
<td>BTRP – Float tails</td>
<td>0.90</td>
<td>0.58</td>
<td>0.52</td>
<td>5.22</td>
</tr>
<tr>
<td>CSO</td>
<td>0.43</td>
<td>0.88</td>
<td>0.66</td>
<td>0.49</td>
</tr>
</tbody>
</table>

The particle size distribution analyses of BTRP and Cooke CSO material are listed in Table IV, and are fairly typical for the kind of operations under test.
Table IV. Particle size distribution of laboratory test work samples

<table>
<thead>
<tr>
<th>Source</th>
<th>% passing 75 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTRP</td>
<td>85</td>
</tr>
<tr>
<td>BIOX tails</td>
<td>85</td>
</tr>
<tr>
<td>BTRP float tails</td>
<td>72</td>
</tr>
<tr>
<td>CSO</td>
<td>72 – 76</td>
</tr>
</tbody>
</table>

High-shear pre-oxidation tests were performed using a laboratory Aachen reactor, equipped with a small centrifugal slurry pump (Warman ½-1) to drive the shear unit. Once the relevant pre-oxidation phase was concluded, the slurry was transferred to rolling bottles and the leach and adsorption phases conducted as required.

Cyanidation tests were carried out as discrete bottle rolls in 2 L Schott bottles with the roller mechanism rotating at 70 r/min. The experiments were carried out using a 1:1 solids to liquid ratio at room temperature (approx. 20°C) and atmospheric pressure. Analytical grade sodium cyanide was used for the cyanidation tests. Leach parameters were monitored using a Thermo Scientific Orion Star A329 pH, redox, and DO meter, fitted with a RDO probe.

The cyanidation tests were terminated at 24 hours, after which the slurry was filtered and the solids phase dried overnight at 70°C. The dried residue was submitted for total gold analysis by fire assay. The solution phase was analysed for CN using a SI Analytics TitroLine® autotitrator, and for gold by atomic absorption. Analyses were conducted at an accredited analytical laboratory.

**Example 1: BTRP laboratory tests**

The two main BTRP feed materials, BIOX residue and flotation tails, were individually exposed to a two-pass simulated Aachen pre-oxidation phase, followed by cyanidation at various cyanide additions.

Pre-oxidation was carried out by pumping the material through the laboratory Aachen reactor at a slurry flow rate of 2.2 m³/h, while oxygen was introduced at 0.38 kg/t. The slurry was agitated for 3 hours to simulate the envisaged pre-oxidation circuit. The slurry was then transferred into bottles for the cyanidation phase at 20 g/L carbon addition and cyanide additions of 1, 2, and 3 kg/t to evaluate the effect on gold dissolution.

Comparative direct cyanidation tests were conducted on both feed materials using the same conditions as described above, matching plant cyanide additions of 3.0 kg/t.

The test work results are presented in Table V and Table VI.

Table V. Laboratory test work results for BTRP BIOX residue sample

<table>
<thead>
<tr>
<th>Test work module</th>
<th>Head Au (g/t)</th>
<th>Residue Au (g/t)</th>
<th>NaCN consumption kg/t</th>
<th>CaO consumption kg/t</th>
<th>Au dissolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-pass pre-ox 1 kg/t NaCN</td>
<td>2.82</td>
<td>2.04</td>
<td>0.66</td>
<td>1.96</td>
<td>27.5</td>
</tr>
<tr>
<td>2-pass pre-ox 2 kg/t NaCN</td>
<td>2.82</td>
<td>1.70</td>
<td>1.61</td>
<td>1.98</td>
<td>39.6</td>
</tr>
<tr>
<td>2pPass pre-ox 3 kg/t NaCN</td>
<td>2.82</td>
<td>1.28</td>
<td>2.65</td>
<td>2.15</td>
<td>54.5</td>
</tr>
<tr>
<td>Plant base 3.0 kg/t NaCN</td>
<td>2.82</td>
<td>1.81</td>
<td>2.80</td>
<td>1.80</td>
<td>35.7</td>
</tr>
</tbody>
</table>

The BIOX residue plant-based cyanidation test yielded a gold recovery of 36% (1.81 g/t Au in solids residue) at a cyanide addition of 3 kg/t. Lime addition of 1.94 kg/t CaO was required to achieve the desired leach pH environment of 10.5.

The Aachen pre-oxidation test work achieved a maximum gold dissolution of 54.5% (1.28 g/t Au in solids residue) at a cyanide addition of 3 kg/t. The lower cyanide additions of 1 and 2 kg/t resulted in lower gold dissolutions of 27.5% and 39.6% respectively.
Table VI. Laboratory test work results for BTRP flotation tails

<table>
<thead>
<tr>
<th>Test work module</th>
<th>Head</th>
<th>Residue</th>
<th>NaCN consumption</th>
<th>CaO consumption</th>
<th>Au dissolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Au (g/t)</td>
<td>Au (g/t)</td>
<td>kg/t</td>
<td>kg/t</td>
<td>Au %</td>
</tr>
<tr>
<td>2-pass pre-ox 1 kg/t NaCN</td>
<td>0.90</td>
<td>0.38</td>
<td>0.36</td>
<td>2.34</td>
<td>57.8</td>
</tr>
<tr>
<td>2-pass pre-ox 2 kg/t NaCN</td>
<td>0.90</td>
<td>0.37</td>
<td>1.33</td>
<td>2.37</td>
<td>58.9</td>
</tr>
<tr>
<td>2-pass pre-ox 3 kg/t NaCN</td>
<td>0.90</td>
<td>0.28</td>
<td>2.38</td>
<td>2.51</td>
<td>68.9</td>
</tr>
<tr>
<td>PlantbBase 3.0 kg/t NaCN</td>
<td>0.90</td>
<td>0.34</td>
<td>2.79</td>
<td>2.22</td>
<td>62.2</td>
</tr>
</tbody>
</table>

The float tails plant-based cyanidation test yielded a gold recovery of 62% (0.34 g/t Au in solids residue) at a cyanide addition of 3 kg/t. Lime addition of 2.48 kg/t CaO was required to achieve the desired leach pH environment of 10.5.

The Aachen pre-oxidation testwork yielded a maximum gold dissolution of 69% (0.28 g/t Au in solids residue) at a cyanide addition of 3 kg/t. The lower cyanide additions of 1 and 2 kg/t resulted in lower gold dissolutions of 58% and 59% respectively.

Example 2: Cooke Surface Operations laboratory tests

10 litres of CSO thickener underflow material was exposed to a two-pass simulated Aachen pre-oxidation phase, followed by cyanidation at plant-specific leach conditions.

Pre-oxidation was carried out by pumping the material through the laboratory Aachen reactor at a slurry flow rate of 2.2 m³/h, while oxygen was introduced at 0.38 kg/t. The slurry was agitated for 1 hour to simulate the envisaged pre-oxidation circuit. The slurry was then transferred into rolling bottles for the cyanidation phase at 20 g/L carbon addition and cyanide additions of 0.25, 0.5, and 1.5 kg/t to evaluate the effect on gold dissolution.

A comparative direct cyanidation test was conducted on as-is thickener underflow material using the same conditions as described above, matching plant cyanide addition at 0.76 kg/t.

The test work results are listed in Table VII.

Table VII. Laboratory test work results for Cooke Surface Operations sample

<table>
<thead>
<tr>
<th>Test work module</th>
<th>Head</th>
<th>Residue</th>
<th>NaCN consumption</th>
<th>CaO consumption</th>
<th>Au dissolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Au (g/t)</td>
<td>Au (g/t)</td>
<td>kg/t</td>
<td>kg/t</td>
<td>Au %</td>
</tr>
<tr>
<td>2-pass pre-ox 0.25 kg/t NaCN</td>
<td>0.43</td>
<td>0.11</td>
<td>0.12</td>
<td>5.5</td>
<td>74.2</td>
</tr>
<tr>
<td>2-pass pre-Ox 0.50 kg/t NaCN</td>
<td>0.43</td>
<td>0.09</td>
<td>0.38</td>
<td>5.5</td>
<td>78.9</td>
</tr>
<tr>
<td>2-pass pre-ox 1.50 kg/t NaCN</td>
<td>0.43</td>
<td>0.09</td>
<td>1.22</td>
<td>5.5</td>
<td>78.9</td>
</tr>
<tr>
<td>Plant base 0.76 kg/t NaCN</td>
<td>0.43</td>
<td>0.21</td>
<td>0.67</td>
<td>8.0</td>
<td>50.8</td>
</tr>
</tbody>
</table>

The plant-based direct cyanidation test achieved a gold recovery of 51% (0.21 g/t Au in solids residue) at a cyanide addition of 0.76 kg/t. Lime addition of 8 kg/t CaO was required to achieve the desired leach pH environment of 10.5.

The Aachen pre-oxidation testwork resulted in a maximum gold dissolution of 79% (0.09 g/t Au in solids residue) at cyanide additions of 0.5 and 1.5 kg/t. The lower cyanide addition of 0.25 kg/t led to starvation of the leach and resulted in 5% lower gold dissolution. The pre-oxidation test work required a lower lime addition to achieve the desired pH environment of 10.5.

Initial validations based on plant data

Example 1: BTRP plant-sourced trial data

The Barberton Tailings Retreatment Project is a gold producer with a CIL circuit capacity of 3800 t/d. The gold head grade is typically 1.5 g/t and feed material consists of flotation tails and BIOX tails at a 3:1 blend ratio. To alleviate the effects of cyanide and oxygen consumers in the feed material and maximize gold recovery, a three-pass Aachen pre-oxidation circuit was commissioned in July 2013 and followed up with a metallurgical / economic performance assessment in November 2013.
Reactor parameters
The pre-oxidation circuit is equipped with a single REA 450 unit, driven by a Warman 8:6 AH equivalent slurry pump, which produces a slurry flow rate of 700 m³/h at 400 kPa pressure. The oxygen feed rate is controlled at 0.36 kg/t.

Performance assessment
The assessment was conducted on an on/off basis and the metallurgical performance monitored with specific focus on gold recovery. The campaign ran from 1 to 22 November 2013, with the REA 450 reactor offline from 10 to 13 November. All other process parameters remained unchanged during the monitoring period. The plant-monitored DO levels were >20 ppm during the Aachen operational phase and approximately 10 ppm while the units were offline.

The leach feed and the residue stream were sampled by collecting slurry from the designated auto-samplers throughout the assessment campaign. All the samples were pressure filtered and the solids and solution phases submitted to SGS laboratories for gold analysis.

Results showing gold recovery and residue grade for the duration of the campaign are given in Figure 3. The shaded area indicates the reactor off-time during the short trial phase.

Figure 3 – BTRP: gold recovery (%) and residue grade as a function of time

The results indicate that the gold recovery dropped to approximately 49% during the restricted phase, i.e. operating without Aachen pre-oxidation. Once the reactor was back online the gold recovery increased and stabilized at around 60%, the progressive average recovery for the month of November.

In order to understand the net effect of the process change, a CUSUM chart technique was used to interpret plant data. Graphical data interpretation by this technique relies on the slope of the graph, a negative slope suggesting below-target/average and a positive slope above-target/average. Figure 4 represents the CUSUM for plant recovery vs. time over the evaluation period, 1–22 November.
Building a Resilient Gold Mining Industry

Figure 4 – BTRP: CUSUM of gold recovery as a function of time

The average plant recovery of 62% for the period 1–10 November was considered to be the target for the campaign comparisons. Figure 4 shows that the plant recovery was adversely affected during the off period, indicated as region (a), with recovery significant below the prior average. Once the Aachen reactor was back online, the net effect was an immediate increase in gold recovery to values above the average recovery, illustrated by region (b).

Both regions (a) and (b) illustrate the benefit that the Aachen pre-oxidation circuit lends to the BTRP processing plant.

Example 2: Cooke Surface Operations, plant trial data

Cooke Surface Operations (CSO) is a gold producer with a historical CIP circuit capacity of 12 500 t/d. The gold head grade used to be 0.45 g/t when the feed consisted of Dump 20 sands material only. To alleviate the effects of cyanide and oxygen consumers in the feed material and maximize gold recovery, a two-pass Aachen pre-oxidation circuit was commissioned in July 2012.

Reactor parameters

The pre-oxidation circuit is equipped with two REA 450 units, driven by 2 D-frame Weir pumps (1210) AH equivalent slurry pump, producing a slurry flow rate of 1 500 m³/h at 450 kPa pressure to the reactors. The oxygen feed rate is controlled at 0.73 kg/t. The pre-oxidation tank is of the pachuca type and relies on the Aachen-based circulation flow to sustain solids in solution during the transition.
Aachen Reactors™, a proven system to realize hidden economic potentials

Performance assessment

For the purpose of this paper, the assessment of the CSO plant was conducted for the period April 2012 to April 2013, providing 3 months’ data prior to commissioning and 10 months’ data post-commissioning of the Aachen pre-oxidation circuit. The plant-monitored DO levels were as high as 20 ppm during the Aachen operational phase and 2–4 ppm when the units were offline.

The thickener underflow and the plant residue stream were sampled by collecting slurry from the designated autosamplers throughout the assessment campaign. All the samples were pressure-filtered and the solids and solution phases submitted to SGS Performance Laboratories for gold analysis.

Results showing gold recovery and residue grade for the duration of the campaign are given in Figure 6. The red line indicates the introduction of the Aachen reactors and subsequent elimination of extreme dissolution fluctuations.
The results for the period April to July indicate an erratic gold recovery averaging 69%, which increased to 73%, the progressive average recovery, once the reactors were commissioned.

Figure 7 and Figure 8 represent the CUSUM charts for cyanide addition and residual gold values in deviation of set and agreed target averages (0.195 g/t for residual gold, 0.670 kg/t for NaCN addition). Notwithstanding the usual noise in plant data, the trend appears to point in the desired direction towards sustainable gains.
Aachen Reactors™, a proven system to realize hidden economic potentials

Figure 7 – CSO: CUSUM of residue grade as a function of time

Figure 8 – CSO: CUSUM of NaCN consumption as a function of time
Results and discussion

As is often the case, the direct comparison of laboratory test work results to those obtained at plant level is difficult as a result of changes in feed material. Nevertheless, the data obtained during the plant trials, even though differing from the laboratory tests due to changes in the feed material blends and operational fluctuations, was at this stage seen as sufficiently supportive of the targeted benefits.

Example 1: BTRP

It was assumed that a tailings monitoring blend ratio of near two parts of flotation tails to one part of historical BIOX residue would generate the gold head grade of 1.51 g/t confirmed in the plant trial, based on the original laboratory test work (Table VIII). Using this blend ratio, a predicted leach residue gold content of 0.60 g/t would be expected. This appears to be confirmed by the average residue content of 0.58 g/t for the period in question.

Table VIII. BTRP: Laboratory test work compared to plant trial results

<table>
<thead>
<tr>
<th>Material source</th>
<th>Head grade Au g/t</th>
<th>Residue Au g/t</th>
<th>Recovery % Au</th>
<th>NaCN consumed kg/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory test work</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIOX residue</td>
<td>2.82</td>
<td>1.28</td>
<td>54.5</td>
<td>2.65</td>
</tr>
<tr>
<td>Float tails</td>
<td>0.90</td>
<td>0.28</td>
<td>68.9</td>
<td>2.38</td>
</tr>
<tr>
<td>Plant trial</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blend (unknown ratio)</td>
<td>1.51</td>
<td>0.58</td>
<td>62.0</td>
<td>1.56</td>
</tr>
</tbody>
</table>

The plant-based gold recovery data for the short period the Aachen unit was offline averaged 52%. Thus the recovery benefit when the Aachen unit is running could be as high as an additional 10%, based on a head grade of 1.51 g/t gold. However, due to the limited time of the trial period, it might be more prudent to evaluate the differences in residual gold, which can be quantified as 0.62 g/t for the offline phase and 0.55 g/t following this period. The resulting difference of 0.07 g/t would represent a very conservative benefit estimation.

For the derived basic economical evaluations, the following cost inputs were used:

- Oxygen cost R 2.00 per kg
- Power cost R 1.00 per kWh
- Gold price US$ 1200 per ounce.

The recovery increase based on the potential 10% would equate to over 400 ounces of gold, or US$0.5 million, per month. The more conservative residue difference would contribute US$275 000 per month in additional revenue. This would be offset against an OPEX figure of around US$30 000 per month, including power, oxygen, and rental fees for the Aachen reactor. This difference leaves enough margin for a substantial benefit even under conservative estimates and without considering the cyanide saving.

Example 2: Cooke Surface Operations

The installation of the Aachen units at the CSO tailings reclaim unit was driven largely by the need to reduce the excessive cyanide consumption resulting from high amounts of ferrous iron that originated from Dump 20. As the test work showed additional potential to increase the recovery, attention was paid to both issues. Table IX compares results obtained from the laboratory tests and the plant trial.

A slight deviation in head grade between the two sets of results has obvious impacts on the gold recovery data.

Table IX. CSO: Laboratory test work compared to plant trial results

<table>
<thead>
<tr>
<th>Material source</th>
<th>Head grade Au g/t</th>
<th>Residue Au g/t</th>
<th>Recovery % Au</th>
<th>NaCN consumed kg/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory testwork</td>
<td>0.43</td>
<td>0.09</td>
<td>78.9</td>
<td>0.38</td>
</tr>
<tr>
<td>Plant trial</td>
<td>0.55</td>
<td>0.14</td>
<td>72.7</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The plant data comparison is based on daily data sourced over 80 days prior installation and over 300 days thereafter with both Aachen 450 units in full operation.
Table X. CSO: Pre- and post-installation leach characteristics

<table>
<thead>
<tr>
<th>Trial phase</th>
<th>Head grade Au g/t</th>
<th>Residue Au g/t</th>
<th>Recovery % Au</th>
<th>NaCN consumed kg/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to Aachen installation</td>
<td>0.759</td>
<td>0.191</td>
<td>70.9</td>
<td>0.650</td>
</tr>
<tr>
<td>2 x Aachen 450 units</td>
<td>0.529</td>
<td>0.143</td>
<td>72.2</td>
<td>0.331</td>
</tr>
</tbody>
</table>

As the feed material head grade changed considerably over time, the benefit evaluation might again be conservatively based on residue differences and the cyanide savings.

Thus, for a rough cost benefit estimation, the following observed differences can be applied:
- 0.048 g/t additional gold recovery
- 0.320 kg/t saved cyanide.

Combining these figures with the historical plant throughput of around 300 000 t/month suggests a derived benefit of around US$0.5 million for additional gold recovery and a saving of around US$0.2 million for cyanide. Weighed against the OPEX estimate of US$50 000 per month (considering power, oxygen, and rental fees), this application shows similar cost/benefit ratios to the previous case study and should contribute a considerable benefit towards the bottom line.

Conclusions

The field trials demonstrated that the potential benefits suggested by laboratory data can be translated into tangible profits of comparable levels, provided the feed material is unchanged. Pre-oxidation using Aachen reactors has now been utilized for 2 years at BTRP and 3 years at CSO, and work continues to further optimize the shear and oxygen transfer conditions for different feed materials.

The BTRP trial was of limited duration; a repeat with more extended offline phases should be attempted to further quantify the observed differences, generating sound statistical data in place of the 'snapshot' presented here.

Furthermore, the current empirical approach focused on gold recovery and reagent consumption should be supported by mineral phase surface characterization and more intense analysis of the solution parameters. This might help to assess the various impacts of oxygen and shear in obtaining the desired benefits from a metallurgical perspective.

Nevertheless, the data generated to date from these two operations, as well as yet unpublished records from sites further afield in West and East Africa, suggest that the Aachen high-shear reactors may make a valuable contribution in unlocking hidden potential in certain applications.

These may be characterized as situations where
- Leach kinetics are hindered as a function of limiting oxygen
- Reagent access to gold surface is restricted (coatings or slow diffusion)
- Reagent consumptions are excessive due to oxygen- and cyanide-consuming constituents

With future gold ore sources becoming more complex, there is merit in assessing all available options.

References


